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Orbital elements of the double B star HR 2875

S. Vennes

Department of Mathematics and Astrophysical Theory Centre, Australian National University, Canberra, ACT 0200, Australia
(vennes@maths.anu.edu.au)

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Abstract. Echelle spectroscopy has been obtained at Lick Observatory and at Mount Stromlo Observatory which reveals that the B star plus white dwarf system HR 2875 is actually a triple system comprised of the B3.5 primary, a B6 secondary and the white dwarf. Orbital parameters for the two B stars have been determined and indicate a period P =15.0811 days and an eccentricity e =0.68. The location of the white dwarf relative to the pair of B stars is unknown but may be sufficiently close to perturb their orbit. Further studies of the triple system are planned.

Key words: stars: binaries: spectroscopic – stars: early-type – stars: individual: HR 2875 – stars: white dwarfs – ultraviolet: stars

1. Introduction

The detection of the B star HR 2875 (y Puppis; Hoffleit & Jaschek 1991) by the ROSAT WFC and *Extreme Ultraviolet Explorer* (*EUVE*) revealed the presence of a white dwarf companion (Vennes et al. 1997; Burleigh & Barstow 1998). Systematic searches for white dwarf companions to main-sequence stars aim at defining the initial conditions for the formation of cataclysmic variables (e.g., King et al. 1994), but properties (age, mass) of the white dwarfs in such binaries also help constrain the initial-mass to final-mass relations of stellar evolution (e.g., Vassiliadis & Wood 1993). Candidate systems in the *ROSAT* WFC and *EUVE* extreme ultraviolet (EUV) surveys (see Vennes et al. 1998, and references therein) or the TD-1 far ultraviolet (FUV) survey (e.g., Landsman et al. 1996) show great diversity in pairing of hot white dwarfs with other stars: companions to white dwarf stars range from red dwarfs to high-mass early main sequence star such as HR 2875.

In this work I show that the bright component of the B star plus white dwarf pair HR 2875 is itself a *double-line spectroscopic binary*, making the system triple. Sect. 2 describes new high-dispersion spectroscopic observations and Sect. 3 presents an analysis of the orbital elements and of Hα/Si II line profiles. I summarize in Sect. 4.

2. Observations

I supplement the original radial velocity program at Lick Observatory with new data obtained with Mount Stromlo Observatory's 74-inch telescope between 1997 November and 1999 February. Spectroscopy was performed at the coude focus using the 32-inch camera and a 600 lines mm^{-1} grating resulting in a dispersion of 0.152 Å pixel^{-1} (6.9 km s^{-1} pixel^{-1}) at Hα in the 2nd order, and 0.102 Å pixel^{-1} (7.8 km s^{-1} pixel^{-1}) at Ca H and K in the 3rd order. The spectra were wavelength calibrated with Cu-Ar spectra and flat-fielded with quartz spectra. A resolution element is defined by 2 pixels approximately.

Insufficient data left Vennes et al. (1997) unable to interpret the irregular line profile variations. Additional observations and a closer examination of He I and Si II absorption lines show that the B star is in fact a double-line spectroscopic binary. The deep red-shifted Hα line core is identified with component A and a shallower blue-shifted core with component B. HR 2875A is characterized by strong He I absorption lines, which are lacking in component B. HR 2875A also shows numerous Si II absorption lines, all of them duplicated in HR 2875B, which also appears as the sole absorption component of Si II 4s4P-4p4D lines (6660.532, 6665.026, 6671.841 Å). Table 1 lists He I$\lambda 6678.15$ velocities for component A, and Si II 4s4P-4p4D velocities for component B obtained using gaussian fit within the IRAF "splot" routine. The He I$\lambda 6678.15$ line is strong in all spectra and allows accurate velocity measurements of HR 2875A with an expected error not exceeding one tenth of a resolution element (1.4 km s^{-1}). The Si II 4s4P-4p4D triplet is relatively weaker with estimated measurement errors of the order of 3 km s^{-1}, but it is the only unblended velocity marker of HR 2875B.

3. Analysis

3.1. Orbital elements

A period search identifies the orbital period as $P = 15.^{\rm d}08$, leading to velocity residuals of only $\sigma = 1.5$ km s^{-1}, corresponding to a reduced $\chi^2 \sim 1$. General solutions were calculated for a given period P (or frequency $= P^{-1}$) with χ^2 minimizations of T_0 (time of passage at Periastron), γ (systemic velocity), K (velocity amplitude), e (eccentricity), and ω (longitude of pe-

Table 1. Radial velocities.

HJD (2450000+)	$v_{\rm rad}$ (km s^{-1})	HJD (2450000+)	$v_{\rm rad}$ (km s^{-1})
HR 2875A: He I λ6678.15			
456.86390	+70.5	819.99584	+28.6
457.87830	+29.8	865.00029	+29.7
458.91457	+17.8	865.94693	+20.9
459.81889	+16.3	866.00458	+19.2
485.72036	+40.4	866.95657	+15.2
485.82688	+42.6	867.18872	+15.4
488.69803	+20.3	892.00373	+33.1
488.81002	+19.8	892.12720	+33.1
519.70363	+16.9	906.92075	+31.7
562.87709	+45.2	907.99353	+40.1
562.96105	+42.7	908.95321	+69.1
563.91044	+22.8	954.83741	+53.1
772.09152	+39.1	993.85925	+21.6
772.16855	+41.0	993.86665	+20.3
772.23392	+41.1	993.87252	+20.0
772.25327	+40.6	1146.24390	+22.8
787.13242	+38.1	1221.91214	+22.5
787.14058	+37.5	1221.92951	+22.1
787.14862	+36.4	1221.94687	+22.0
787.16039	+38.7	1222.08159	+24.6
812.14293	+20.7	1222.18436	+25.2
812.24225	+20.4	1222.93366	+25.8
817.03901	+39.3	1223.03366	+26.0
817.04439	+39.1	1223.15240	+26.1
817.06418	+39.3	1223.23296	+29.5
817.07179	+37.7	1223.92322	+32.5
819.97194	+28.3	1224.11975	+35.1

Table 1. (continued)

HJD (2450000+)	$v_{\rm rad}$ (km s^{-1})	HJD (2450000+)	$v_{\rm rad}$ (km s^{-1})
HR 2875B: Si II λ6660.532, 6665.026, 6671.841			
562.87709	−14.4	865.00029	+15.8
562.96105	−4.4	865.94693	+29.0
563.91044	+25.8	866.00458	+30.1
772.09152	+0.6	866.95657	+36.1
772.16855	+1.7	867.18872	+32.5
772.23392	+0.6	892.00373	+16.2
772.25327	+0.3	892.12720	+15.5
787.13242	+2.1	906.92075	+18.7
787.14058	+7.7	907.99353	−2.4
787.16039	+4.5	908.95321	−45.6
812.14293	+34.4	954.83741	−13.2
812.24225	+35.4	993.85925	+37.8
817.04439	+11.5	993.86665	+36.2
817.07179	+14.2	993.87252	+31.1
819.99584	+24.2	1146.24390	+27.4

riastron), using P. Maxted IDL routine and following Heintz (1978); average radial velocity residuals were calculated as a function of P. The solution at a period of $P = 15\overset{\rm d}{.}08$ appeared distinctly superior to its first harmonic at a period of $7\overset{\rm d}{.}54$.

The orbit of component B is then computed holding the orbital period fixed at the best value. Table 2 lists the orbital parameters and Fig. 1 shows phased velocities and orbital solutions for both components. Supposing a mass of 5-6 $M_\odot$ for the primary HR 2875A, the measured mass ratio $q = M_A/M_B = 1.45 \pm 0.17$ shows that HR 2875B has a mass of 3.5-4.2 $M_\odot$, and is a likely B5-7 V star ≈ 1 mag fainter.

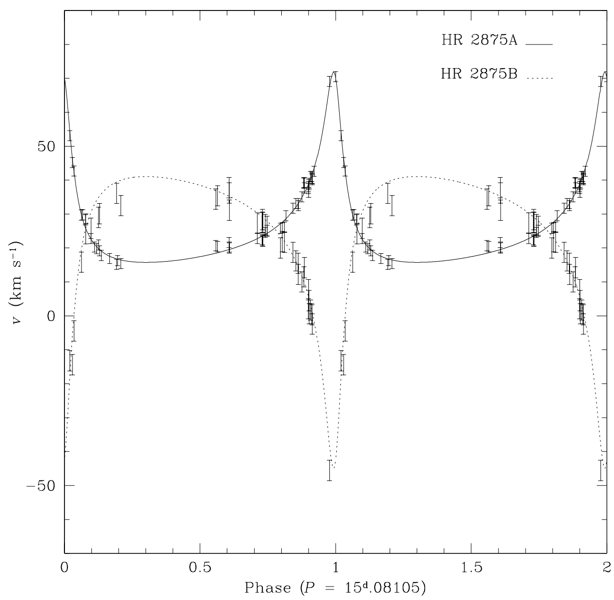

Fig. 1. Phased radial velocities of the newly identified double B star HR 2875AB. The pair is accompanied by a hot white dwarf identified in *EUVE* spectroscopy.

3.2. Hα and Si II *spectroscopy*

The high-dispersion spectrum obtained on 1998 April 5 (HJD = 2450908.95321) at orbital phase $\Phi = 0.9773$ shows well resolved Hα line cores from both stars. A second spectrum with coverage of the upper Balmer line series as well as Ca H and K and Si II lines was obtained the same night (HJD = 2450908.96705) at orbital phase $\phi = 0.9782$. I analyze the combined Hα line profile using H/He ($y = 0.1$) non-LTE model atmospheres (TLUSTY version 195; see Hubeny & Lanz 1995), and using a set of isochrones (age= $1, 2, 3, 4, 5, 6, 7, 8 \times 10^7$ years) computed with the code "iso.f" presented by Meynet et al. (1993) and stellar models at $Z = 0.02$ (Schaller et al. 1992). For a given age, the code supplies the effective temperature, surface gravity, and absolute magnitude as a function of mass. With the requirement that the two stars be the same age, the procedure reduces the number of free parameters from five ($T_{\rm eff,A}$, $T_{\rm eff,B}$, log $g_{\rm A}$, log $g_{\rm B}$, and flux ratio at V, $f_{\rm V,A}/f_{\rm V,B}$) to just three ($T_{\rm eff,A}$, $T_{\rm eff,B}$, and log $g_{\rm A}$).

Fig. 2 shows an analysis of the combined Hα line profile in the ($T_{\rm eff}$, log g) plane along with theoretical isochrones. Böhm-Vitense (1981) reviewed the effective temperature scale for B stars and nominal spectral types are shown along the effective temperature axis. Confidence contours at 66, 90 and 99% show

Table 2. Orbital parameters.

	HR 2875A	HR 2875B	Weighted mean
P (days)	15.0811±0.0001	...	15.0811±0.0001
γ (km s^{-1})	25.7±0.5	23.3±0.5	24.9±0.5
K (km s^{-1})	28.0±1.9	40.4±2.0	...
e	0.685±0.017	0.662±0.020	0.677±0.010
ω (deg)	20±1	16±2	19±2
T_0 (HJD 2450000+)	411.62±0.02	411.56±0.02	411.60±0.02

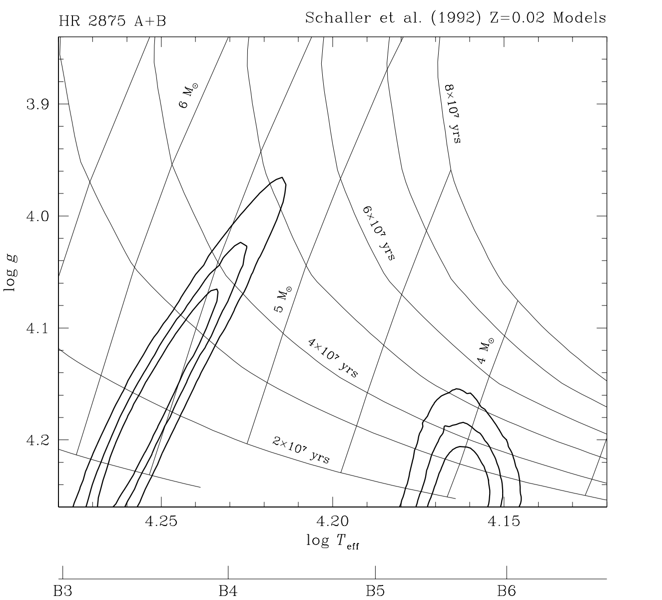

Fig. 2. Theoretical Hertzsprung-Russell diagram in (log $T_{\rm eff}$, log g) plane showing isochrones at 1, 2, 3, 4, 5, 6, 7 and 8×10^7 years and curves of constant masses at 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5 $M_\odot$. Confidence contours at 60, 90, and 99% show likely stellar parameters for HR 2875A and B.

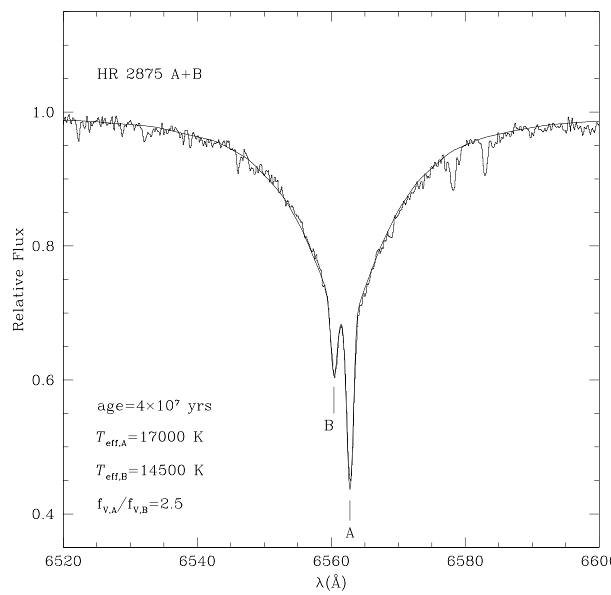

Fig. 3. MSO spectroscopy and best model combination at $T_{\rm eff,A} = 17000$K and $T_{\rm eff,B} = 14500$K. Relative flux contribution of the two stars at V is $f_{\rm V,A}/f_{\rm V,B} = 2.47$. The best model fit is convolved with a rotation broadening function matching the few central pixels (v sin i= 20 km s^{-1}).

Table 3. Stellar parameters at 90% confidence ($3.2 \times 10^7 \leq$ age $\leq 4.5 \times 10^7$ years).

	HR 2875A	HR 2875B
$T_{\rm eff}$ (K)[a]	16800-17500	14200-14800
log g (c.g.s.)[b]	4.05±0.03	4.20±0.02
$M_{\rm V}$ (mag)[b]	-1.0 ± 0.2	-0.1 ± 0.1
M ($M_\odot$)[b]	5.3-5.7	3.8-4.2
log Si/H[c]	-4.6 to -5.2	-2.8: to -3.2:

[a] From Hα spectral synthesis.
[b] From Schaller et al.'s (1992) models and Meynet et al.'s (1993) isochrones.
[c] From Becker & Butler's (1990) equivalent width tables.

distinct solutions for the hot component A and the cooler component B. Some implications are:

Age of the system. Low surface gravities are excluded showing that the two stars are still on the main sequence with a maximum age $\leq 4.5 \times 10^7$ years. A minimum age is set by the cooling age of the present day white dwarf added to its prior lifetime. Adopting Vennes et al.'s (1997) parameters of a $1 M_\odot$ white dwarf and Wood's (1995) evolutionary models, the cooling age of the white dwarf is estimated at 10^7 years; adding H-burning and He-burning lifetimes for a white dwarf progenitor between 8 and $10 M_\odot$ to the white dwarf cooling age, I estimate the total age of the system between 3.2 and 4.5×10^7 years. Given the age of the pair of B stars, an agreement between the total evolutionary age of the white dwarf and the age of the B-star pair is only possible if the mass of the white dwarf progenitor was $\geq 8 M_\odot$. A lower mass for the white dwarf progenitor is possible for shorter white dwarf cooling age.

Parameters of the B stars. Surface gravity, effective temperature, absolute luminosity and mass of the B stars are estimated from the 90% confidence contours and by restricting the age of the system to 3.2-4.5×10^7 years. Fig. 3 shows the best fit to the combined line profile using best parameters at an age $= 4 \times 10^7$ years, and Table 3 presents likely parameters. The effective temperature and surface gravity measurements suggest that HR 2875A is a B3.5 V star and HR 2875B is a B6V, and also imply a mass ratio $M_A/M_B = 1.4 \pm 0.1$ consistent with the orbital solution. Adopting the above masses, I infer a low binary inclination of $i = 16°$, a major axis of $a \sim 54\ R_\odot$, and a minor axis of $b \sim 40\ R_\odot$.

Silicon abundance. The measured equivalent widths of Si II $\lambda\lambda$4128.067, 4130.893 were corrected for continuum dilution, using model flux ratios at $\lambda \sim 4130$Å, by a factor of 1.4 for HR 2875A ($E.W._{\lambda 4128} =$ 95 and $E.W._{\lambda 4130} =$ 120 mÅ) and a factor 3.6 for HR 2875B ($E.W._{\lambda 4128} =$ 360 and $E.W._{\lambda 4130} =$ 460 mÅ). The silicon abundance is estimated from these adjusted equivalent widths and from Becker & Butler's (1990) tables with $v_{\rm turb}$ allowed to vary between 0 and 6 km s^{-1}. The silicon abundance in HR 2875A is below solar, but line strengths in HR 2875B suggest an abundance well in excess of 10^{-4}, the largest abundance tabulated by Becker & Butler. The silicon abundance in HR 2875A (log Si/H$= -4.6, -5.2$) may be compared to samples of early B-type stars. The effective temperatures in Kilian's (1992) sample extend from 32,000 down to 21,000 K, with the optical silicon abundance decreasing to a minimum value of log Si/H~ -5.3 at $\sim$21,000K. Pintado & Adelman (1993) and Adelman & Philip (1994) list optical measurements showing the silicon abundance increasing with effective temperature to a value of log Si/H~ -4.5 at $\sim$15,000 K. Singh & Castelli (1992) obtained ultraviolet abundance measurements between log Si/H$= -4.5$ and -5.0 in a sample of objects with effective temperatures between 10,320K and 23,470K. The abundance in HR 2875A is clearly within the range of normal B stars. On the other hand, with a silicon abundance of log Si/H> -4.0, HR 2875B is a likely B6VpSi star. Artru & Lanz's (1987) analysis of ApSi and BpSi stars reveals ultraviolet silicon abundance close to log Si/H~ -3.0, possibly similar to the abundance in HR 2875B. An extrapolation of Becker & Butler's (1990) tables suggests an abundance between log Si/H$= -2.8$ and -3.2. The ApSi stars are generally slow rotators (Abt 1979), a phenomenon often associated with age or the effect of magnetic braking (see a discussion in North 1998). Narrow Hα cores (see Fig. 3) impose a low projected rotation velocity of v sin $i = 20$ km s^{-1}, or, for a system inclination of $i = 16°$, a rotation velocity of 73 km s^{-1} comparable to ApSi stars. Moreover, given the presence of a degenerate star in the system, HR 2875B is a relatively old main sequence star with log $age =$ 7.6, an age at which the ApSi phenomenon appears more frequently (Abt 1979).

4. Summary

The bright star HR 2875 (y Puppis) is a triple system with two B stars (B3.5 V + B6 V) in a close eccentric orbit. The apparent line profile variations and intermittent emission reported previously are entirely explained by the double-lined nature of the spectrum of this binary. Buscombe & Morris' (1958) radial velocity measurements are also within the orbital velocity amplitude and certainly reflected these variations. The mass ratio determined from the stellar parameters and evolutionary models ($M_A/M_B = 1.4 \pm 0.1$) is consistent with the mass ratio determined from the orbit ($M_A/M_B = 1.45 \pm 0.17$).

The silicon abundance appears normal in HR 2875A but is much larger in HR 2875B, possibly responsible for the line strength anomaly noted by Hiltner et al. (1969).

The photometric variability noted by Vogt et al. (1998) is possibly related to the binary nature of HR 2875 or to the probable B6VpSi classification of HR 2875B, but eclipses are excluded by the low system inclination.

The location of the white dwarf relative to the B stars is unknown but may be detectable through perturbation of the orbit, possibly resulting in a drift of the systemic velocity with time (γ). Further radial velocity studies of the system are planned.

If the third star has already evolved into a white dwarf it must have been more massive than $\sim 5.5 M_\odot$, therefore all main sequence stars with masses up to at least $\sim 5.5 M_\odot$ will likely evolve into white dwarfs as well. Taking into consideration prior evolution of the present day white dwarf, the upper mass limit for the formation of white dwarf stars may well extend to $\sim 8 M_\odot$.

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