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The massive Wolf–Rayet binary SMC WR7

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ABSTRACT

We present a study of optical spectra of the Wolf–Rayet star AzV 336a (=SMC WR7) in the Small Magellanic Cloud. Our study is based on data obtained at several Observatories between 1988 and 2001. We find SMC WR7 to be a double-lined WN+O6 spectroscopic binary with an orbital period of 19.56 d. The radial velocities of the He absorption lines of the O6 component and the strong He II emission at λ4686 Å of the WN component describe anti-phased orbital motions. However, they show a small phase shift of ∼1 d. We discuss possible explanations for this phase shift. The amplitude of the radial velocity variations of He II emission is twice that of the absorption lines. The binary components have fairly high minimum masses, ∼18 and 34 M$_\odot$ for the WN and O6 components, respectively.

Key words: binaries: spectroscopic – stars: individual: AzV 336a (=SMC WR7) – stars: Wolf–Rayet.

1 INTRODUCTION

Many of the most luminous stars in the central cluster of the 30 Doradus Supergiant H II region in the Large Magellanic Cloud are stars with emission lines of nitrogen and helium in their spectra (Massey & Hunter 1998), classified as Wolf–Rayet (WR) stars of WN type. The luminosities of these stars in 30 Dor, when compared with numerical evolutionary tracks of massive stars, would correspond to stars of initial masses of 80–120 M$_\odot$. However, no stars more massive than ∼60 M$_\odot$ are known from studies of binary star orbits, the most massive at present being R136-038, an eclipsing O3 star in the R 136 cluster (Massey, Penny & Vucovich 2002).

In our Galaxy, the most massive star known in a binary system, with a mass of 50–60 M$_\odot$, is the WN type star HD 92740 in the Giant Carina H II region (cf. Schweickhardt et al. 1999, and references therein). This seems to suggest that WN stars, at least those associated with giant H II regions, are related with the upper limit of the stellar masses. Indeed, the new stellar evolutionary tracks which take rotation into account (cf. Meynet & Maeder 2000) predict high mass loss rates at young ages for the most massive stars. Empirical determination of stellar masses from binary star orbits are needed for stars with WN spectra in H II regions to elucidate the role played by these stars at the upper mass limit.

In this paper we present a radial velocity study of a star with WR spectrum in an H II region in the Small Magellanic Cloud (SMC), namely SMC WR7, showing it to be a double-lined spectroscopic binary with components of high minimum masses.

In their search for stars with WR spectra in the SMC, Azzopardi & Breysacher (1979) found a star that showed broad He II 4686 Å emission in the optical spectrum. The star was called SMC/AB7, and interpolated with the number 336a in the catalogue of SMC members (Azzopardi & Vigneau 1979). In their recent new survey for WR stars in the SMC, Massey & Duffy (2001) proposed to use the denomination of SMC WR7 instead, according to the IAU nomenclature recommendations, which we will follow here.

Azzopardi & Breysacher (1979) considered the spectrum of SMC WR7 to be of peculiar WN3 type, because no N emission lines were observed. The presence of a companion was inferred from the observed strong continuum in the spectrum. Absorption lines were subsequently detected in the spectrum of SMC WR7 by Moffat (1988) and Conti, Massey & Garmany (1989). Moffat (1988) assigned an approximate spectral type O7 for the absorption line spectrum, and also found the radial velocity of the absorption and emission lines to be variable, but could not determine a binary period. Massey & Duffy (2001) classify the emission line spectrum as WN2, and the absorption line spectrum as type O6.

SMC WR7 lies embedded in the bright H II region N76-A (Henize 1956), and is one of the few Population I stars surrounded

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Table 1. Observational details used for digital (CCD) spectra of SMC WR7.

Nr.	Observatory	Epoch(s)	Telescope	Spectrograph[a]	disp. (Å/px)	$\Delta\lambda$ (Å)	exp.time (min)	S/N
1	CTIO	1988 November	1-m	2DF	.4	3750–5050	30	20
2	CTIO	1990 December	1-m	2DF	.4	3750–5050	60	35
3	ESO	1992 December	1.5-m	B&C	1.9	3700–7100	20	80
4	CASLEO	1994 January	2.1-m	REOSC	2.2	3800–6000	15	80
5	ESO	1995 January	1.5-m	B&C	.5	3900–4900	30	30
6	ESO	1995 December	1.5-m	B&C	.5	3950–4950	60	40
7	CTIO	1996 October	1.5-m	Cass.	1.1	3750–5050	10	45
8	CASLEO	1996 December, 1997 December	2.1-m	B&C	2.2	3900–5000	30	120
9	CASLEO	1996 January, 1998 September	2.1-m	REOSC	.3	4620–4750	45	30
10	CTIO	1999 January	4.0-m	R-C	.4	3700–5000	10	100
11	CTIO	1999 October, 2000 October	1.5-m	Cass.	.6	4100–4750	15	45
12	CASLEO	1999 November, 2000 July, September	2.1-m	REOSC	1.8	3900–5500	60	200

[a] Details of the spectrographs can be found in the User's Manuals of the respective Observatories.

Table 2. Journal of observations of SMC WR7.

HJD	Heliocentric Radial Velocity (km s^{-1})			HJD	Heliocentric Radial Velocity (km s^{-1})		
	Nr.OD	O6 abs.(n)	He II4686 em.		Nr.OD	O6 abs.(n)	He II4686 em.
7469.630	1	235(3)		10 432.628	8	116(2)	257
7474.720	1		394	10 434.632	8	161(2)	113
7475.729	1		396	10 435.628	8	190(2)	44
7477.702	1		328	10 436.601	8	214(2)	19
7479.702	1	124(1)	272	10 437.625	8	249(2)	−6
7480.578	1		69				
7481.618	1		66	10 810.589	8	275(3)	3
				10 811.575	8	277(3)	16
8249.592	2	270(5)	−51				
8250.592	2	272(5)	13	10 966.918	8		−27
8251.587	2	216(5)	148				
8252.587	2	168(4)	214	11 077.649	9		324
8253.592	2	141(3)	264	11 078.747	9		171
				11 079.724	9		74
8982.535	3	66(6)	355	11 080.718	9		81
8982.643	3	62(3)	327	11 083.706	9		0
8983.552	3	88(2)	328	11 084.689	9		−71
8983.594	3	85(3)	267:	11 085.689	9		−75
8983.619	3	80(2)	287				
				11 182.543	10	272(4)	−10
9372.602	4		347	11 183.527	10	278(4)	36
9373.546	4		341	11 185.527	10	262(4)	139
9374.558	4		341				
				11 470.527	11	126(3)	136
9742.542	5	106(2)	322	11 471.660	11	192(3)	122
9743.533	5	103(3)	382	11 472.493	11	196(1)	67
9744.531	5	93(3)	383	11 474.614	11	240(1)	−27
9744.555	5	78(2)	386	11 475.705	11	288(3)	−10
9745.528	5	72(2)	377	11 477.563	11	295(3)	67
9745.551	5	105(3)	389	11 479.497	11	239(3)	154
				11 480.515	11	209(3)	213
10 077.537	6	72(3)	387				
10 077.563	6	92(2)	392	11 496.620	12	258:(3)	71
10 079.541	6	107(3)	308				
10 080.544	6	104(3)	232	11 751.805	12	287(3)	86
10 081.591	6	142(2)	180	11 753.784	12	217(1)	201
10 086.620	9		26	11 806.746	12	247(3)	14
10 383.579	7	215(2)	72	11 827.496	11	289(3)	−19
10 385.497	7	189(3)	173	11 828.511	11	271(2)	0
10 386.495	7	142(2)	230	11 829.500	11	270(2)	32
10 387.493	7		261				

Notes: HJD = Heliocentric Julian Date − 2 440 000 d. Nr. OD refers to the observational details listed in Table 1, and (n) is the number of He absorption lines included in the mean velocity of the O6 component.

by extended nebular emission of He II 4686 Å (cf. Testor & Pakull 1989; Niemela, Heathcote & Weller 1991). The high ionization of the nebula led Pakull & Bianchi (1991) to propose a very high effective temperature for the WN star in SMC WR7.

Massey, Waterhouse & DeGioia-Eastwood (2000) studied the surrounding OB association Hodge 53 and predicted a very high progenitor mass (>50) for SMC WR7, based upon the turn-off mass of the cluster. They also determined an absolute magnitude $M_V = -5.9$, and a lower limit for the bolometric correction (B.C.) of ~ -4.5. However, the coevality of star formation within Hodge 53 was ranked 'questionable' by Massey et al. (2000), and the binary nature of SMC WR7 is not yet fully recognized.

2 OBSERVATIONS

We have obtained 69 digital optical spectral CCD images of SMC WR7, mainly in the blue spectral region, with several telescopes and spectrographs between 1988 and 2001 at Cerro Tololo Interamerican Observatory (CTIO) and European Southern Observatory (ESO) in Chile, and the Complejo Astronómico El Leoncito (CASLEO[1]) in Argentina. The telescopes and instrumental configurations are listed in Table 1. Our main aim was to determine the radial velocity orbit of this WN + O binary.

One-dimensional spectra were extracted from our two-dimensional spectral images using either IRAF (CTIO and CASLEO spectra) or MIDAS (ESO spectra) routines. These spectra were subsequently wavelength-calibrated for the determination of positions of spectral lines. Radial velocities for all spectra were determined using IRAF routines. For the absorption lines we fitted gaussian profiles to the lines. Because the nebular emission is strong in hydrogen Balmer absorptions, we chose to use only He lines, mainly He II absorptions, for the mean radial velocities of the O-type component. Depending on the observed wavelength range, the radial velocity of the O-type component was determined as an average of the lines of He II $\lambda\lambda$4200, 4541, 5411, occasionally including He I $\lambda\lambda$4026, 4387, 4471, 5875 Å.

The spectrum of the WN component is dominated by the strong emission of He II 4686 Å, the only emission line for which we could determine radial velocity values in all of our spectra. The radial velocities for this emission were determined by both fitting a Gaussian and finding the line centre. When these two values were noticeably different, which happened when the emission appeared to be asymmetrical, then the line centre was preferred; otherwise a mean of the two was used. The mean radial velocities of the absorption lines and the He II 4686 Å emission are listed in Table 2.

3 RESULTS AND THEIR DISCUSSION

Early results of part of our observations showed that SMC WR7 indeed is a binary with a probable mass ratio of ~0.5 (Niemela 1994); and a preliminary orbital solution (Niemela & Morrell 1999) indicated very massive binary components.

3.1 The period

The data in Table 2 clearly confirm the variability of the radial velocities. We have searched for periodicities in the radial velocity variations of both the absorptions and of the He II emission listed in Table 2. We used the algorithm published by Cincotta, Mendez & Nuñez (1995). For the radial velocity variations of the He II emission we also included the velocities published by Moffat (1988). We find the best period for the radial velocity variations of the absorption lines to be P = 19.563 ± 0.003 d, and that of the He II emission P = 19.5600 ± 0.0003 d. This latter period appears to be more accurate because of the longer time baseline in adding the previously published data. The previously published absorption line velocities appeared too noisy for an improvement in the period. Thus we have adopted the orbital period of SMC WR7 to be 19.560 d.

3.2 The radial velocity orbit

The radial velocities of the absorptions and the He II emission listed in Table 2 describe opposite orbital motions when phased with the period of 19.56 d, thus confirming that SMC WR7 is a double lined O + WN binary system. However, a small phase lag of ~1 d appears between the two radial velocity curves. This is illustrated in Fig. 1, which depicts the radial velocities phased with the period of 19.56 d adopting a common origin for the phases. In this figure the maxima and minima of the radial velocities of the He II emission and the absorption lines do not coincide exactly as expected from opposite orbital motion.

Phase-lags between the He II 4686-Å emission line and the orbit defined by the absorption lines of the binary companion are observed in other WR + OB binary systems, e.g. WR97 in our Galaxy (Niemela, Cabanne & Bassino 1995). However, the origin of these phase lags is not understood. Also, in active binaries with compact components, e.g. the cataclysmic binaries and X-ray binaries, the He II 4686-Å emission line orbit is slightly out of phase from the absorption line orbit. This effect is then ascribed to a hotspot in an accretion disc. Stars with Wolf–Rayet spectra are usually not thought to have discs, but (spherically symmetric?) strong winds. The phase lag may be related to the colliding winds of the binary components.

We have performed an orbital fit separately for the radial

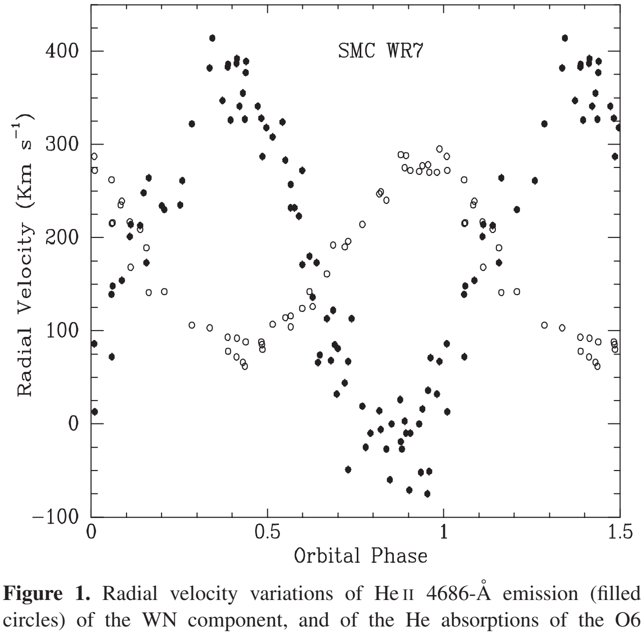

Figure 1. Radial velocity variations of He II 4686-Å emission (filled circles) of the WN component, and of the He absorptions of the O6 component (open circles) in the SMC WR7 binary system, phased with the period of 19.56 d. Note the phase shift of the radial velocity curves, which have a common origin in HJD 2 447 468.0.

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[1] CASLEO is operated under agreement between CONICET, SECYT, and the National Universities of La Plata, Córdoba and San Juan, Argentina.

velocities of the O star and the WN star. The orbital elements are listed in Table 3. These orbital elements are still to be considered preliminary, since the observed phase lag between the absorption line orbit and the He II 4686-Å emission casts some doubts on this last line as representative of the true orbital motion of the WN component. We note that the minimum masses of the binary components appear to be quite high, 34 and 18 $M_{\odot}$ for the O6 and WN2 components, respectively. With such high minimum masses we would expect to observe light variations, if not eclipses.

Table 3. Preliminary orbital parameters for SMC WR7.

	abs.	He II4686 em.
$a \sin i$ [$R_{\odot}$]	39 ± 1	75 ± 1
K [km s^{-1}]	101 ± 2	196 ± 4
V_o[km s^{-1}]	172 ± 2	172 ± 3
$M \sin^3 i$ [$M_{\odot}$]	34 ± 4	18 ± 2
e	0.10 ± 0.02	0.07 ± 0.02
ω [deg]	28 ± 12	101 ± 16
T_o [HJD] 2.440.000+	7468.0 ± 0.6	7480.7 ± 0.8
P [d]	19.560 ± 0.0005	

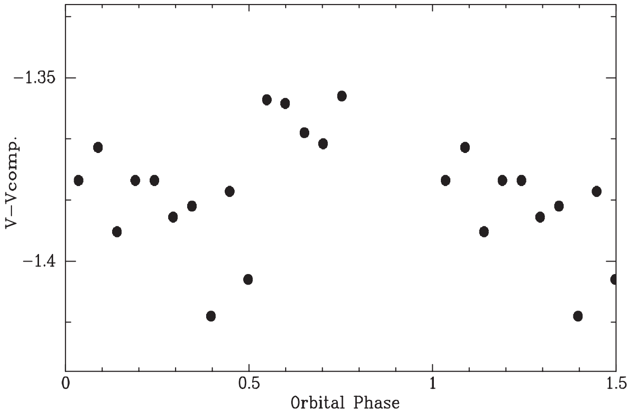

Figure 2. Photoelectric light variations of SMC WR7 phased with the same ephemeris as the radial velocity variations in Fig. 1. Data are from Seggewis et al. (1991).

From photoelectric photometry Seggewiss, Moffat & Lamontagne (1991) found SMC WR7 to be slightly variable. In Fig. 2 we have plotted these light variations with the same ephemeris as the radial velocity curves in Fig. 1. The minimum light then occurs just after the WR star passes in front of the system. This could be a wind eclipse, but more numerous data are needed to confirm the nature of the light variations. A wind eclipse would indicate an orbital inclination of at most ~60°, which would bring the individual masses of the binary components to 28 $M_{\odot}$ for the WN component, and 54 $M_{\odot}$ for the O6 component.

SMC WR7 has also been observed by the Optical Gravitational Lensing Experiment (OGLE) (cf. Udalski et al. 1998) where it appears as the star SMC_SC9 37124. OGLE did not detect photometric variations of SMC WR7 in their 14 *B*, 23 *V*, and 108 *I* broad-band observations to within 0.015, 0.019 and 0.024 mag in each band, respectively. However, because the individual data are not published, their distribution according to the binary orbit is not known.

3.3 Spectra of the binary components

The blue spectrum of SMC WR7 is illustrated in Fig. 3, which shows a spectrum obtained at CTIO in 1999 January. The spectral type corresponding to the OB absorption lines in Fig. 3 confirms the classification as O6 from the relative intensities of He I 4471-Å and He II 4542-Å absorptions. The luminosity class is difficult to ascertain, as the WN emission dominates the He II 4686 Å, which is the main luminosity indicator for early O-type spectra in the blue spectral region. We also note that the O6 spectrum seems to dominate the continuum, hence the absolute magnitude $M_V = -5.9$ of SMC WR7 (Massey et al. 2000) mainly corresponds to the O6 component of the binary.

In several of our spectra there appears a faint emission line at ~λ4640 Å, which we identify as N III. We have been able to determine the radial velocity of this feature in 17 of our spectra. When we phased these velocities with the same ephemeris as those in Fig. 1, it is clear that the N III emission follows the same orbital motion as the O6 component of the binary. Fig. 4 illustrates the radial velocity variations of the N III emission in the spectrum of SMC WR7. Given the high absolute magnitude, the most probable

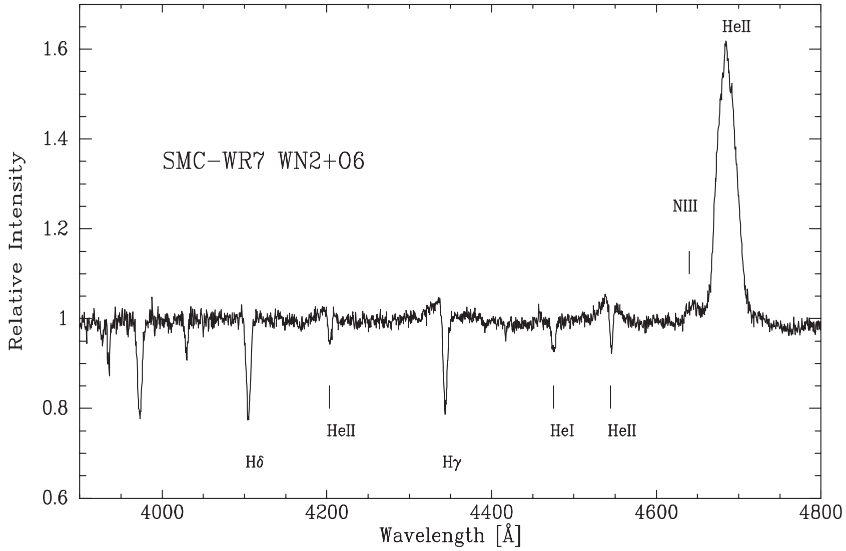

Figure 3. Continuum rectified spectrum of SMC-WR7 obtained at CTIO in 1999 January. Absorption lines are identified below, and emission lines above the continuum.

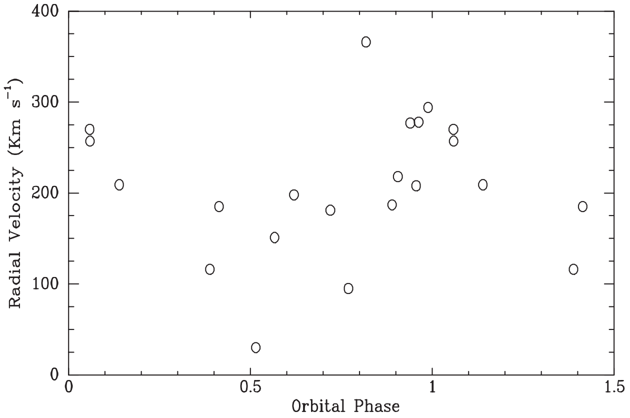

Figure 4. Radial velocity variations of the faint N III emission in the spectrum of SMC WR7 phased with the same ephemeris as the radial velocity variations in Fig. 1.

spectral classification of the absorption line component then is O6I(f).

Otherwise, the emission line spectrum only shows lines of He II. Thus we keep the WN2 classification for the emission line spectrum (cf. Massey & Duffy 2001).

3.4 Comparison with the theoretical WNE mass–luminosity relation

If stars with Wolf–Rayet spectra are bare He-burning cores, they should obey a tight mass–luminosity relation (e.g. Schaerer & Maeder 1992). In this relation, the high minimum mass of the WN2 component of SMC WR7, namely 18 $M_\odot$, would imply $M_{\rm bol}$ higher than -9.5.

Considering that the WN2 star of the SMC WR7 binary appears as the source of the very high ionization in the H II region N76-A, which shows strong nebular He IIλ4686 Å emission, Pakull & Bianchi (1991) estimated a blackbody Zanstra temperature of 80 kK for the WN2 star. Such a high temperature implies a large B. C., certainly higher than the minimum $B.\ C. \sim -4.5$ determined by Massey et al. (2000). Adopting the approximate relation between B. C. and temperature published by Vacca, Garmany & Schull (1996) results in $B.\ C. = -5.8$ for the WN2 star. This is in keeping with the average $B.\ C. \sim -6.0$ for WNE stars found previously (cf. Massey et al. 2000, and references therein).

The OGLE photometry of SMC WR7 gives $V = 13.221$ and $B - V = -0.194$. Because the O6 component dominates the visual light, the intrinsic $(B - V)_o = -0.32$. Adopting the distance modulus 18.9 for the Small Magellanic Cloud (e.g. van den Bergh 2000), then results in $M_v = -6.1$ for the binary system. This is similar to the previously published values $M_v = -5.9$ (Massey et al. 2000), and $M_v = -6.2$ found by Crowther (2000), who also estimated $M_v = -5.2$ for the WN component of the binary. If this component contributes only 30 per cent to the optical light of the system (cf. Pakull & Bianchi 1991), then the WN2 star has $M_v \sim -4.6$. With the $B.\ C. = -5.8$ (see above), this star would then have $M_{\rm bol} = -10.4$. Within the uncertainties, this value corresponds to a star of 28 $M_\odot$ according to the mass–luminosity relation for models of WNE stars (Scharer & Maeder 1992), indicating an orbital inclination close to ~60° for the SMC WR7 binary system. Further discussion on the mass–luminosity relation shall await a careful photometric analysis of the SMC WR7 binary system in order to establish a reliable estimate of the orbital inclination.

4 SUMMARY

From spectral observations of SMC WR7 over several years, our findings are as follows.

(i) Opposite radial velocity variations of the absorption lines and He II λ4686-Å emission show this star to be a double lined O6 + WN2 spectroscopic binary system.

(ii) The most probable period of the radial velocity variations is 19.560 d.

(iii) In this period, the radial velocity orbit of He II λ4686-Å emission describes an orbit with a small phase lag of ~1 d relative to the orbit defined by the absorption lines.

(iv) Minimum masses of the binary components are quite high; 18 and 34 $M_\odot$ for the WN and O6 components, respectively.

(v) Published photoelectric data of SMC WR7 phased with the 19.560-d period may indicate a wind eclipse of the O6 star when the WN component is in front of the system, precluding high orbital inclinations.

(vi) If the WN2 component obeys the theoretical mass–luminosity relation for WNE stars (Schaerer & Maeder 1992), an orbital inclination of the order of 60° is predicted.

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