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THE WN4 + O4–6 WOLF-RAYET BINARY HD 90657

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ABSTRACT

HD 90657 is shown to be a WN4 + O4–6 binary, much like the WN4 + O9 binary HD 186943 with mass ratio M(W-R)/M(O) ≈ 0.52. The best W-R orbit is derived from the emission lines of highest excitation, which show the least phase shift relative to the (reliable) absorption-line orbit due to the O component. Light curve variations restrain the masses to the range ≈11–14 $M_\odot$ for the WN4 component, and 21–28 $M_\odot$ for the O-type component.

Subject headings: stars: binaries — stars: early-type — stars: individual — stars: Wolf-Rayet

I. INTRODUCTION

Recently, evidence has been accumulating that not all Population I Wolf-Rayet stars have similar masses (Niemela and Sahade 1980; Niemela, Conti, and Massey 1980; Niemela 1981; Massey 1981*b*). But whether all Population I Wolf-Rayet stars that exhibit similar spectra, i.e., those with similar spectral subtype, also have similar mass *ratios* M(W-R)/M(O) (or possibly even masses) as proposed by Moffat (1981), is still an unsettled question. This can only be answered by more observations of double-line binary systems with W-R type components leading to estimates of individual stellar masses.

HD 90657 is a moderately bright ($v = 9.80$, $b - v = 0.30$) double-line spectroscopic binary located near the Carina Nebula in the southern sky. A preliminary orbit of this binary, containing an early O-type (O4–6) and a W-R star of the hot WN sequence (WN4), has been published by Niemela (1976, 1980). Here we report new spectroscopic and photometric observations of HD 90657, with an improved orbital solution.

II. OBSERVATIONS

Thirty-three new, blue, slit spectrograms of HD 90657 were obtained by V. S. N. at the Cerro Tololo Interamerican Observatory, Chile. Twenty-eight of these spectra (plates labeled E) were secured with the Cassegrain spectrograph equipped with an image-tube at the 1.0 m Yale telescope. Five spectra (plates labeled C) were obtained with the Cassegrain spectrograph (without image-tube) at the 1.5 m reflector. The C plates have a reciprocal dispersion of 38 Å mm^{-1} on N_2-baked Kodak IIa-O emulsion with 0.6 mm widening; the E plates have a reciprocal dispersion of 45 Å mm^{-1} on Kodak IIIa-J emulsion, baked in forming gas, with 1 mm widening.

All lines visible in the spectrograms were measured for radial velocity by V. S. N. with the Grant oscilloscope measuring engine at the Instituto de Astronomia, Buenos Aires. The individual radial velocities of the best emission lines, due to N IV λ4057, N V λ4603, and He II λ4685, and the mean radial velocities of the absorption lines are listed for the new plates in Table 1. The number of absorptions included in each mean value depends only on the visibility of the lines and varies from plate to plate, due to the fact that some spectrograms were less exposed than others.

For a description of the spectrum, see Niemela (1976). Van der Hucht *et al.* (1981) classify HD 90657 as WN4 + O4–6, which we endorse here.

Photoelectric photometry of HD 90657 was performed by A. F. J. M. using the single-channel photometer of the Bochum University's 0.6 m telescope on La Silla, Chile. One observation was secured on each of 26 nights, spanning a total interval of 37 days in 1975 February 4–March 13. HD 90657 was observed alternately with the late B-type comparison star HD 90490, situated 16′ from the former. The constancy of the comparison star's magnitudes was confirmed by comparison with several other (constant) stars measured during the same period. A diaphragm of 18″ diameter was used with the three interference filters of central wavelength and FWHM, respectively, of 3635, 70; 4680, 130; and 5640, 110 Å. The first and last filters measure predominantly the blue and red continuum, respectively, while the second filter is nearly centered on the strongest emission line in the optical spectrum of HD 90657, due to He II λ4685. Integration times were about 60 s per filter-observation. The observations are listed in Tables 2 and 3.

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TABLE 1

HELIOCENTRIC RADIAL VELOCITIES FOR HD 90657 (km s^{-1})

Plate No.	JD 2,440,000+	N V Em. 4603.73	N IV Em. 4057.76	He II Em. 4685.68	Mean Abs.[a]	Ca II[b]
C-4748	3142.812	+180	+35	+48	−87 (10)	−10
C-5016	3910.741	+185	+94	−13	−65 (8)	+05
C-5020	3911.754	+09	−47	−179	+16 (11)	−02
C-5022	3912.609	+91	−257	−274	+64 (8)	−02
C-5025	3912.814	−118	...	−264	+62 (5)	...
E-2568	3913.716	−200	−184	−92	+62 (14)	−11
E-2569	3913.835	−179	−235	−116	+58 (9)	...
E-2572-4	3914.640	−48	−90	+06	+09 (8)	...
E-2573	3914.782	−102	−165	−03	+12 (9)	−33
E-2576	3915.654	+43	−05	+54	−33 (11)	−07
E-2577-1	3915.768	+79	−54	+253	−49 (8)	−05
E-2577-6	3915.853	+71	+83	+262	−79 (8)	−09
E-2579-2	3916.636	...	+130	+198	−122 (10)	+04
E-2579-9	3916.715	+176	+137	+263	−139 (10)	−05
E-2583-3	3917.652	+222	+204	+199	−140 (14)	−02
E-2583-9	3917.745	+261	+222	+216	−114 (14)	−08
E-2584	3917.804	+235	+173	+241	−128 (13)	+25
E-2587-3	3918.652	+149	+112	+46	−117 (13)	−28
E-2587-8	3918.724	+110	+83	+24	−102 (11)	−10
E-2590	3919.666	+02	−151	−127	+04 (8)	−05
E-2592	3919.771	+25	+13	−134	−03 (10)	−01
E-2594-1	3920.612	−62	−159	−280	+22 (11)	+17
E-2594-8	3920.704	−138	−303	−262	+41 (13)	+17
E-2595	3920.800	−151	−244	−241	+49 (11)	+09
E-3342	4265.775	+137	+66	−14	−93 (10)	−04
E-3345	4266.755	−46	−111	−173	−06 (8)	−04
E-3351	4269.750	−99	−107	+40	−09 (11)	−06
E-3355	4270.779	+140	+17	+204	−94 (11)	+10
E-3358	4271.740	+212	+182	+272	−118 (11)	−10
E-3361	4272.688	+211	+175	+227	−135 (12)	−22
E-3368	4274.807	−01	−45	−87	−05 (12)	−12
E-3375	4276.686	−170	−229	−116	+86 (10)	−09
E-3381	4277.749	−120	−239	+23	+41 (10)	−14

[a] Numbers in parentheses indicate how many lines were included in the mean.
[b] Interstellar Ca II H + K.

III. ANALYSIS OF THE OBSERVATIONS

a) The Radial Velocity Orbit

From the unbroken sequence of spectral observations performed during 11 consecutive nights in 1979 February, it is clear that the 6-day period found earlier is too short, and that the correct period is of the order of 8 days (cf. Niemela 1980). To determine the period of the binary more accurately, we applied the Lafler and Kinman (1965) method to all the radial velocity data together, i.e., the present 33 observations and the 14 plates published previously (Niemela 1976). The best period we found is 8.255 days.

Limiting ourselves now to the more precise, present data, we computed orbital elements with the program published by Berthiau and Grobben (1968) for the O star's mean absorption-line velocities, and for the W-R star's emission lines of N V λ4603, N IV λ4057, and He II λ4685, respectively. The elements are recorded in Table 4, with the standard errors of the mean calculated by the orbital analysis program.

The observed and calculated radial velocities are shown in Figures 1*a*–1*d*. From these and from Table 4, it is evident that the emission lines present different amplitudes of orbital motion and that the He II emission is also phase-shifted relative to the other emission lines, which are in nearly exact antiphase with the absorption component. This kind of effect is often seen in other W-R binaries, and also to some extent in X-ray binaries (e.g., Hutchings *et al.* 1977).

The best orbit is defined by the absorption lines of the O star, which has zero eccentricity. Therefore, we have assumed that the W-R star also has a circular orbit, although a slightly elliptic orbit would fit the He II λ4685 emission observations better, as shown in Figure 1*d* and Table 4.

The different amplitudes of the orbital motion appear to be in the sense that lower amplitude is shown by the highest excitation line (N V). This is similar to the situation for the WN4+O9.5 V binary HD 186943, with $P = 9.6$ d, $K(\text{N V } \lambda4603) = 178 \pm 7$ km s^{-1}, $K(\text{He II } \lambda4685) = 239 \pm 3$ km s^{-1}, and $M(\text{W-R}) \approx 9$–11 $M_\odot$ (Massey 1981*a*). This kind of effect introduces considerable uncertainty into the determination of the mass ratio of the binary components, which varies from 0.52 ± 0.02 for N V to 0.42 ± 0.01 for He II. The reason

TABLE 2

PHOTOELECTRIC MAGNITUDES OF HD 90657 MINUS HD 90490[a]

JD −2,440,000 (1)	m(5640) (2)	m(3635) − m(5640) (3)	m(4680) − m(5640) (4)
2447.744	2.891	−1.341	−1.736
2448.649	2.905	−1.323	−1.746
2449.697	2.904	−1.314	−1.776
2451.657	2.903	−1.328	−1.769
2453.683	2.899	−1.326	−1.755
2454.747	2.933	−1.361	−1.766
2455.762	2.909	−1.302	−1.758
2457.756	2.872	−1.348	−1.778
2458.744	2.892	−1.334	−1.773
2459.770	2.891	−1.344	−1.773
2460.741	2.879	−1.318	−1.765
2462.643	2.928	−1.312	−1.726
2463.621	2.867	−1.320	−1.752
2464.600	2.895	−1.309	−1.765
2465.609	2.892	−1.364	−1.754
2466.618	2.895	−1.338	−1.766
2467.737	2.883	−1.332	−1.787
2468.774	2.894	−1.326	−1.754
2470.693	2.928	−1.335	−1.768
2471.571	2.916	−1.321	−1.755
2474.654	2.914	−1.363	−1.786
2477.617	2.945	−1.338	−1.772
2481.698	2.925	−1.322	−1.775
2482.691	2.900	−1.294	−1.774
2483.691	2.888	−1.308	−1.756
2484.672	2.879	−1.334	−1.755
Mean	2.898	−1.329	−1.763
σ	0.019	0.018	0.014

[a] Due to a peculiarity in the reduction procedure, the following magnitudes should be added to columns (2), (3), (4), respectively: −0.314, +1.786, +1.962.

TABLE 3

BROAD-BAND MAGNITUDES AND COLORS[a]

Star	V	$B-V$	$U-B$
HD 90657	9.69	0.40	−0.58
HD 90490	7.00	−0.10	−0.55

[a] 1975, one observation.

for the phase shift and differences in the amplitudes of the orbital motions from different emission lines probably lies in the lack of spherical symmetry of the W-R envelope. We adopt the N v solution to correspond most closely to the true orbit, since the orbit for He II deviates most in shape and phase from the absorption-line orbit.

We also note that the systemic velocity, as determined from the radial velocities of the O star absorption lines, is considerably blueshifted with respect to the radial velocity expected from circular galactic rotation. This may be caused by an expanding photosphere similar to those seen in Of stars (Hutchings 1976). However, if this were the case, we would expect to observe a velocity progression in the Balmer lines, which does not occur. Also the systemic velocity of the N IV λ4057 emission is nearly identical to that of the absorption lines, while the other emissions are redshifted. This appears to occur in other early-type WN stars as well, although the N IV λ4057 emission can also be significantly blueshifted compared to the absorption. It is probably still too early to say whether there exists a correlation of these effects with other parameters such as line width, line strength, or binary separation. If the absorption line systemic velocity truly reflects the center of mass motion of the HD 90657 binary system, then, with $V_{\rm LSR} = -40$ km s^{-1} (obtained from a distance $d = 4.4$ kpc according to Moffat and Isserstedt 1980 and Smith 1968; and a flat rotation curve with parameters from Gunn, Knapp, and Tremaine 1979 and solar motion for B stars from Balona and Feast 1974), it has a peculiar radial velocity of ~40 km s^{-1} in excess of the galactic rotation. This would marginally place HD 90657 in the category of runaway OB stars ($|\Delta v_r| \geq 40$ km s^{-1}: Bekenstein and Bowers 1974). The peculiar radial velocity increases to 51 km s^{-1} using the larger distance, 5.8 kpc, of Hidayat, Supelli, and van der Hucht (1981).

b) The Photometric Variations

In Figure 2 we plot the light curves of HD 90657 using the N v ephemeris in Table 4. In order to reduce the noise, we have taken running averages in groups of five data points for every second original point. These reveal

TABLE 4

ORBITAL ELEMENTS OF HD 90657 (WN4 + O4–6)

Element	Mean Abs.	N v 4603 Em.	N IV 4057 Em.	He II 4685 Em.
V_0 (km s^{-1})	−35 ± 2	43 ± 4	−33 ± 6	20 ± 5
K (km s^{-1})	104 ± 2	202 ± 7	221 ± 9	246 ± 7
e	0.01 ± 0.02	0.04 ± 0.03	0.03 ± 0.04	0.08 ± 0.03
T_0 (JD 2,443,900+)[a]	...	...	...	20.1 ± 0.5
ω (°)	...	...	...	146 ± 22
$a \sin i$ ($R_\odot$)	17	33	33	40
ϵ (km s^{-1})[b]	9	22	30	26
$M_0 \sin^3 i$ ($M_\odot$)	...	16.3	20.1	25.9
$M_{\rm WN} \sin^3 i$ ($M_\odot$)	...	8.4	9.4	10.9

NOTE.—$P = 8^{\rm d}.255$ (fixed).

[a] T_0 is the time of periastron passage.

[b] ϵ is the rms scatter about the computed curves.

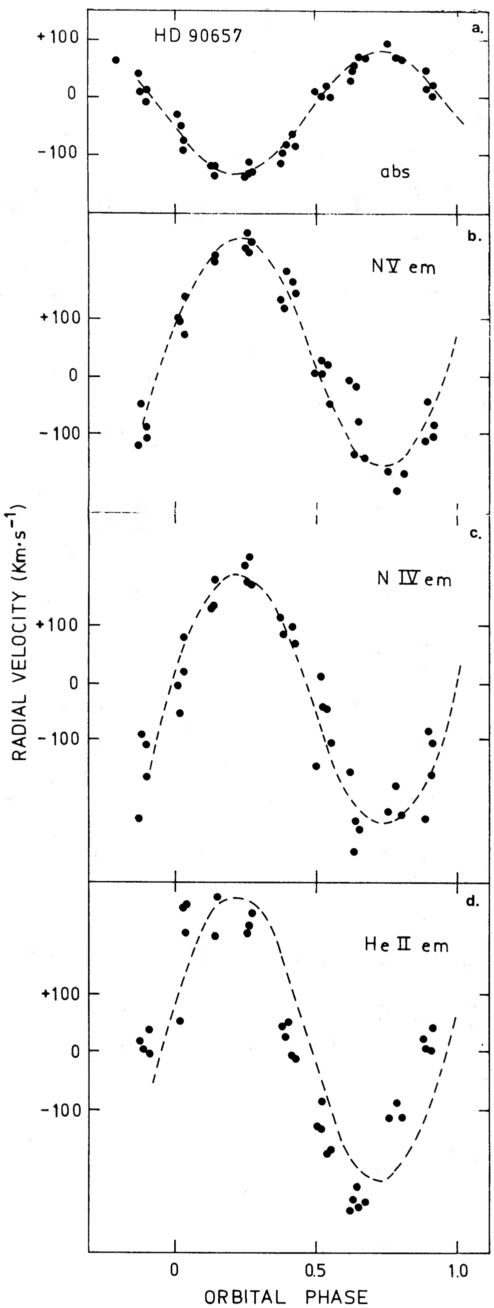

FIG. 1.—(*a*) The radial velocity variations of the mean absorptions as a function of the orbital phase. The dashed curve represents the theoretical radial velocities as defined by the orbital elements in Table 4. Zero phase has been assumed to be JD 2,443,923.7. (*b*) The same as Fig. 1*a* for the emission lines of N V λ4603. (*c*) The same as Fig. 1*a* for the emission lines of N IV λ4057. (*d*) The same as Fig. 1*a* for He II λ4685, but here the dashed curve represents a circular orbit with the semiamplitude from Table 3 and the same zero phase as Fig. 1*a*–1*c*.

a single, broad, symmetric minimum (depth ≈ 0.035 mag) in continuous light at phase zero (WN4 star in front) and an asymmetric minimum in the emission line filter, displaced to phase $\sim$0.15, with depth ≈ 0.02 mag. There is no evidence for a second minimum with depth $\geq$ 0.01 mag at phase 0.5 (O star in front). This can be compared to the well-known eclipsing WN5 + O6 system, V444 Cygni, whose continuous light curve at $\lambda \sim 5000$ Å shows a primary minimum of 0.32 mag at phase 0.0 and a secondary minimum of 0.16 mag at phase 0.5 (Cherepashchuk and Khaliullin 1973).

Since the minimum in the continuum light curve is relatively broad, it cannot be due to a narrow eclipse of the O star by the W-R core. Indeed, the depth is constant over an interval of $\sim$2000 Å and suggests that it is the electron scattering envelope of the W-R star that passes in front of, and scatters light from, the O star. Without detailed knowledge of the W-R envelope density structure, it is not possible at present to place accurate constraints on the orbital inclination. However, a rough estimate can be obtained from the following condition:

$$R(\mathrm{O}) + R_c(\text{W-R}) < a \cos i < R(\mathrm{O}) + R_e(\text{W-R}) ,$$

where $R(\mathrm{O})$ = radius of the O star; R_c, R_e = radii of the W-R core and the emission producing envelope, respectively. Taking $R(\mathrm{O}) \approx 18\ R_\odot$ (Allen 1973), $R_c(\text{W-R}) \approx 3\ R_\odot$ for WN4 (Rublev 1975), $R_e(\text{W-R}) \approx 5\ R_c$ (Underhill 1969) and $a \sin i = 50\ R_\odot$ (N V), yields:

$$50/33 < \tan i < 50/21, \quad \text{i.e., } 57° < i < 67° .$$

This leads to the masses

$$21 < M(\mathrm{O})/M_\odot < 28 \quad \text{and} \quad 11 < M(\text{W-R})/M_\odot < 14 .$$

However, if $R_c(\text{W-R}) = 10\ R_\odot$, as proposed for all W-R stars (Underhill 1981), this leads to

$$46° < i < 61°$$

and would somewhat increase the masses. We note that adopting $M(\mathrm{O}) = 45\ M_\odot$ (Conti and Burnichon 1975) leads to $i = 45°$ (N V). In any case, the mass ratio (0.52) is almost identical to that of the WN4+O9.5 V binary HD 186943 (Massey 1981*a*).

The λ4680 filter observations show a dip at phase $\sim$0.1–0.2, (Fig. 2), or an increase at phase $\sim$0.5 (W-R behind). Since the O star probably does not emit line radiation at λ4685 (if it did we should not observe an increased velocity variation amplitude, but a decreased one), then the dip can only be due to an occultation effect involving an asymmetric line-emitting region, in the sense that the major emission comes from the W-R hemisphere facing the O star. The observed minimum near phase 0.15 is roughly consistent with the radial velocity phase lag of the He II λ4685 emission line.

The λ4680 light curve cannot be due to the folding of the approximately Gaussian filter profile with the emission line as it moves back and forth in wavelength (± 4 Å) as was the case for the off-center emission in HD 97152 (Davis, Moffat, and Niemela 1981). One would then expect the light curve to pass through two maxima

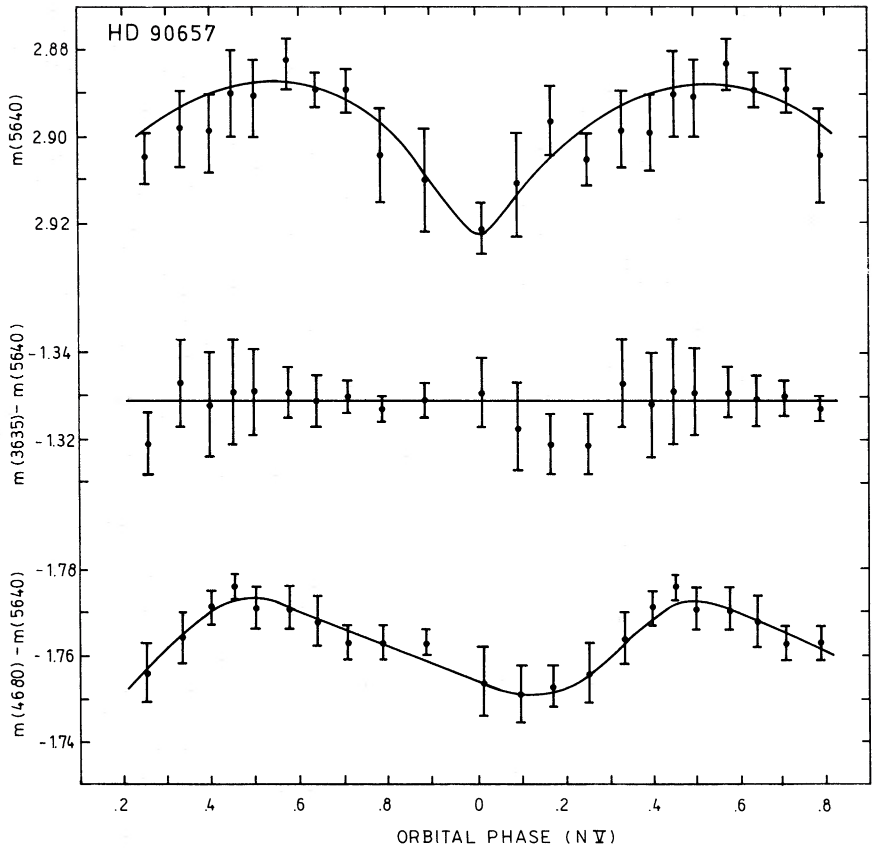

FIG. 2.—Photoelectric light curves of HD 90657. Running means are shown for five data points, every two points, along with the s.e.m. The curves are hand-drawn interpretations of the trends.

per cycle if the λ4685 line were nearly central in the filter, or, if not, to cause a maximum in the λ4680 light curve at phase ~0.25 or ~0.75, which is also not seen.

IV. CONCLUSIONS

From new spectroscopic and photometric data we have derived improved orbital parameters for the WN4 + O4–6 binary HD 90657. Our photometric observations show a partial occultation of the O star by the tenuous outer W-R envelope, but the inverse process, i.e., partial occultation of the W-R atmosphere by the O star, is not at all evident in our data. This circumstance allows us to limit the orbital inclination values and thus to estimate the masses of the binary components from the radial velocity variations.

The mass of the WN4 component of HD 90657, 11–14 $M_{\odot}$, is like the classical value for hot WN stars (cf. Niemela 1981; Massey 1981*b*), while the O type component appears to be somewhat less massive than would correspond to an O4–6-type main-sequence star. This implies that HD 90657 is an evolved binary in which mass has been lost from the system as a whole.

The mass ratio of HD 90657 fits in with the trend noted by Moffat (1981), that the mass ratio decreases with hotter W-R subclasses (this star was already included in Moffat's plot using the data of Niemela 1980).

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