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WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS. VI. SPECTROSCOPIC ORBITS OF WC BINARIES AND IMPLICATIONS FOR W-R EVOLUTION[1]

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ABSTRACT

Spectroscopic orbits are obtained for the first time for the three brightest WC + O binary systems in the LMC. An improved orbit is obtained for the bright WO + O system in the SMC. In one of the LMC systems the observed O companion is stationary; the remaining three systems show antiphased orbits of both components. Two of the LMC binary systems have very short periods (1.9 and 3.0 d), similar to the lower limit for periods of known WN + O and O + O binary systems in general. This means that orbital angular momentum must have been lost from the system in addition to that associated with the extreme mass loss of the present WC components, but not necessarily via mass transfer.

On the basis of the double-line orbits for 10 known WC + O binaries in the Galaxy and the Magellanic Clouds, there emerges a continuous decrease of mass ratio $M(\mathrm{WC})/M(\mathrm{O})$ with WC subtype, from 0.5 for WC8 to 0.2 for WC4, WO. Assuming that the initial mass ratio was $\gtrsim 1$, this implies that WC stars can evolve from WN stars and from cooler to hotter subtypes within the WC sequence, with mean mass-loss rate $\sim 4 \times 10^{-5}$ $M_\odot$ yr^{-1}. It is noted that in WC + O binaries it is the *mass ratio*, not the mass, which probably best reflects the degree of evolution of the WC component to hotter subtypes, regardless of the initial mass.

Subject headings: galaxies: Magellanic Clouds — stars: binaries — stars: evolution — stars: Wolf-Rayet

I. INTRODUCTION

With the products of He-burning in their winds, the Wolf-Rayet (W-R) stars of the carbon sequence (WC) appear to be the final observable stage in the evolution of massive stars (Abbott and Conti 1987). Previous spectroscopic studies of binary WC + O stars have yielded mass ratios that strongly support this view (see Moffat *et al.* 1986), assuming that the WC star was originally more massive than the present, less-evolved secondary and that mass transfer has not played an important role. The mass estimates of the WC component in binary systems themselves give less clear results (Massey 1981), mainly because of the uncertainty in $\sin^3 i$ and the variation in initial mass. This problem can be overcome by the normalization process of considering mass ratios.

In this investigation, we enlarge and improve the sample of orbital parameters for WC + O binaries on the basis of spectroscopic monitoring of the four visually brightest such objects in the Magellanic Clouds, namely B22, B31, and B32 in the LMC (see Breysacher 1981) and AB 8 in the SMC (see Azzopardi and Breysacher 1979). Note that the WC stars B9 and B67 *appear* to be as bright as the observed stars; however, they are actually fainter members of visual multiple systems. The high luminosity of the observed objects (all have $M_v < -5.5$) is a consequence of the fact that we are dealing with WC + O *binaries*, in which the O star is much brighter than the WC component. We also reexamine the possibility of an evolutionary connection among different WC subtypes and with other stars.

Previous papers in this series have dealt with individual W-R binary systems (Papers I, II, III, IV: see Moffat 1982*b*; Breysacher, Moffat, and Niemela 1982; Moffat, Breysacher, and Seggewiss 1985; Moffat and Seggewiss 1986) and a resumé of the eight known SMC W-R stars (Paper V; Moffat 1988).

II. OBSERVATIONS

Photographic image-tube spectra in the blue spectral region and CCD spectra in the red were obtained for the three brightest WC stars in the LMC and the only WC/WO star in the SMC using the 1 m Yale telescope at CTIO, supplemented by IDS spectra from the ESO 1.5 m telescope. All four stars show clear O-type absorption lines in their spectra. Reduction techniques for the photographic spectra are described in previous papers of this series, while the IDS techniques are given for similar spectra of other stars studied during the same run by Moffat, Seggewiss, and Shara (1985).

The CCD spectra were obtained using a GEC chip with 11 e$^-$ readout noise and 2 Å × 1″ pixels. Each stellar CCD spectrum was preceded by a He-Ar-Ne comparison obtained at the same telescope position. Extraction was carried out at La Plata Observatory using custom-designed software. Wavelength calibration of each stellar spectrum was done using the corresponding comparison spectrum. Radial velocities (RV) were derived for the C IV 5808 Å emission line by cross-correlation

[1] Based partly on observations collected at the European Southern Observatory (ESO), Chile.

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TABLE 1

JOURNAL OF RADIAL VELOCITY OBSERVATIONS FOR B22

JD-2,440,000	RV (C IV emission) (km s^{-1})	RV (absorption) (km s^{-1})	Source
3839.661......	236	185	1
3840.644......	−33	195	1
3842.646......	−147	290	1
3843.640......	−91	270	1
3844.640......	−92	292	1
3845.647......	−1	273	1
3846.640......	76	294	1
3847.657......	185	196	1
4254.704......	296	173	1
4256.671......	259	174	1
4258.663......	55	210	1
4260.642......	−108	292	1
4261.633......	−164	317	1
4262.668......	−110	335	1
4975.673......	−30	206	1
4978.763......	−141	332	1
4981.723......	50	224	1
5310.607......	126	...	2
5312.709......	319	...	2
5315.626......	190	...	2
5310.715......	156	...	3
5312.740......	233	...	3
5313.732......	290	...	3
5315.723......	348	...	3
6040.711......	64	...	4
6043.702......	268	...	4
6045.601......	295	...	4
6046.643......	284	...	4
6047.723......	281	...	4
6049.628......	138	...	4
6051.583......	−66	...	4
6052.632......	−149	...	4

SOURCE.—(1) = photographic image tube with baked IIaO plates, from rectified photographic density. C IV emission from λ_0 4658.0 Å, absorption mean of H8, δ, γ, and He II 4199, 4541; (2) = IDS, C IV 4658; (3) = IDS, C IV 5808; (4) = CCD, C IV 5808.

NOTE.—The RV data from sources 2–4 were adjusted in zero point to match those of source 1 (this applies also to Tables 2 and 3).

TABLE 2

JOURNAL OF RADIAL VELOCITY OBSERVATIONS FOR B31

JD-2,440,000	RV (C IV emission) (km s^{-1})	RV (absorption) (km s^{-1})	Source[a]
3839.683......	475	267	1
3840.681......	94	306	1
3841.754......	43	278	1
3842.662......	413	266	1
3843.654......	96	291	1
3844.654......	−9	278	1
3845.683......	546	262	1
3846.657......	232	300	1
3847.676......	23	295	1
4255.628......	253	304	1
4255.823......	220	284	1
4256.550......	39	275	1
4256.843......	−185	328	1
4257.542......	141	291	1
4260.849......	257	311	1
4976.558......	173	241	1
4977.820......	−10	229	1
4978.815......	−165	252	1
5310.624......	393	...	2
5311.730......	−13	...	2
5312.724,.....	84	...	2
5313.579......	348	...	2
5314.551......	−13	...	2
5315.557......	−32	...	2
5310.726......	489	...	3
5311.741......	−32	...	3
5312.733......	118	...	3
5313.722......	525	...	3
5314.714......	−63	...	3
5315.729......	−22	...	3
6040.755......	107	...	4
6041.869......	426	...	4
6042.628......	15	...	4
6046.672......	25	...	4
6047.690......	402	...	4
6048.602......	−85	...	4
6050.592......	392	...	4
6051.694......	−71	...	4

[a] Cf. Table 1, except that the absorption mean is based on H8, δ, γ, and He I 4026, 4471.

and be centroid determination, and the results were averaged. The rms errors are ≈ 20 km s^{-1}.

Tables 1–4 list the journals of observations and the RVs for each star (B22, B31, B32 in the LMC and AB 8 in the SMC). The typical rms error of an absorption-line velocity listed in Tables 1–4 is ~ 30 km s^{-1}. Note that the emission-line velocities listed in Tables 1–3 are from two different (blended) lines using three different observing techniques. Even allowing for phase-dependent variations, systematic residuals among the four RV sources of up to ~ 200 km s^{-1} can arise. Sources 2–4 in Tables 1–3 were thus shifted in RV in order to match to the RVs of source 1. IDS mean spectra of the LMC stars are shown in Figures 1–3; a photographic spectrum of the SMC star is shown in Paper III.

We note that all four WC + O binaries are located in the direction of young open star clusters and their associated H II nebular emisssion. Inspection of the $\sim 2'$ fields around each star using the high-quality visual image-tube eyepiece at the 1 m Yale telescope showed that all four stars appeared to be visually single in $\lesssim 1''$ seeing. Occasional fainter companions separated by $\gtrsim 3''$ were seen around some WC stars; these do not contribute significantly to the photographic spectra and are easily separated in the analysis of the CCD spectra. Prévot-Burnichon *et al.* (1981) list close companions to LMC W-R stars. In particular, they list a relatively bright companion ($\Delta m < 1$ mag) to B22 at a separation $d = 5''$ and position angle $\theta = 250°$. However, the closest companion that we were able to locate even near this magnitude difference is the B0 I star R89, which is brighter than B22, at $d \simeq 11''$ and with radial velocity (RV) = +285 km s^{-1} (Feast, Thackeray, and Wesselink 1960). Prévot-Burnichon *et al.* (1981) also find the WC star (A) to be a possible close double ($d < 2''$?, $\theta \simeq 330°$?, $\Delta m < 1$?). We find no evidence for such a bright companion at $d \gtrsim 1''$. We are thus inclined to treat the relatively low resolution, photographic data of Prévot-Burnichon *et al.* with some caution.

III. ORBITAL ANALYSIS

The data in Tables 1–4 show variable RVs for all the stars studied here, hence supporting their binary nature. The first orbital parameter to be established is the period. We first plotted the RVs for each star versus time for each observing

TABLE 3

JOURNAL OF RADIAL VELOCITY OBSERVATIONS FOR B32

JD-2,440,000	RV (C IV emission) (km s^{-1})	RV (absorption) (km s^{-1})	Source[a]
3839.708......	279	199	1
3840.705......	−99	290	1
3842.686......	−257	275	1
3843.678......	318	205	1
3844.674......	−161	254	1
3845.705......	264	187	1
3846.676......	−97	245	1
3847.699......	264	216	1
4257.657......	219	...	1
4258.558......	−173	315	1
4258.854......	−250	291	1
4259.566......	251	204	1
4259.854......	175	256	1
4976.543......	221	182	1
4977.833......	−120	256	1
4978.828......	−37	256	1
5310.638......	39	...	2
5311.618......	290	...	2
5313.699......	264	...	2
5314.699......	−148	...	2
5310.733......	−156	...	3
5311.748......	231	...	3
5313.713......	283	...	3
5314.723......	−233	...	3
6040.773......	30	...	4
6042.644......	133	...	4
6043.851......	183	...	4
6046.687......	−154	...	4
6047.675......	134	...	4
6048.624......	−150	...	4
6050.576......	−177	...	4
6051.679......	209	...	4

[a] Cf. Table 1, except that the absorption mean is based on Hδ, γ, and He II 4199, 4541.

TABLE 4

JOURNAL OF RADIAL VELOCITY OBSERVATIONS FOR AB 8

JD-2,440,000	RV (C IV emission) (km s^{-1})	RV (absorption) (km s^{-1})	Source[a]
4255.589......	...	170	1
4256.610......	...	68	1
4257.578......	...	136	1
4258.586......	...	104	1
4259.599......	...	143	1
4260.568......	...	167	1
4261.567......	...	162	1
4262.585......	...	166	1
4584.675......	...	186	1
4585.547......	...	200	1
4587.619......	...	126	1
4588.576......	...	109	1
4594.653......	...	140	1
4595.617	...	137	1
4598.590......	...	239	1
4599.622......	...	224	1
4974.627......	...	104	1
4976.651......	...	160	1
4980.635......	...	204	1
4982.544......	...	192	1
4983.545......	...	176	1
4983.552......	...	150	1
4983.558......	...	159	1
4984.534......	...	165	1
4984.601......	...	194	1
4985.538......	...	143	1
4986.531......	...	126	1
4986.599......	...	116	1
6040.663......	0	...	4
6041.563......	−21	...	4
6043.546......	−153	...	4
6044.558......	−252	...	4
6045.537......	−280	...	4
6046.535......	−257	...	4
6047.539......	−184	...	4
6048.540......	−152	...	4
6049.539......	−67	...	4
6050.537......	0	...	4
6051.547......	16	...	4
6052.547......	75	...	4

[a] Cf. Table 1, with absorption-line data based on the same spectra as discussed in Paper III but mean of H8, δ, γ, β, and He II 4541. The C IV 5808 RVs were obtained by cross-correlation relative to the first spectrum.

run. From these plots, it was obvious that B22 had a period longer than 10 days, while B31 and B32 both had periods between 1 and 4 days. We have searched for the period of each star using a sine-wave fitting technique as well as the nonparametric technique of Lafler and Kinman (1965). For B22 and B32, the best periods obtained from emission and absorption-line orbits were mutually consistent within the errors. However, because the emission line data are more numerous than the absorption-line data, we adopted the emission-line periods for the systems as a whole (see Table 5 for a resumé of the orbital parameters and Figs. 4–7 for plots of the orbits). Also, emission and absorption RVs move in antiphase within the errors; we thus adopted the emission-line epochs to define the origin of the phases when the W-R component is in front. Note that the systemic (γ) velocities in Table 5 are significantly different for the absorption and emission lines. While this effect is seen in other W-R binaries, the differences here seem very large, possibly due to the extreme width and asymmetries in the emission lines.

Our new observations for AB 8 nicely confirm the period found in Paper III. For one object (B31), the amplitude of the absorption line RVs of the supergiant companion is insignificantly different from zero. This is similar to the Galactic system θ Mus (Moffat and Seggewiss 1977) and the LMC system R130 (Moffat and Seggewiss 1986), in which the supergiant companions show no detectable motion. We presume that B31 also is a triple system and limit further discussion to its emission-line orbit alone.

In Table 5 we also list quantities derived from the orbital elements. In particular, the orbital inclination i was estimated on the basis of the spectroscopic mass of the O component. Until we have more reliable estimates of i (e.g., from polarization modulation—now in progress), the actual masses are subject to considerable uncertainty.

IV. DISCUSSION

In Table 6 we present a list of all known WC binaries with orbits. Our new data have increased the previous data bank by 50%.

Perhaps the most striking feature in Table 6 is the existence of periods among WC binaries that are nearly as short (1.9d) as those found among O-type ($P_{\min} \simeq 1.3$d) and WN-type ($P_{\min} \simeq 1.6$d) binaries. Several years ago, Smith (1973) noted that the then known WC binaries tended to have significantly

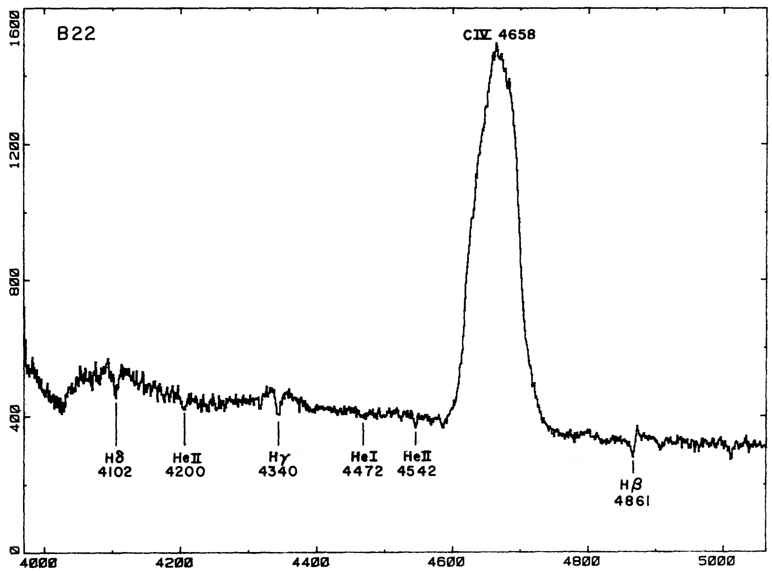

FIG. 1*a*

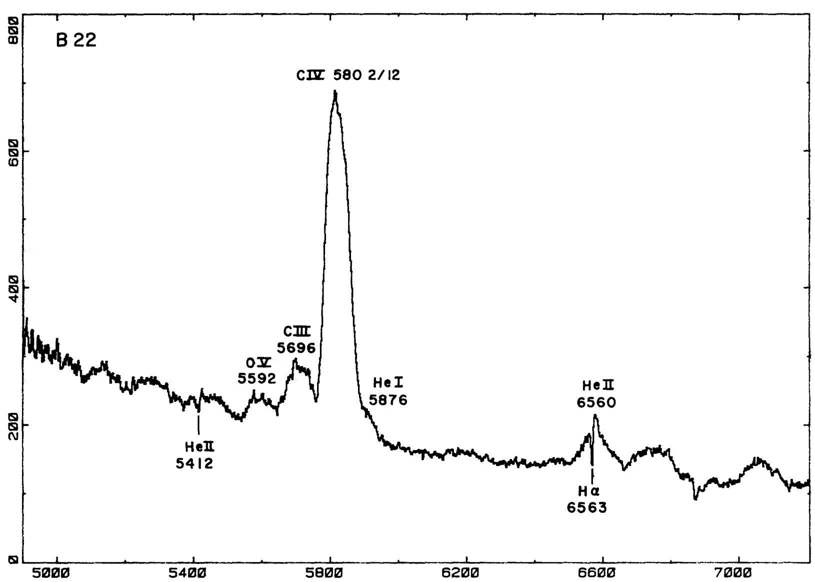

FIG. 1*b*

FIG. 1.—Mean IDS spectra of B22. Major lines have been identified. Abscissa is wavelength in Å; ordinate is flux in units of 2×10^{-16} ergs s^{-1} cm^{-2} Å^{-1}.

wider orbits (hence longer periods) than WN binaries. This was interpreted to be a possible result of extreme mass transfer, with WC stars being more evolved than their WN predecessors.

The question of mass loss can be approached from two extreme viewpoints.

1. Taking *conservative mass transfer*, i.e., constant total mass and angular momentum during the transfer process, leads to the ratio of final to initial period:

$$P_f/P_i = (M_{1i} M_{2i}/M_{1f} M_{2f})^3 ,$$

where M_{1i} is the initial primary star mass, M_{2i} is the intial secondary star mass, M_{1f} is the final primary star mass (the present WC star), and M_{2f} is the final secondary star mass (the present O star).

Now, with initial and final mass ratios $q_i = M_{1i}/M_{2i}$ and $q_f = M_{1f}/M_{2f}$ and conservation of mass, $M_{1i} + M_{2i} = M_{1f} + M_{2f}$, gives

$$P_f/P_i = (q_i/q_f)^3[(1 + q_f)/(1 + q_i)]^6 .$$

With the most extreme value from Table 6, $q_f = 0.2$, we find

$$P_f/P_i = 6 \ldots 4 \text{ for } q_i = 1 \ldots 2 .$$

(The initial mass ratio q_i is found to differ from unity only by a small factor for massive, close binaries: Garmany, Conti, and Massey 1980).

2. Assuming that all the mass loss takes place spherically symmetrically in the rotating frame of the binary system *without mass transfer*, and that the entire angular momentum loss from the system is carried by the wind, one has (see Collins and Newsom 1988):

$$\frac{1}{P}\frac{dP}{dt} = -2\,\dot{M}/M$$

with $\dot{M} < 0$ and M the *total* mass at any tme t. Integration gives

$$P_f/P_i = (M_i/M_f)^2 .$$

Now, with the above definitions for intial and final mass ratios and $r_2 = M_{2f}/M_{2i}$ yields

$$P_f/P_i = [(1 + q_i)/(1 + q_f)r_2]^2 .$$

Thus, with $q_f = 0.2$ and $r_2 \approx 0.8$ (e.g., a 30 $M_\odot$ O-star with $\dot{M} \approx 2\text{–}10^6\ M_\odot\ \mathrm{yr}^{-1}$ will lose $\sim 6\ M_\odot$, i.e., $\sim 20\%$ of its original mass in the $\sim 3.10^6$ yr it takes for the more massive primary to become a W-R star) we find

$$P_f/P_i = 4 \ldots 10 \text{ for } q_i = 1 \ldots 2 .$$

In both cases (1 and 2 above), the period gets *longer* by a similar factor (≈ 5); thus neither process has a clear, *a priori*

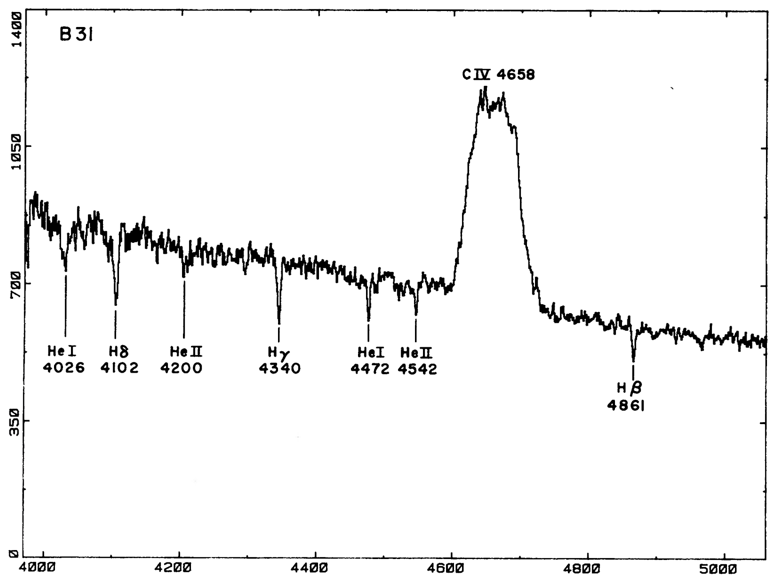

FIG. 2*a*

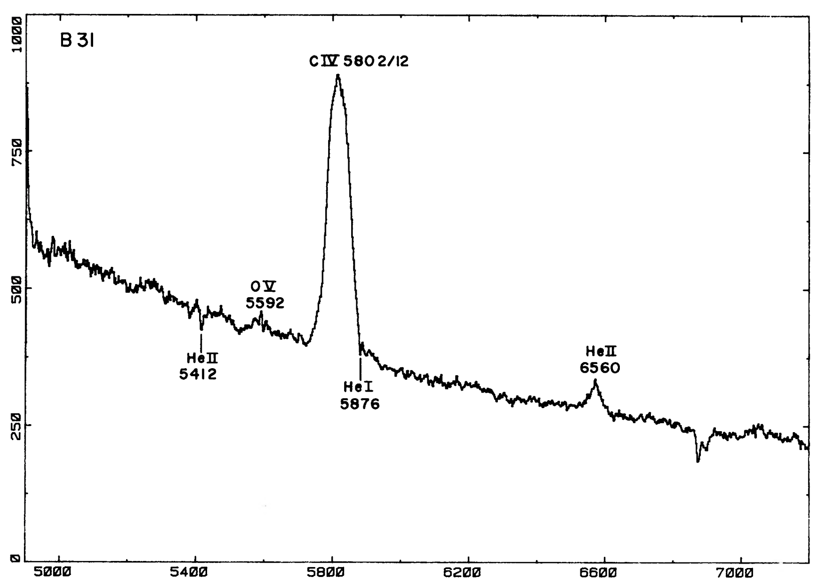

FIG. 2*b*

FIG. 2.—Mean IDS spectra of B31, as in Fig. 1

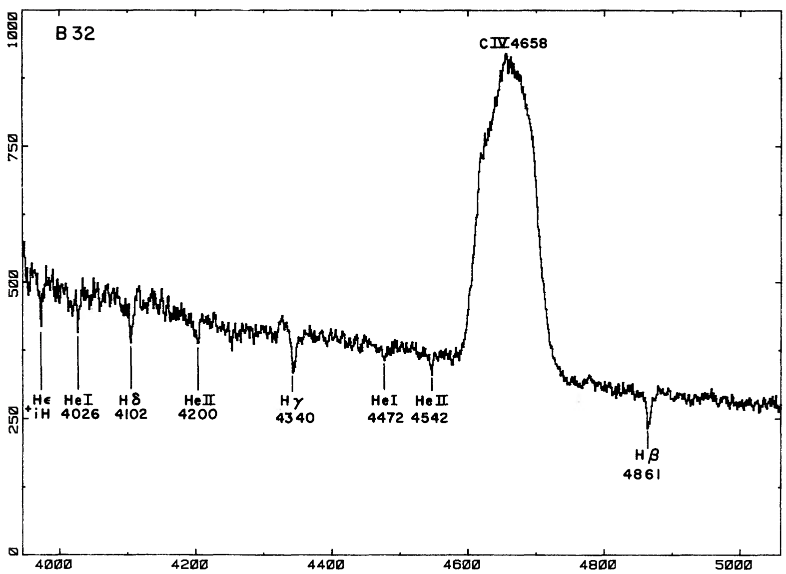

FIG. 3*a*

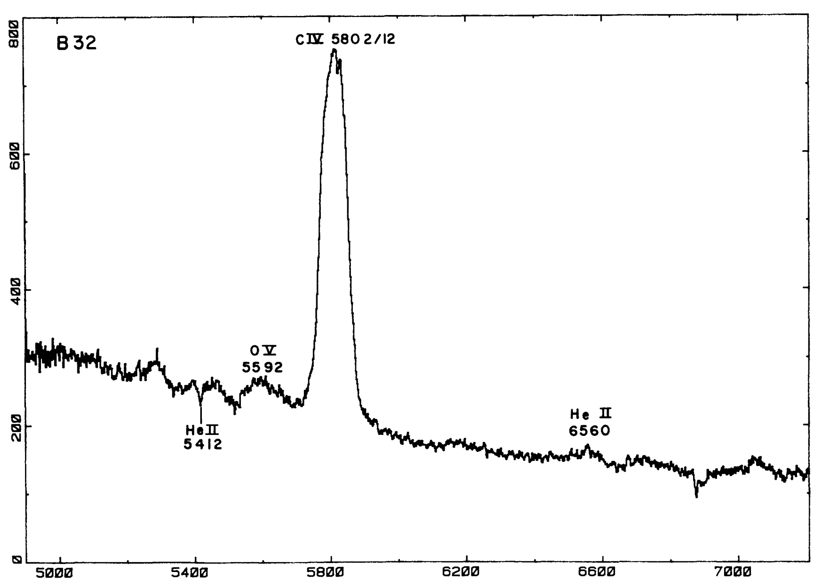

FIG. 3*b*

FIG. 3.—Mean IDS spectra of B32, as in Fig. 1

advantage over the other. For the shortest period in Table 6, $P_f = 1.9$d, this means $P_i \approx 0.4$d, which is shorter than allowed for normal O-star pairs (observed minimum ~ 1.3d: see Hilditch and Bell 1987). Thus, additional angular momentum loss is required in either case (e.g., magnetic field braking, dynamical friction, ...?).

Although theoretical arguments have been given that "prove" that mass transfer must have taken place in close W-R + O binaries (see Vanbeveren 1987; De Greve, Hellings, and van den Heuvel 1988), they hinge on the unproven assumption that the H-burning lifetime on the upper main sequence is nearly constant. This follows from a nearly linear mass-luminosity relation ($L \sim M$) for stars of initial mass $M_i > 40$–$50\ M_\odot$, in contrast to the well-known $L \sim M^3$ relation for masses below this limit. In this way, the presence of very early, main-sequence O-star companions to some WC stars (e.g., O4 V in both AB 8 and WR 140) is explained by rejuvenation of the present O-star companion via a hefty mass transfer from the original primary. Otherwise, for a linear *L-M* relation, both stars in massive systems must evolve at similar rates, regardless of their actual masses, making it difficult to explain the simultaneous presence of a highly evolved, W-R star and a very massive main-sequence companion.

However, the observations do not support this hypothesis. In fact, they rather support a lack of significant mass transfer. For example, the existence of relatively short-period WC binaries (B22 and AB 8 in Table 6) with *elliptical* orbits is difficult to account for if significant mass transfer has taken

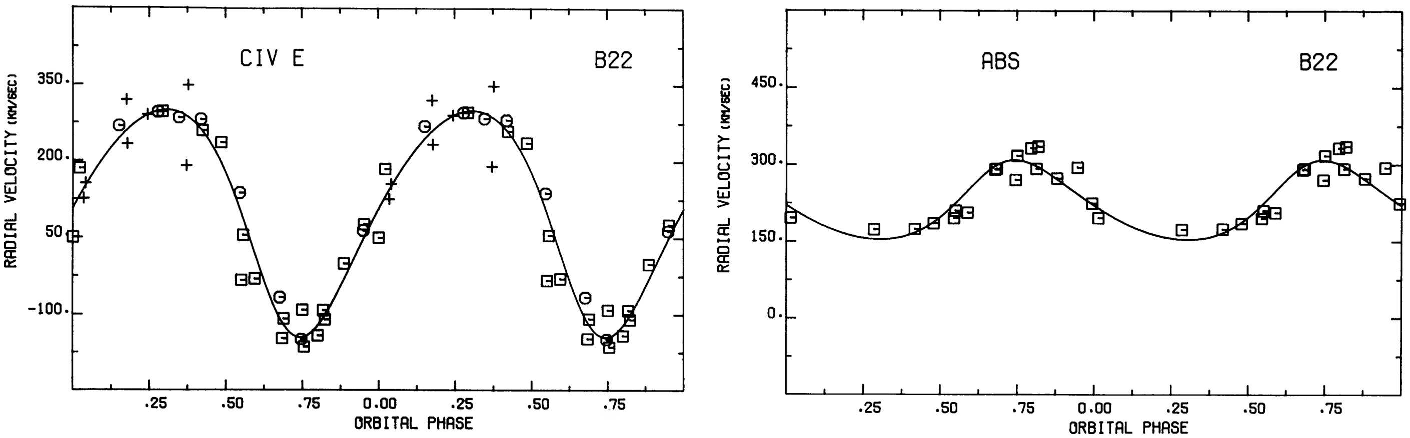

FIG. 4*a*

FIG. 4*b*

FIG. 4.—Radial velocity orbital fit to the data in Table 1 for B22, based on the parameters in Table 5. Squares refer to photographic data, crosses to IDS data, and circles to CCD data.

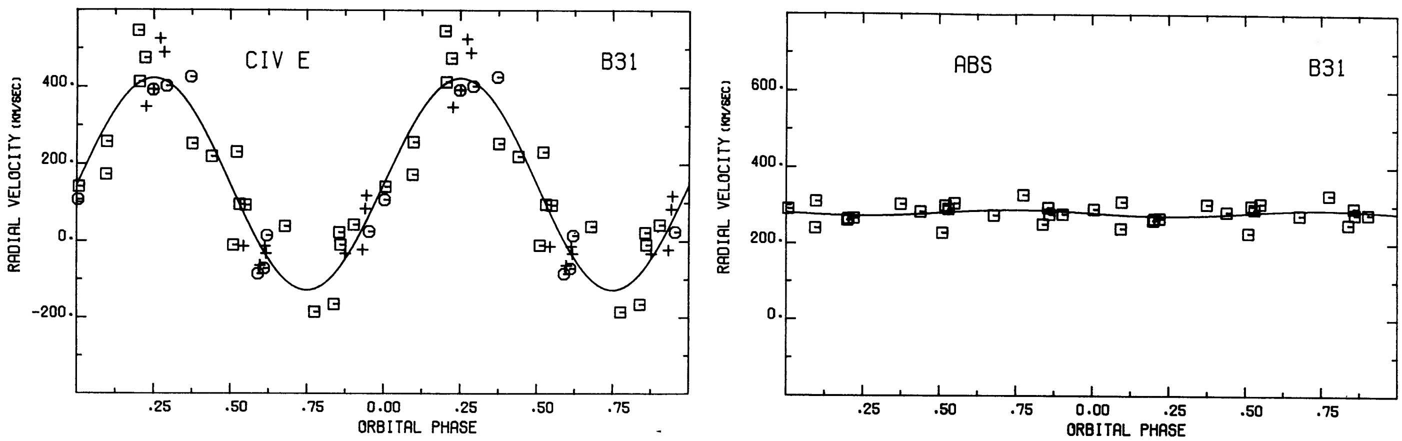

FIG. 5*a*

FIG. 5*b*

FIG. 5.—As in Fig. 4, for B31

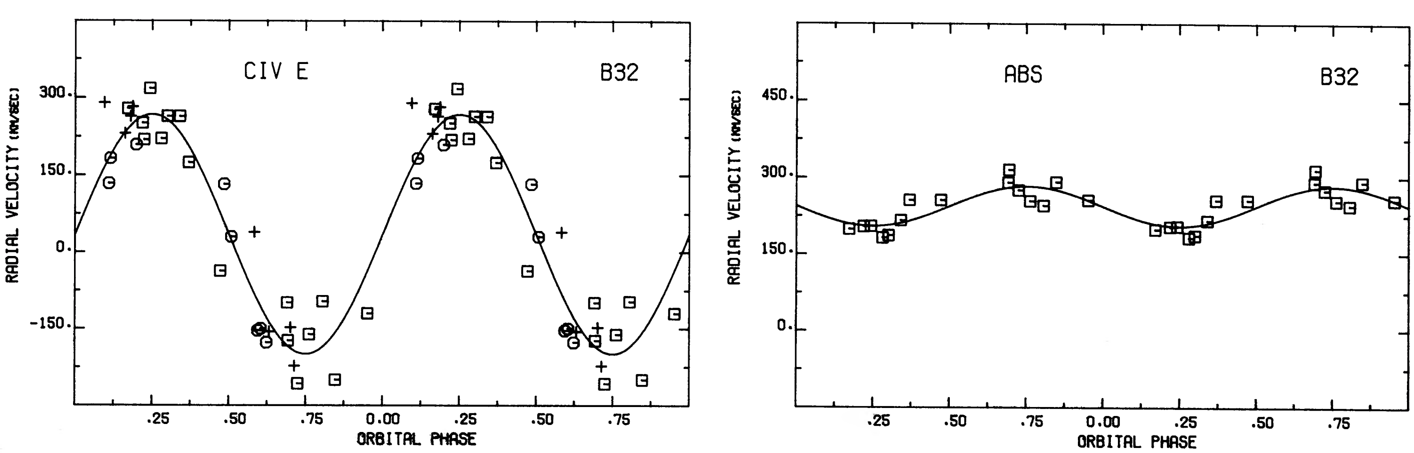

FIG. 6*a*

FIG. 6*b*

FIG. 6.—As in Fig. 4, for B 32

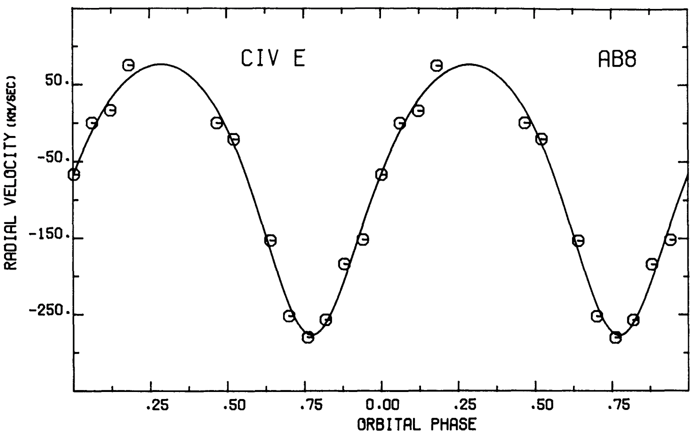

FIG. 7a

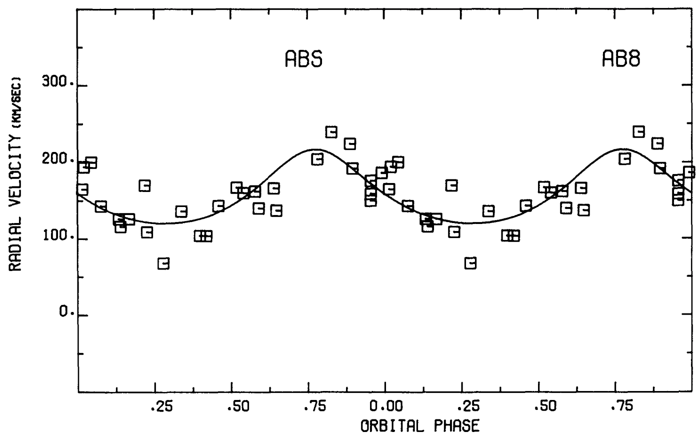

FIG. 7b

FIG. 7.—As in Fig. 4, for AB 8

place, since mass transfer tends to circularize the orbit very effectively (cf. Sybesma 1986). Also, the parallel existence of O4 V companions in the systems of widely differing separation, AB 8 ($P = 16.6$d, $a \approx 0.5$ AU) and WR 140 ($P = 7.9$ yr, $a \approx 15$ AU) forces one to question the efficiency of mass transfer at all. It is expected that mass transfer will be much less efficient in very wide systems in which the stars are mutually located in the tenuous, *rapid*, exterior part of the wind of the other star, where litttle accretion is expected. Even in fairly close systems, the accretion cross section cannot be large.

In fact, we question the theoretical, linear *L-M* relation (cf. de Jager 1981). A $L \sim M^3$ relation for all massive stars (except perhaps those very near the Eddington limit) would allow a greater age spread for a given range of mass and an easy expla-

TABLE 5

PARAMETERS AND DERIVED QUANTITIES FOR THE FOUR WC/WO BINARIES

Quantity	B32 (Sk −68° 80; HD 36521) (LMC)	B31 (Sk −67° 104; HD 36402) (LMC)	B22 (Sk −69° 104) (LMC)	AB 8 (Sk 188) (SMC)
$V_0 - M_v = 18.5$[a]	−6.5	−7.3	−6.6	
$V_0 - M_v = 18.9$[b]	…	…	…	−5.7
$V_0 - \bar{M}_v = \bar{18.2}$	−6.2	−7.0	−6.3	
Spectral Type	WC4 + O6V − III	WC4(+O?) + O8I:	WC6 + O5 − 6V − III	WO4 + O4V
γ(km s^{-1})[c] Absorption	+244 ± 6	+281 ± 6	+220 ± 7	+159 ± 5
γ(km s^{-1})[c] Emission	+34 ± 11	+147 ± 12	+108 ± 8	−67 ± 8
K(km s^{-1}) Absorption	39 ± 7	8 ± 9	77 ± 10	48 ± 9
K(km s^{-1}) Emission	234 ± 14	275 ± 17	222 ± 10	176 ± 8
P(days)	1.91674	3.03269	14.926	16.644
e	0.0 adopted	0.0 adopted	0.17 ± 0.05	0.19 ± 0.04
$\omega°$(em)[d]	…	…	145	174
T_0(JD-2,440,000)	…	…	4260.5	6045.6
E[e](JD-2,440,000)	4259.15	4260.55	4250.4	6049.5
σ_{o-c}(km s^{-1}) Absorption	22	25	25	26
σ_{o-c}(km s^{-1}) Emission	60	72	43	14
$f_{WC}(m)(M_\odot)$	2.6	6.6	16.2	8.9
$M_{WC} \sin^3 i\,(M_\odot)$	0.6 ± 0.2	(1.9)	10.2 ± 2.7	3.9 ± 1.3
$M_O \sin^3 i\,(M_\odot)$	3.5 ± 0.7	(9.5)	29.5 ± 5.0	14.5 ± 2.8
M_{WC}/M_O	0.17 ± 0.04	(0.2 adopted)	0.35 ± 0.06	0.27 ± 0.06
$a_{WC} \sin i\,(R_\odot)$	8.8 ± 0.5	16.5	64.1 ± 2.8	56.5 ± 2.6
$a_O \sin i\,(R_\odot)$	1.5 ± 0.3	(3.3)	22.2 ± 2.9	15.4 ± 2.8
i[f](°)	29	…	71	44
$a(R_\odot)$	21	…	91	104
$R_O(S_p)(R_\odot)$	10–20:	…	11–22:	14

[a] From Breysacher 1981.

[b] From Moffat, Breysacher and Seggewiss 1985.

[c] Using $\lambda_0 = 4658.0$ or 5812 RVs shifted to match 4658.0. For AB 8 λ_0 is arbitrary but near 5812 Å.

[d] ω(abs) taken to be ω (em) + 180°.

[e] Origin of the phases taken to be when the W-R component passes in front.

[f] Cf. Table 6.

TABLE 6

DATA COLLECTED FOR ALL KNOWN WC + O ORBITS

Star	Spectral Type	P (d)	e	K(W-R) (km s^{-1})	K(O) (km s^{-1})	$q = M_{\text{W-R}}/M_{\text{O}}$	$M_{\text{W-R}} \sin^3 i$ ($M_\odot$)	$M_{\text{O}} \sin^3 i$ ($M_\odot$)	i (°)	Ref. (i)	$M_{\text{W-R}}$ ($M_\odot$)
WR 9	WC5 + O7	14.305	0	197 ± 15	56 ± 3	0.28 ± 0.03	5.3	18.8	64°	1, 2	7
WR 11	WC8 + O9 I	78.5002	0.40	130 ± 6	70 ± 2	0.54 ± 0.03	17.6	32.7	70°	3	21
WR 30	WC6 + O6–8 V	18.82	0	195 ± 11	94 ± 12	0.47 ± 0.07	15.4	31.9	70:°	4, 5	19
WR 42	WC7 + O7 V	7.886	0	144 ± 4	85 ± 1	0.59 ± 0.02	3.7	6.2	43°.5	3	11
WR 48	WC6(+O?) + O9.5 I	18.341	0	173	((≤ 6))[a]	(0.4)[b]	(7.7)[c]	(19.4)[d]			
WR 79	WC7 + O5 V	8.893	0	142 ± 3	51 ± 3	0.36 ± 0.02	1.8	4.9	44°.8	3	5
WR 113	WC8 + O8–9 V–III	29.707	0	149 ± 3	71 ± 4	0.48 ± 0.03	10.6	22.3	67°	6	14
WR 140	WC7 + O4 V	2886.	0.7	40 ± 17	22 ± 3	0.55 ± 0.25	9.2	16.8	44°	7	27
B22	WC6 + O5–6 V–III:	14.926	0.17	222 ± 10	77 ± 10	0.35 ± 0.05	10.2	29.5	71°	8	12
B31	WC4(+O?) + O8 I:	3.03269	0	275 ± 17	((8 ± 9))[a]	(0.25)[b]	(2.6)[c]	(10.2)[d]			
B32	WC4 + O6 V–III:	1.91674	0	234 ± 14	39 ± 7	0.17 ± 0.03	0.6	3.5	29°	9	5
AB 8	WO4 + O4 V	16.644	0.19	176 ± 8	48 ± 9	0.27 ± 0.05	3.9	14.5	41°	7	14

[a] Not W-R orbiting companion.
[b] Assumed from W-R spectrum by interpolation in Fig. 8.
[c] From $M_{\text{W-R}} \sin^3 i = (M_{\text{O}} \sin^3 i)q$.
[d] From $M_{\text{O}} \sin^3 i = f_{\text{W-R}}(m)(1 + q)^2$.

REFERENCES FOR i.—(1) From M_{O}(Sp) = 26 $M_\odot$ assuming luminosity class V (Schmidt-Kaler 1982). Values for the most massive stars from this source are revised from 120, 60, 37 $M_\odot$ to 60, 40, 30 $M_\odot$ for 03 V, 05 V, 06 V, respectively This makes the masses more compatible with observed values (cf. Moffat, Breysacher, and Seggewiss 1985); (2) Value compatible with preliminary polarimetry (Moffat, Niemela, and Seggewiss 1989); (3) From polarimetry of St-Louis *et al.* 1987; (4) Value compatible with preliminary photometry (Drissen, Lamontagne, and Moffat 1989); (5) M_{O}(Sp) = 23–30 $M_\odot$, slightly less than $M_{\text{O}} \sin^3 i$; (6) From photometry of Lipunova 1982; (7) From M_{O}(Sp) = 50: $M_\odot$ (cf. ref. 1); (8) From M_{O}(Sp) = 35 $M_\odot$ (cf. ref. 1); (9) From M_{O} (Sp) = 30 $M_\odot$ (cf. ref. 1).

nation of the early-type main-sequence companions in some WC + O binaries. This would also bring the maximum mass estimates in massive binaries (cf. Garmany, Conti and Massey 1980; Doom and De Loore 1984) in better line with theoretically based $M(L)$ values.

In what follows, we will assume that mass transfer plays only a minor rôle, if any at all, in all but possibly the closest, massive binary stars. This implies that properties deduced for W-R stars in binaries should also apply to single, isolated W-R stars.

Finally, we look at the question of the masses of WC stars and their variation with WC subtype. Figure 8 shows a plot of all the known WC binaries listed in Table 6: while the WC mass shows a very loose correlation with WC subtype (hotter WC stars tend to be less massive), the WC/O mass ratio shows a tighter, clearer correlation in the sense that early-type WC stars tend to show lower ratios than late-type WC stars. While part of the lower noise in the mass ratio, compared to the masses, versus subtype correlation may be due to poor estimates for the orbital inclinations, it is as likely that the difference is real. The reason for this may be that *the mass ratio is a normalized quantity, expressing the degree of evolution via wind mass loss mainly of the original primary star into its W-R phase, regardless of the initial mass* (other than its being greater than the mass of the original secondary). This occurs in the plausible way that as the W-R star loses mass, it exposes hotter and smaller cores, becoming less luminous in the process (cf. the tight theoretical L-M relation for W-R stars of Maeder and Meynet 1987). Indeed, hotter subtype WC stars do appear to be less luminous than cooler subtypes both visually and bolometrically (Lundström and Stenholm 1984; Smith and Maeder 1989). Furthermore, abundance estimates suggest that WCE stars have higher C/He abundance ratios (Smith and Hummer 1988, but cf. Torres 1988 and de Freitas Pacheco and Machado 1988) as expected if they are more advanced in their nuclear burning than WCL stars. Note that despite their different environments (e.g., metallicity and subtype distribution), the Galaxy, LMC, and SMC stars tend to blend together in mass-ratio versus spectral subtype. Also, there is no correlation of mass ratio with period, as one might be led to believe if close systems were to favor mass transfer.

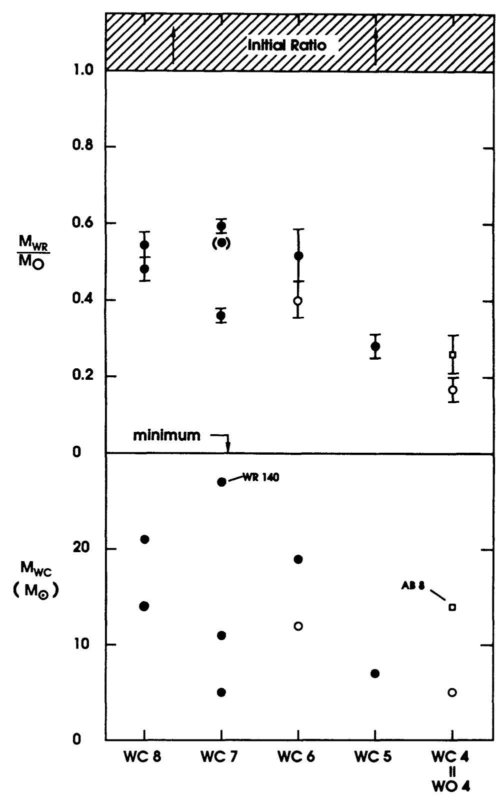

FIG. 8.—Mass and mass ratio for all known WC stars in double-line spectroscopic binaries (cf. Table 6), vs. WC subtype. Filled circles refer to Galactic stars, open circles to LMC, and open squares to SMC. Value in parentheses refers to WR 140, which has a large error bar.

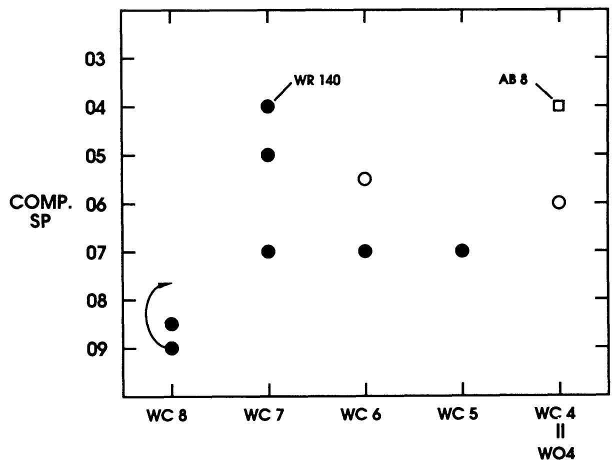

FIG. 9.—Spectral type of the O-companion vs. spectral subtype of the WC star in double-line binaries (cf. Table 6). The arrow gives the equivalent luminosity class V type.

Could the relation of mass ratio versus WC subtype in Figure 8 simply be the result of larger O-companion masses (i.e., earlier spectral types) as one goes to earlier WC subtypes, while the masses of WC stars show no correlation with subtype? This is investigated in Figure 9, which indeed does show a correlation between the spectral type of the companion and the WC subclass. (Preliminary versions of Figs. 8 and 9 have been previously shown and discussed by Moffat *et al.* 1986). Including the possible WC9 + BO I system WR 70 (Niemela 1989) reinforces the trend, which is otherwise strongly dependent on the two WC8 binaries. However, even if a weak trend prevails in Figure 9, one would still have to explain why in Figure 8 WCE stars in binaries have lower *mass ratios* than WCL stars in binaries; i.e., WCE stars must have peeled off relatively more mass than WCL stars.

From the mass ratios in Figure 8, we note a change of $\Delta M(\text{W-R})/M(\text{O}) \approx -0.3$ in passing from WC8 to WC4. Assuming that the O star loses negligible mass during the time that the WC star evolves from WC8 through WC4 (in $\approx$half the total W-R lifetime, $t_{\text{W-R}} \approx 4 \times 10^5$ yr; cf. Maeder and Meynet 1987), and adopting a typical O-star companion mass of 30 $M_\odot$, we derive an average mass-loss rate

$$\dot{M}(\text{WC}) = \frac{\Delta M(\text{W-R})}{0.5 t_{\text{W-R}}} \approx \frac{0.3 \times 30\ M_\odot}{2 \times 10^5\ \text{yr}} \approx 4 \times 10^{-5}\ M_\odot\ \text{yr}^{-1}\ .$$

This is very similar to "instantaneous" values of mass-loss rates derived, e.g., from radio continuum data of WC stars (van der Hucht, Cassinelli, and Williams 1986) and lends support to the subtype evolutionary scenario

$$\text{WC8} \rightarrow \text{WC7} \rightarrow \text{WC6} \rightarrow \text{WC5} \rightarrow \text{WC4} \rightarrow \text{WO}\ .$$

This does not mean, however, that all W-R stars are obliged to pass through all or even part of this WC sequence. It merely implies that should a W-R star reach the WC phase at any particular subtype, and if there is sufficient time before the final fate of the star, the WC star *will* evolve toward hotter types in the sense indicated. Indeed, the absence of WCL stars in the Magellanic Clouds suggests that W-R stars in those galaxies transfer from WN to WC at lower mass ratios (i.e., to WCE). The transition subtype is probably a function of the ambient metallicity (cf. Moffat 1982*a*). Note that it is still unclear how WC9 stars fit into the above scenario.

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