WOLF-RAYET STARS WITH COMPACT COMPANIONS

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ABSTRACT. Evidence is accumulating in favour of a heretofore missing link in the evolution of massive binary stars -a second WR phase in which the companion to the WR star is a neutron star of mass 1-2 $M_{\odot}$, or in some cases a more massive black hole. The discovery of such objects is also important in assessing the role of duplicity in the formation of WR stars.

I. PREDICTION AND EXISTENCE

The discovery of OB binary X-ray sources during the Uhuru era has led to significant advances in our understanding of massive binary-star evolution with mass exchange and mass loss. One outcome of this was the prediction of a second WR binary phase in the evolution of massive binaries (eg. Tutukov and Yungelson 1973: de Loore and De Grève 1975; van den Heuvel 1976):

$$OB_1 + OB_2 \xrightarrow[RLOF]{\dot{M}} WR_1 + OB_2' \xrightarrow[SN]{\dot{M}} \text{(runaway) } c' + OB_2'' \xrightarrow[RLOF]{\dot{M}} c + WR_2,$$

where c $\equiv$ compact star, remnant of the supernova. The probability that the WR + c [note the change of order since the spectrum is dominated by the WR component] system remains bound is high, since the less massive star explodes (de Loore et al. 1975). For mass ratios $M(OB_1)/M(OB_2)$ in the commonly observed range $\gtrsim 1.0$, the secondary will evolve only somewhat less rapidly than the primary, leading to a low frequency of OB + c binaries (as observed?) and in a few cases to $WR_1 + WR_2$ systems instead (de Loore 1981; Doom and De Grève 1982). On the other hand, the frequency of WR + c systems might be expected to be similar to that of WR + OB systems. However, this is by no means certain (Vanbeveren 1982), so that the determination of the WR + c frequency might help tie down the evolutionnary scenario. It is also important for theories on the formation of WR stars in general to determine what fraction of the single-line WR stars are truly single, WR + c, or WR + OB in which the OB component is drowned out. In a sense, the WR + c phase was a missing link; all preceding phases were known to exist, as well as the following phase of runaway pulsars, even binary in some cases.

The first real hint that WR + c stars do exist came from a study of the distribution perpendicular to the galactic plane of all galactic WR

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stars for which reliable distances could be derived. On the basis of Smith's (1968) catalogue, Moffat and Isserstedt (1980a) found that single-line WR stars tend to lie further from the plane in the mean than double-line (presumed WR + OB binary) stars, which behave like normal population I. In a limited sample reaching out to 6 kpc and $v < 12$ mag for which the assessment of spectral duplicity was expected to be reliable, they found $\overline{|z|}$ = 133 pc for single-line and 79 pc for double-line WR stars. Adjusting the volume and magnitude limits changed the numerical values somewhat, but not the trend, which has subsequently been verified using different selection criteria by Hidayat et al. (1982) on the basis of the more complete WR catalogue of van der Hucht et al. (1981). The conclusion is that, among the single-line sample, there exists a significant fraction of runaway WR stars which were accelerated most likely by the recoil of a SN explosion in a close binary prior to the second WR phase. Many, if not all, of these runaways are expected to be WR + c systems in the evolutionary scenario of van den Heuvel (1976). Among the O-stars, a similar situation may prevail (Stone 1981).

The next step would be to look at individual stars for more direct evidence. This paper gives an overview mainly of the observational status of such evidence.

II. DETECTION OF WR STARS WITH COMPACT COMPANIONS

By analogy with OB + c systems, the presence of the compact companion in WR + c systems is not expected to be very evident in the optical, UV or IR spectrum per se. Furthermore, the dense winds of WR stars will cause all but the hardest accretion-produced X-rays (of low intrinsic flux) to be absorbed (cf. Moffat et al. 1982). Therefore, one must resort to the tedious procedure of searching for periodic variations (in radial velocity RV, line profiles, continuum light, polarization, etc.) related to the orbital motion of the WR-star.

A necessary minimum requirement is a reliable measure of the RV semi-amplitude of the WR component, K_{WR}, which leads to an estimate of the mass of the unseen companion, after assuming a mass for the WR star and the orbital inclination. If the mass of the secondary turns out to be in the range $\sim$ 1-2 $M_\odot$, it could well be a neutron star; if more than $\sim 3M_\odot$ a black hole companion. Supporting evidence would come from phase-dependent line profile variations like those observed in OB + c, X-ray binaries, or from the establishment of runaway properties.

Two modes of attack are possible: (a) Search for duplicity among a selected sample of stars with high probability of finding WR + c systems; e.g. single-line WR stars of high $|z|$ in the galaxy, high $|V_{pec}|$, surrounded by a ring nebula (ejected during the phase of rapid mass transfer from the pre-WR star to the compact star? - cf. van den Heuvel 1976), or already suspected for showing variability. Some galactic candidates chosen along these lines are listed by Moffat and Seggewiss (1980b). (b) Same kind of search as in (a), but in a complete sample of WR stars, e.g. to a given magnitude limit, or, better, in a given volume. This approach is much longer but less susceptible to selection effects than (a) and is essential to estimate the relative frequency of WR + c versus WR + OB stars and even WR binaries as a whole.

Both approaches, which are not mutually exclusive, are presently being pursued. It is noted that the number of OB + c systems found so far is very low (cf. de Loore 1982; but cf. Stone 1981). This may be a real effect, but it may also be partly due to the difficulty in detecting low-amplitude RV variations in weak, often washed-out absorption lines in O-stars. The chance of detecting such variations among WR stars is aided by (1) the generally lower mass of WR-stars compared to O-stars (cf. Massey 1981), and (2) the availability of relatively strong lines, even if they are due to emission in an extented source and are subject to some degree of random fluctuation.

Table 1: WR + compact candidates: SB1's with low mass functions

HD	Sp	assoc. HII	z(pc)	P(d)	e	K_{WR}(km s^{-1})	$M_{WR}/M_\odot$	Ref.
50896	WN5	S308(r)	-356	3.8	0.34	36	12	1
192163	WN6	NGC 6888(r)	+53	4.5	0.3	20	27	2
193077	WN6(+OB)	S109	+29	2.3	0	16	51	3
97950	WN6(+OB)	NGC 3603	-68	3.8	0	54	(5)	4
38268	WN6(+OB)	30 Dor	-	4.4	0	43	(7)	10
197406	WN7	-	+799	4.3	0.11	90	(1.3)	5
96548	WN8	RCW 58(r)	-342	4.8	0	10	71	6
86161	WN8	282.2-2.0	-181	10.7	0	6	104	7
209 BAC	WN8	S80(r)	+264	2.4	0	13	68	8
177230	WN8	-	-824	1.8	0	22	35	8
164270	WC9	-	-228	1.8	0	20	41	9

Ref: (1) Firmani et al.(1980); (2) Koenigsberger et al. (1980), Aslanov and Cherepashchuk (1981); (3) Lamontagne et al. (1982); (4) Moffat and Niemela (in preparation); (5) Moffat and Seggewiss (1979, 1980), Bracher (1979); (6) Moffat and Isserstedt (1980); (7) Moffat and Niemela (1981); (8) Lamontagne and Moffat (1982); (9) Isserstedt and Moffat (1981); (10) Moffat (in preparation; an alias period of 1.3d is also possible).

Notes: z (pc) from Hidayat et al. (1982) except for HD 97950 in NGC 3603 with a distance 7-8 kpc (Moffat 1974; van den Bergh 1978). M_{WR} calculated from P, e and K_{WR} by assuming $i = 60°$ and a mass of the unseen companion 1.6 $M_\odot$.

III. WR + c CANDIDATES

Table 1 presents a list of all WR + c candidates for which a periodic orbit with low mass-function ($f(m) \lesssim 0.3\ M_\odot$) has been claimed so far. Presumably, many more such stars remain to be detected. Note the preponderance of WN stars, especially of low excitation. Only one WC star is listed, also of low excitation. This probably represents one or more selection effect, e.g. in favour of narrow, relatively symmetric emission lines in cooler envelope stars where RV variations are less likely to be masked by noise.

Three stars of type WN6 appear to show absorption-line spectra; this is likely incidental, since the OB-component does not partake in the indicated orbit. In the case of HD 97950, the RV amplitude probably reflects the orbit of a WN6 star with an unresolved (compact?) star located near the centre of the central dense star cluster in the massive, visible galactic HII region NGC 3603. Similar results were obtained for the WN6 component in the dense core HD 38268 of the giant LMC HII region 30 Dor. Section IV devotes particular attention to these two objects.

The low mass-functions for the stars in Table 1 indicate unseen companions of mass $M_2 \sim 0.5-2\ M_\odot$ in most cases, compatible with the presence of neutron star (NS) companions. We thus assume $M_2 = 1.6\ M_\odot$, an appropriate mean value for NS in X-ray binaries (Crampton et al. 1978), in order to derive the WR-star masses. Except for 3 cases, these are quite reasonable: The WN5 star HD 50896 has a mass of 12 $M_\odot$, compatible with the WR component ($\sim$ 10 $M_\odot$) in the well-known WN5 + O6 eclipsing binary V444 Cygni (Münch 1950). The WN6-stars HD 192163 and 193077 have a mean mass of 39 ± 12 $M_\odot$, like the minimum mass (40 $M_\odot$) of the WR component in the WN6 + 06 binary HDE 311884 (Niemela et al. 1980). The four WN8 stars have a high mean mass of 70 ± 14 $M_\odot$, while the WC9 star HD 164270 has a mass like that of WN6 stars. This is in line with stars of these subclasses in WR + OB binaries (Moffat 1982).

Table 2: WR + BH candidates, with assumed M_{WR} and i = 60°

HD	Sp (WR)	$M_{WR}/M_\odot$	$M_2/M_\odot$
97950	WN6	50	6.8
38268	WN6	50	5.6
197406	WN7	60	14.0

For the three WR-stars HD 97950, 38268 and 197406, whose masses in Table 1 clearly fall well below those expected for their subclasses, we reverse the process by adopting plausible WR-masses in order to calculate the mass of the unseen companion (Table 2). These turn out to be greater than 3 $M_\odot$ and get even larger for smaller i. To be O-stars ($\gtrsim 30 M_\odot$) we need i<27° (HD 197406) and $i \lesssim 13°$ (HD 97950, 38268) for which the probability in a random sample is low. We are thus possibly dealing with black holes (BH). If so, the relative number fraction BH/NS in our incomplete sample of WR stars is low (∿ 20%), like that among massive X-ray binaries (Crampton 1980).

It is unlikely (but of course not entirely impossible) to find moderate-mass (∿5-15 $M_\odot$) main-sequence companions to (originally) very massive WR stars. This statement is strengthened for HD 197406, which is an extreme runaway. Its very clear orbit yields a mass of ∿14 $M_\odot$ for the unseen star. The light curve shows a shallow dip of ∿0.04 mag close to when the WR component passes in front, in support of a moderatly high orbital inclination and thus the compact nature of the companion. The light curve may be a result of the optical depth variations in the line of sight towards the compact source, which emits degraded radiation from an accretion disk, as it orbits in the dense WR wind (Moffat and Seggewiss 1979). The amplitude of the modulated optical intensity of HD 197406 is ∿4% x L_{WN7} ∿ 10^{38} erg s^{-1}, a non-negligible fraction of the Eddington luminosity associated with a 14 $M_\odot$ collapsar. The fact that HD 197406 was not detected as an Einstein X-ray source [L_X (0.5 - 3.0 keV) $\lesssim 10^{32}$ erg s^{-1}: Moffat et al. 1982] is not incompatible with the idea of absorption of X-rays and degradation to lower energy in the dense wind ($N_H \gtrsim 10^{24}$ cm^{-2}).

Table 3: Possible scenario for HD 197406 (i = 60°)

Stage	Component Primary (orig)	Component Secondary	P(d)	e	z(pc)	V_Z (km s^{-1})
(1)just before SN	≥65 $M_\odot$(WR)	80 $M_\odot$(O)	2.0	0	0	0
(2)just after SN	14 $M_\odot$(BH)	80 $M_\odot$(O)	≥8.0	≥0.54	0	≥264
(3)now (≲3.10^6y after (2))	14 $M_\odot$(BH)	60 $M_\odot$(WN7)	4.2	0.11	799	≥258

Note: ═ observed, ___ assumed, --- deduced.

What recoil velocity is needed to bring HD 197406 up to its present high separation from the galactic plane? This was estimated by Moffat and Seggewiss (1979) assuming a rather low mass for the WN7 component. In Table 3, we show a revised scheme using the same methods but improved numerical values. In particular, an O-type progenitor with mass 80 $M_\odot$ can remove enough matter by stellar wind to become the present WN7 star (Noels et al. 1980). The maximum age of the system after the SN explosion places lower limites on some of the other parameters. The resulting kick velocity in z is high even compared to high-velocity, massive, single-line O-stars, which may have been accelerated by a SN recoil, leaving behind a BH companion (Stone 1981). The peculiar radial velocity of HD 197406 is high but not extreme (cf. Table 5). The pre-SN system may resemble the WN6 + O binary HDE 311884 (Niemela et al. 1980) with mass ratio WR/O $\sim$0.8.

Among the other candidates in Table 1, several objects deserve special mention. HD 50896 = EZ CMa is the only object studied so far whose variable optical spectrum shows clear evidence of relatively narrow emission associated with the secondary. This may be related to the degraded spectrum from a supercritical accretion disk around the NS. More reçent data strengthen these findings and also suggest a period change $P/\dot{P} \simeq -1100$ y. If confirmed, such a change would have interesting consequences concerning the evolution of this system (spiral-in? orbital circularization? - but the mass loss rate of the WN5 component appears too low to explain this). This star also exhibits phase-dependent variations in polarization (McLean 1980).

HD 193077 may be a triple system in which the late O-component is in a 1763-day orbit around the short-period WN6 + c pair. A SN explosion would produce less recoil in such a system. HD 96548 appears to show the largest amplitude of random photometric variability in the continuum of any WR star known; the periodic behaviour is barely discernable above the noise. 209 BAC is the clearest case of a runaway, the radial component of its peculiar velocity being $\sim$ 150 km s^{-1} (cf. Table 5). Luckily, the narrow, symmetric emission lines in WNL stars (espec. NIV 4057) can be used to estimate the true stellar radial velocity (Moffat and Seggewiss 1979). HD 177230 is the furthest star from the galactic plane in Table 1; its orbit (K $\simeq$ 22 km s^{-1}) is easily detected. In the case of HD 96161, it is the double-wave light-curve which points most strongly to a WR + c candidate.

IV. THE CORES OF NGC 3603 AND 30 DOR

While it seems apparent that the core HD 97950 of the massive galactic HII region NGC 3603 consists of a dense star cluster, in which some individual stars are resolved (Walborn 1973), such is not obviously the case for the core HD 38268 of 30 Dor in the LMC, which has recently been claimed to be a single, supermassive ($\sim$2000 $M_\odot$) star (Cassinelli et al. 1981). This is based mainly on (1) the claim that there is not a sufficient number of hot, luminous stars other than HD 38268 to provide ionizing UV photons to explain the observed radio flux of the 30 Dor nebula, and (2) the high level of ionization and flux of the UV spectrum of HD 38268. While the latter argument makes for a strong case, it is plagued by several uncertainties such as the UV extinction and what to expect for the UV spectrum of a dense cluster of massive, hot O-stars with interacting winds. Furthermore, the first argument is dealt with by Melnick (1982) who notes that in the association surrounding HD 38268, there are $\sim$ 100 hot stars brighter than M_V = -5, sufficient to ionize the 30 Dor nebula, and that the central object is little more than a continuation of the association to higher central star density. Indeed, if the core of NGC 3603 were displaced to the LMC, one would see a fuzzy star-like object, the separation of the dominating stars A & B (cf. Walborn 1973) being reduced from $\sim 0\overset{''}{.}6$ to $\sim 0\overset{''}{.}08$ ($\sim$ 0.02 pc), considerably smaller that the maximum dimensions ($\sim$ 0.1 pc) quoted for HD 38268 by Cassinelli _et al_. (1981).

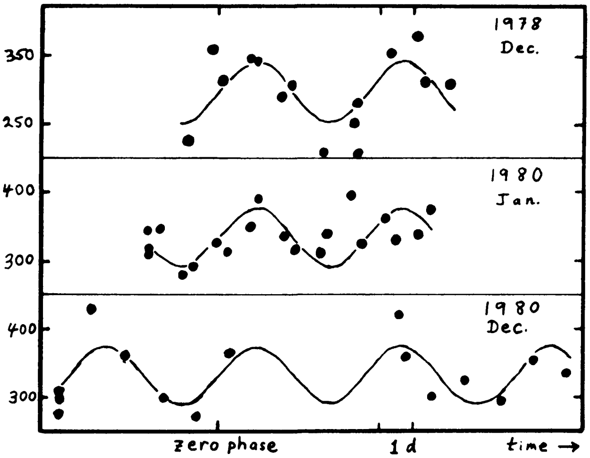

Fig. 1: RV variations of HD 38268 (core of 30 Dor). The curve is a fitted circular orbit with P = 4.377 d. A shift of 33 km s^{-1} for the 1978 data gives a better fit.

As summarized in Tables 1 and 2, the present optical spectroscopy indicates periodic RV variations of the emission component in HD 97950 and in HD 38268 (cf. Fig. 1). The O-type absorption lines do _not_ appear to follow this variation. Since HD 97950 has been resolved, it seems likely that we are dealing here with a WR star orbiting another star (possibly compact) in a dense cluster. Which star this is cannot be identified at present although the best candidate is star A. Analogously, the core of 30 Dor indicates a similar situation. To illustrate this further, we show in Fig. 2 the mean of $\sim$ ten photographic spectrograms of each star. The WR emission spectra are very similar: the relative NIII, NIV, NV line strengths indicate a subclass WN6 (cf. van der Hucht _et al_. 1981) in either case. The absorption spectra are also similar, showing an early O-type, as noted by Walborn (1973). But there are some differences. While the absorption-line spectrum of HD 38268 is somewhat stronger than that of HD 97950, its emission spectrum is noticeably weaker by a factor 2-3. HD 97950 also shows broad emission at the Balmer lines. One very simple explanation of these differences is that we are seeing the superimposed spectrum of a luminous WN6-star and a cluster of O-stars. In HD 38268, the number of O-stars must be greater than in HD 97950, thus causing the WN6 spectrum to have a more drowned-out appearance, while the absorption spectrum is stronger in HD 38268. This is illustrated more quantitatively in Table 4 in which we calculate the expected ratio of diluted to intrinsic emission and absorption-line equivalent widths (We'/We, Wa'/Wa) for each of HD 97950 (M_V = -9.6) and HD 38268 (M_V = -10.6) (van den Bergh 1978).

Taking M_V (WN6) = −8 for the assumed intrinsically identical WR stars, which is within the range of WN6 stars in the LMC (cf. catalogue of Breysacher 1981), we find that the emission (absorption) spectrum of HD 38268 is 0.4 x (1.2 x) that of HD 97950, in qualitative agreement with what is observed in Fig. 2. Also, the WR component in HD 38268 appears considerably diluted compared to other WN6 stars in the LMC. In Table 4, the number of equivalent stars each with M_V = −7 is ∿ 25 in HD 38268 and ∿ 8 in HD 97950. Some of these can be very hot O-stars, others cooler O and even early B supergiants (cf. Moffat 1974 for stars surrounding HD 97950), producing a mean O5 absorption spectrum. It would be instructive to see the (highly reddenned) UV spectrum of HD 97950 in which there is little problem accepting a dense star cluster.

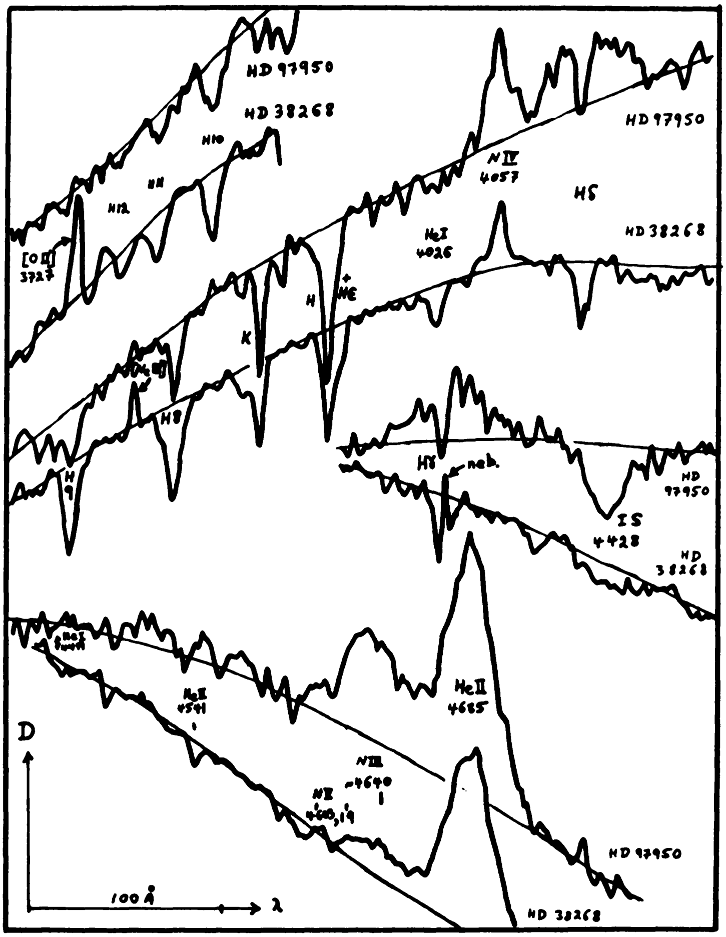

Fig. 2: Mean photographic spectra of the dense cores of NGC 3603 (HD 97950) and 30 Dor (HD 38268).

V. BINARY STATISTICS

With the discovery of WR binaries containing compact companions, we are potentially in a better position to estimate the real frequency

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Table 4: Dilution of emission and absorption lines by superposition of N O-stars, each of $M_V = -7$, and one WN6-star of varying magnitude for each of HD 97950 and HD 38268

	M_V(WN6)	Integrated M_V (O)	N(O)	We'/We	Wa'/Wa	
	-4	-9.59	11	.006	.994	
	-5	-9.58	11	.015	.985	
	-6	-9.56	11	.036	.964	HD 97950
	-7	-9.50	10	.091	.909	$M_V = -9.6$
	-8	-9.32	8	$\boxed{.229}$	$\boxed{.771}$	
	-9	-8.67	5	.575	.425	
	-4	-10.60	27	.002	.998	
range of	-5	-10.59	27	.006	.994	
WN6 in	-6	-10.58	27	.015	.985	HD 38268
LMC	-7	-10.56	27	.036	.964	$M_V = -10.6$
	-8	-10.50	25	$\boxed{.091}$	$\boxed{.909}$	
	-9	-10.32	21	.229	.771	

of duplicity among WR stars. However, in view of the difficulty in measuring RV's among the hotter WR stars, which often have broad, asymmetric emission lines, it is better to limit our discussion to the generally narrower-line WNL stars. Down to b = 12^m.3, there are 15 galactic WNL stars (Table 5), all but one of which have been studied in sufficient detail to determine their binary status. From Table 5, we note: (1) 57% (8/14) are binary, i.e. more than the estimated 36% duplicity among O-stars (Garmany et al. 1980). This may be due mainly to the existence of 2 WR phases and a short O + c phase (cf. Lamontagne and Moffat 1982). (2) The relative frequency of WNL + c and WNL + OB systems is 5:3. For small-number statistics, this is close to parity as expected if there are 2 WR-phases of massive binaries, whose initial mass ratios are not too far from unity. (3) WNL + c candidates are located at a mean distance from the galactic plane $\overline{|z|}$ = 482 pc, compared to 75 pc for the remaining WNL stars with or without OB companions. The same groups yield mean radial components of peculiar velocity of 50 and 9 km s^{-1}, respectively, after adding a systematic correction of 26 km s^{-1} (based on the non WR + c stars) to the observed velocities. This supports the runaway nature of WR + c stars as opposed to single WR stars and WR + OB binaries which show normal movement for population I. The mean z-component of the kick velocity necessary to reach z=482 pc in $\sim 3.10^6$ y is Z ≃ 160 km s^{-1}, which is high even compared to the most extreme single-line O-type runaways (Stone 1981). This may be due to selection effect, favouring distant, high - z stars of lower IS extinction. (4) Among the 3 WNL-stars with ring nebulae, 2 have suspected compact companions; nothing is known about the third star. This is in line with the formation process of WR + c systems (van den Heuvel 1976), although other mechanisms are possible to explain the ring nebulae (Chu 1981). (5) The frequency of WN8 + c systems is high, but not 100%. This may be the result of small-number statistics.

It will be interesting to see if similar conditions prevail among the WR stars of lower luminosity (and mass: Moffat 1982): WNE, WC.

VI. ALTERNATE MECHANISMS

Beside orbital motion, one should consider other processes which could in principal, produce the observed low-amplitude, periodic RV and light variations among the WR + c candidates: (a) Pulsation: massive He-stars (identified primarily with WNE, WC stars) have radial pulsation periods in the range of 30 min (Stothers and Simon 1970), much shorter

Table 5: Parameters of galactic WNL stars with b $\lesssim$ 12.3 mag

WR	Other	Sp (ring neb)	z (pc)	V_{Hel}	ΔV_{LSR} (O-C)	ΔV_{LSR} +26	Duplicity	Ref.
12	MR 13	WN7	-282	-	-	-	SB1(+OB,23.9d)	11
16	HD 86161	WN8	-181	-23	-36	-10	SB1(+c,10.7d)	7
22	92740	WN7+abs	-34	-26	-23	+3	SB1(+OB,80.4d)	12, 13
24	93131	WN7+abs	-52	-36	-32	-6	Const RV	12, 13
25	93162	WN7+abs	-38	-26	-23	+3	Const RV	13, 14
40	96548	WN8 (r)	-342	-16	-6	+20	SB1(+c,4.3d)	6
55	117688	WN8 (r)	+26	-	-	-	?	
78	151932	WN7	+44	-48	-25	-5	Const RV	15
108	313846	WN8	-59	+9	-4	+22	Const RV	8
123	177230	WN8	-824	+65	+3	+29	SB1(+c,1.7d)	8
124	209 BAC	WN8 (r)	+264	+157	+122	+148	SB1(+c,2.4d)	8
148	HD 197406	WN7	+799	-139	-78	-42	SB1(+c,4.2d)	5
155	214419	WN7+O	-83	-60	-19	+7	SB2(+OB,1.6d)	16
156	MR 119	WN8	+71	-92	-42	-16	Const RV	8
158	MR 122	WN7	+9	-98	-37	-11	Const RV	8

Ref: (see also Table 1); (11) Niemela (1982); (12) Moffat and Seggewiss (1978); (13) Conti et al. (1979); (14) Moffat (1978); (15) Seggewiss and Moffat (1978); (16) Hiltner (1944), Leung et al. (1982).

Notes: Name and Sp. from van der Hucht et al. (1981); z from Hidayat et al. (1981) except WR 108 (cf. ref. 8); V_{Hel} from NIV 4057, not available for WR 108 and 156: Si IV 4089/4116 used instead; $V_{LSR} = V_{Hel} + 10 \cos \ell + 10 \sin \ell$ (km s^{-1}); Galactic rotation calculated using R_o = 8.5 kpc, V_o = 220 km s^{-1} and a flat rotation curve (Gunn et al. 1979).

than any periods observed. A supermassive ($\sim 10^3 M_\odot$) H-burning star would have a pulsation period of 1-2 d, extrapolating the results of Appenzeller (1970). This is in the range found for the RV variations of the WR emission-lines in the core of 30 Dor. However no periodic light variations have been found (cf. Feitzinger and Schlosser 1977), nor do the absorption lines vary in RV. As noted previously, this object may be a dense star cluster. Nothing can be said about the possibility of non-radial pulsations, especially if the WR envelope is involved. (b) Rotation: if the observed periods are due to rotation-associated surface-phenomena, they are generally too long to lead to rotation-induced mass loss. More promising might be the inhomogeneities associated with a magnetic field, which may be an important factor in the acceleration of the wind (Cassinelli 1982).

In any case, one is faced with the observational fact that the WR + c candidates tend to be runaways, with periods in the range typical of massive binaries. The most likely interpretation appears to be that they are recoiled WR + collapsar systems.

Note added

After receiving a preprint of Niemela's (1982) results, it is possible to add an important but puzzling piece of information to Table 5. From NIV 4057 we have for WR12 V_{Hel} = -34 km s^{-1}, which leads to ΔV_{LSR} (O-C) = -113 km s^{-1}. If this is not due to a peculiarity of this spectral line, and assuming that the orbital parameters are reliable, this is the first case of a runaway WR-star with a high (normal for WR + OB) mass-function. The runaway nature is supported by its high z (-282 pc), although part of this may be due to warping in the outer galaxy. Assuming i = 60° and a mass of 60 $M_\odot$ for the WN7 component, the unseen star would have 46 $M_\odot$, compatible with an O-star of moderate mass. This star deserves more attention.

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DISCUSSION

Carrasco: I found difficult to believe in your scheme for HD 197406. It looks to me that even a flight time of 5×10^6 yr to reach z = 800 pc would be too long for the evolution of a $120 M_\odot$ star. I rather prefer a more conservative point of view by assuming that the compact companion is a white dwarf and in this case the WN would really be a low mass object. We should really begin to think about the possibility of finding nitrogen overabundances in low mass stars. I confess that at present the planetary nebulae data points out towards WC association. However, since the WN phenomenon suggests a lower density in the mantles along with higher T_e as compared with WC, then it is possible that this lower density prevents the formation of a planetary nebula around this system.

Moffat: The flight time will be shortened in the final draft. Indeed a reliable, independent test for the distance of this important star would be very welcome.

Massey: Peter Conti and I have looked at two stars in your sample, HD 177230 and HD 193077. In both cases we saw no velocity variations greater than ~15 km/s. If you do the simplest of statistical tests to determine whether this is low amplitude motion or measuring errors, you find it is dominated by measuring errors. No periodic behaviour was present in either star, which violates the principal enumerated the other day by Peter Conti that " periodic velocity variations " was a minimal requirement to consider a WR star a binary.
If you assume a very bright M_V for all WN8 and WN7 stars, it's not surprising you derive high Z plane distances. You will then find high peculiar velocities. If you assume HD 177230 has a more modest M_V, you'll find a more reasonable Z plane distance, and a radial velocity of NIV λ 4058 in accord with galactic rotation. Aren't you a bit concerned about making a circular argument in this regard ?

Moffat: A period search of you best line-data of these two stars reveals best periods compatable with our sets of independent data.

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The true measuring error of a given line is hard to estimate without comparative data for stars of known velocity behaviour. The M_V's assumed here are those from the 6th catalogue leading to Z-displacements given by Hidayat, van der Hucht and The (1981).

Barlow: 1) Was the sample discussed confined to high latitude or high velocity WR stars ?

2) Did any of you samples not show periodic effects ? If all do, then that throws some doubt on the binary hypothesis in my mind because we might expect some single stars.

Moffat: For the WNL binary statistics the only limit was one of magnitude; however, the candidates so far for the WR+c's were often selected for these factors and HII ring nebulosity. Some of the WNL stars were found to have constant velocity implying they may be single.

Cassinelli: One of the original arguments that the central star of 30 Dor is a supermassive object is that it is very bright, and estimates of the total luminosity make it necessary that it has a very large mass. So I don't understand the estimate of $50M_\odot$ that appeared in one of your tables. Did you consider the constraint imposed by the brightness of the star ?

Moffat: This mass corresponds roughly to that of WR stars of similar spectral type seen in spectroscopic binaries. Since we are still not sure about the nature of R136 (supermassive single star or cluster) I only consider the lower mass case for the WR component. By analogy with NGC 3603, where the presence of a WN star near the centre of the cluster can be accepted more readily, such a possibility in R136 becomes more plausible.

Vanbeveren: If you really need 5×16^6 yrs in order to remove the HD 197406 system towards the observed place, there may be a problem in your scenario as the lifetime of a $120M_\odot$ star is only 2×10^6 yrs.

Moffat: This will be changed in the final version.

Conti: I find it curious that none of these WR stars with candidate neutron star or black hole companions are X-ray sources. In our Galaxy the known O+n.s. (or black hole) companions are strong sources. Could you indicate why this is so ?

Moffat: As noted by Moffat and Seggewiss (1979, A&A, 77, 128) the dense WR wind probably absorbs most of the X-rays below ~5^+ keV. This is not the case in massive X-ray binaries where the density leads to cut-offs in the range 1-2 keV.

Abbott: I think there is a conceptual problem of having a supernova in HD 50896. If a supernova precedes the WR wind, there will be essentially no interstellar material for the wind to snow plough.

Moffat: For some WR c's this may be true, although the ejecta, particularly in M1-67 and RCW 58, probably come from the stars in the relatively gentle (cf. a SN) beginning of the WR phase, so one does not necessarily need the snow plough effect. Possibly too, the runaway system after the SN may have time to move to a new location where the snow plough ejection may occur.

Underhill: It is entirely possible that a massive model star such as the ones you are talking about would show an O-type spectrum. Have similar statistically valid searches been made of the magnitude and radial velocity variations of O stars to find out how many double stars consisting of a very massive star and a compact object may exist ?

Moffat: As far as I know, searches for O+c's have been carried out with little definitive success. More intense searches are underway among various groups (e.g. Brussels, Mexico, Toronto ...).

de Loore: Various groups are searching for O stars with compact companions and I am also involved in such a programme. The aim is to have arguments for the scenario we have computed for the evolution of massive binaries. However, until now, nobody has been successful, and this is not astonishing. We have performed computations on the possibility to detect photometrically these stars. If a neutron star is orbiting a massive O star, as a consequence of the tidal influence, the surface will be deformed (by tidal lag) and this deformation can be translated into magnitude changes. Now we have calculated models for various masses of O stars, neutron stars and periods. These compiutations reveal that the magnitude difference to be expected is very low ($0^m.001$ to $0^m.005$). Systems of an O star and a neutron star of periods less than a day should be good candidates. The observations have to be carried out very carefully with a large number of comparison stars.