WOLF-RAYET BINARIES

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ABSTRACT. An updated list of known spectroscopic double-line and single-line Galactic Wolf-Rayet binaries is presented. From this we discuss e.g. mass ratios, the binary frequency and the evidence for low-mass unseen (compact?) companions. Spectroscopic binary orbits of several WR stars in the Magellanic Clouds are noted for the first time.

I. Galactic WR stars with orbits

Our present knowledge of WR-star masses is based exclusively on an incomplete sample of twelve double-line systems brighter than v = 10.5. Another eight single-line binaries and an effectively single-line star in a triple system complete the list for the Galactic WR stars. All 21 are listed in Table 1. It should be noted that the only really conclusive proof of duplicity comes from the observation of periodic orbital phenomena such as radial velocity (RV) variations. The presence of both emission lines and O-star like absorption lines in the same spectrum does not necessarily guarantee a binary nature for those two components. This is manifested by at least two of the stars in Table 1 (B), MR 25 and CQ Cep, whose respective emission and absorption lines mutually follow the same orbit. For this reason, they are assigned single-line spectral types.

From Table 1 which contains the best values form the literature we note the following:

- No orbits (SB1 or SB2) are available for the hot or cool extremes of the nitrogen or carbon sequences (WN3, WN8; WC5, WC9). This is probably due to selection.
- The eccentricity e is significantly different from zero for binaries with long periods ($P > 50^d$) and binaries with suspected compact companions.
- M_{WR}/M_{OB} for the double-line stars appears to be relatively constant, independent of spectral subclass. Mean values are:

0.44 ± 0.08 m.e. for WN,
0.42 ± 0.07 m.e. for WC (excluding θ Mus).

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These imply that the mean masses of WN stars (at least those of lower luminosities: WN3-6) differ insignificantly from those of WC stars, assuming the OB companions to have similar mass in the mean. This puts constraints on the hypothesis that WN stars evolve into WC stars through additional mass loss and exposure of processed core material.
- M_{WR}/M_{OB} is independent of the orbital period, in conflict with the idea that mass tranfer should be most efficient for the closest systems (cf. Vanbeveren and Conti, 1979).
- Among the eight single-line binaries, none is WC, whereas all are WN5-7 with WN7 dominating. In some cases this is probably the result of the drowning out of the OB companion by the luminous WN7 star. In the less luminous WN5,6 stars MR 114 and MR 108 it might be particularly worthwhile looking more carefully with higher signal-to-noise ratio for the presence of an OB companion.
- The deduced mass ratio M_{WR}/M_2 for the five single-line stars MR 114, 108, 25, 111, 118 is slightly larger (0.60 ± 0.10 m.e.; 0.51 ± 0.03 m.e. without MR 25) than for the double-line binaries, subject to assumptions concerning the orbital inclination and WR mass.

Table 1. Galactic Wolf-Rayet binaries with orbits, sorted according to spectral duplicity and WR subclass

MR	HD	v	P	e	Sp	f(m)	m_{WR}/m_2
A Double-line binaries						$M_\odot$	
31	94546	$10^m.69$	$4^d.9$	0.0	WN4 + O	12.4	0.34
94	186943	10.36	9.55	0.0	WN4 + B	3.9	0.42
99	190918	7.48	112.8	0.43	WN4.5 + O9.5 Ia	1.24	0.26
106*	193576 V444 Cyg	8.27	4.21	0.0	WN5 + O6	12.4	0.39
23	90657	9.80	8.2	0.0	WN5 + O6	10.4	0.23
116*	211853 GP Cep	9.20	6.69	0.0	WN6 + O6 I	16.1	0.35
42	311884	11.09	6.3	0.0	WN6 + O	14.4	0.86
105	228766	9.33	10.74	0.0	WN7 + O7.5 I	12.7	0.67
43	113904 θ Mus	5.69	18.34	0.0	WC6 + O9.7 Iab	9.9	(<0.03)
65	152270	6.95	8.89	0.0	WC6-7 + O5	2.7	0.36
36	97152	8.25	7.84	0.0	WC7 + O6	3.7	0.55
12	68273 γ^2 Vel	1.74	78.50	0.40	WC8 + O9 I	13.7	0.53
85*	168206 CV Ser	9.43	29.71	0.0	WC8 + O8-9	15.0	0.24
B Single-line binaries (orbit of WR component only)							(i=60°, m_{WR}=10)
6†	50896 EZ CMa	6.94	3.76	0.34	WN5	0.015	6.9
114*	- CX Cep	12.40	2.13	0.0	WN5	5.4	0.52
108	193928	10.15	21.64	0.0	WN6	4.9	0.55
102†	192163	7.73	4.5	?	WN6	0.00024	29
25	92740	6.44	80.35	0.55	WN7	1.67	0.98
111	-	14.0	22:	?	WN7:	7.7:	0.42:
113†	197406	10.50	4.32	0.11	WN7	0.32	2.1
118*	214419 CQ Cep	8.94	1.64	0.0	WN7	5.1	0.54

Notes: * eclipsing binary
† compact companion?

- The mass ratio M_{WR}/M_2 for the stars MR 6, 102 and 113 is significantly larger than 1.0. Combined with other evidence below, these stars are prime candidates for possessing relatively low-mass, compact companions.
- The ratio of stars with known orbits (SB2 and SB1) to the total number of WR stars decreases steadily from 71% (5/7) for $v \leq 7.0$ to 43% (10/23) for $v \leq 9.0$, where detailed spectroscopic searches for orbits are less complete. From a study of the statistics of double-line WR stars and deduced WR+compact binaries, Vanbeveren and Conti (1979) estimate a frequency of 40 + 40 = 80%, in fair agreement with the value obtained here for brighter stars with known orbits. It may be inferred that the binary nature appears fundamental to the formation of WR stars, except possibly for the more luminous WN7/8 subgroup.

II. Runaway WR stars

From a theoretical point of view, it appears quite plausible that a massive binary can pass through two WR phases of essentially equal duration (Tutukov and Yungelson, 1973; van den Heuvel, 1976). The first corresponds to the WR + OB (SB2) phase observed unequivocally in ~40 - 50% of the cases. This is followed by a supernova explosion of the WR star, leaving in the majority of cases, a compact + OB recoil system which eventually evolves into a runaway single-line WR (SB1) binary corresponding to the second WR phase. Several properties, summarized below can be expected to characterize such WR stars with collapsed companions:
- high peculiar (radial) velocity and/or large separation |z| from the Galactic plane, depending on the direction of the runaway space velocity vector.
- single-line, short period spectroscopic binary with low mass function; such systems will be more difficult to detect than WR + OB binaries. The orbit may be eccentric.
- expanding gas disc ejected during the phase of rapid, non-conservative mass transfer from the evolving OB star. If this occurred not too long ago, one would expect to see it in form of an expanding H II region, otherwise it may be too dispersed to be seen.

Table 2. Runaway WR candidates

MR	type	MR	type	MR	type
3	4	51	4	100	2
6	1,2	53	4	102	1,2,3
7	2	58	4	113	1,3,4
21	2	60	4	M1-67	2,3
34	2	67	4	LS 8	4
49	2	91	4	LS 11	4
50	4	97	2		

Type of peculiarity: (1) low mass function, (2) H II ring, (3) peculiar RV, (4) |z| > 400 pc.

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From Table 1 (B) we see three stars which satisfy at least two of the above criteria: MR 6, 102 and 113. In Table 2 we present a summarizing list of probable runaway WR candidates based on these criteria. The fact that there may be a significant fraction of runaway stars (up to ~50%, comprising most of the single-line WR stars) is strongly supported by the statistical analysis of the z-distribution of Galactic WR stars by Moffat and Isserstedt (1979). The mean absolute separation $|z|$ for WR + OB stars is ~80 pc, like the normal population I objects, while for single-line stars it is ~130 pc, much like the well-known runaway OB stars. Some of these stars may turn out to be X-ray sources but of considerably reduced X-ray flux due to the high efficiency of photoelectric absorption in the dense WR envelopes (cf. Moffat and Seggewiss, 1979).

III. Search for binary orbits among extragalactic WR stars

Beyond the Galaxy, WR stars are known to abound in the Magellanic Clouds: there are now 101 known in the LMC (Azzopardi and Breysacher, 1979b) and 8 in the SMC (Azzopardi and Breysacher, 1979a). Many of these stars are bright enough to make a velocity orbit search feasible. During 10 nights of Nov/Dec 1978 one of us (AFJM) obtained repeated image tube spectra at CTIO, Chile, of 17 stars of magnitude $V \leq 12.5$ at 46 Å/mm.

Whereas about half of the luminous WN7/8 stars appear to be truly single stars (constant RV) as is the case in our Galaxy (Moffat and Seggewiss, 1979) all the rest except FD 68 (WN6) are WR + OB binaries similar to their Galactic counterparts in Table 1 (A). As in the Galaxy, many of these OB companions are supergiants.

From preliminary analysis of the radial velocities, six (35%) double-line spectroscopic binaries have been found (AB 5,6; FD 21,28,29,67). Except for FD 67, which contains the more luminous WN8 subclass, the mass ratio M_{WR}/M_{OB} of the other five stars appears to be significantly lower on the average than for their Galactic equivalents. Although this may be partly due to spurious effects the low mass ratio appears to be intrinsic, possibly the result of differences in chemical composition between the Magellanic Clouds and the Galaxy such that the presently observed OB component in the Clouds has lost less mass on the average.

Furthermore, seven (41%) stars are definite or probable SB1 or possible SB2 (FD 6,20,31,55,62,66,68) while four (24%) are probably single WR stars (all WN7,8) from our sample of 17 stars in the Clouds. Although these fractions compare favourable with those of WR stars in our Galaxy, it is still too early to make confirm conclusions in view of the magnitude selection effect in favour of binary systems with bright OB companions.

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DISCUSSION FOLLOWING NIEMELA AND MOFFAT-SEGGEWISS

Herczeg: Is MR42 perhaps eclipsing? The high M $\sin^3 i$ values in your table may suggest this.

Moffat: I obtained photometry of MR42 on 2 nights in 1973 (3 hour runs each) with no evidence for eclipses (see Moffatt and Haupt, Astron. Astrophys., 1974).

Sugimoto: For the former two systems the mass of the Wolf-Rayet star is smaller than that of its companion. For the latter two systems both of these masses are comparable to each other. They seem to be in different evolutionary states. Is there any indication reflecting such a difference, for example, in the ratio of element abundances such as He/H?

Niemela: Yes, in fact the envelopes of the late type WN stars show H lines in their spectra, but the early type WN envelopes do not.

Popper: Is it your perception and also that of the previous speaker that the Wolf-Rayet-O star binaries are mostly semi-detached rather than detached?

Moffat: I would say they are quasi-detached. The OB star does not generally fill its Roche lobe, nor does the WR core. However, the WR envelopes often extend beyond the classical Roche lobes especially for short-period systems. In such cases, one must also consider the strong, fast stellar wind for which the companion star only represents a perturbation of the wind particle trajectories amd the concept of a Roche lobe must be modified.

Van Paradijs: Given the large mass-loss rates of WR stars, wouldn't your model for the runaway WR stars predict that these stars are strong X-ray emitters?

Moffat: Yes, except that virtually all X-rays up to energies of $\gtrsim$ 10 KeV will be absorbed in the dense WR envelope (cf calculation for WR runaway candidate HD 197406 by Moffat and Seggewiss, A&A, 1979, in press.)

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