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Wolf-Rayet Binaries

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Abstract. A WR binary frequency of 37 % is found in the *VIIth Catalogue of Galactic Wolf-Rayet Stars.* Indications are that perhaps all WR stars are binaries and thus that all WR stars point to massive binary formation regions.

1. Introduction

Population I Wolf-Rayet (WR) stars are generally recognized to represent the final and most conspicuous evolutionary phase of massive stars, before the SN phase (*e.g.*, van der Hucht 1992). From the proceedings of the first IAU Symposium (No. 49) on WR stars, we quote Kuhi (1973): "Are all WR stars binaries? The question has been asked ... and no doubt will continue to be asked ... because there can be no final answer". He counted for $v < 10$ mag a WR binary frequency of $\sim 73\%$, and suggested that, if one allowed for the non-detection of low-luminosity low-mass companions, perhaps all WR stars could be binaries.

Van der Hucht *et al.* (1988) derived a WR binary frequency of 37 % within 2.5 kpc from the Sun. Moffat (1995) counted galactic WR binaries up to 42 %. Reviews on WR binaries have been given by, *e.g.*, Moffat (1995), Cherepashchuk (1996), and Niemela *et al.* (1999).

2. Recent Wolf-Rayet Binary Census

The *VIIth Catalogue of Galactic Wolf-Rayet Stars* (van der Hucht 2000) lists among its 227 WR stars 84 WR (37 %!) binaries and probable binaries. All WR subtypes are represented, except WN2 and WC3 binaries (see Table 1).

Orbital periods among the 84 WR spectroscopic binaries range from 0.2 d to 4700 d and larger. Especially the census of WR binaries with $P \lesssim 1$ d and $P \gtrsim 100$ d is suffering observational bias. As period characterization we adopt the terminology given in Table 2, which gives also the period distribution.

The 84 WR binaries comprise, more or less in order of binarity confidence, the following catagories:
(a) double-line spectroscopic binaries (SB2) with radial-velocity (RV) solutions;
(b) single-line spectroscopic binaries (SB1) with RV solutions;
(c) long-period binaries deduced from high-spatial-resolution IR imaging of spiral (pinwheel) dust formation around systems like WR 98a and WR 104 (Tuthill *et al.* 1999; Monnier *et al.* 1999);
(d) very-long-period binaries inferred from episodic/periodic dust formation, like WR 19, WR 48a, WR 125, WR 137, WR 140 (Williams 1999);
(e) very-long- and extremely-long-period binaries inferred from episodic/periodic

Table 1. WR subtype distribution of binaries and probable binaries

subtype	WN binaries N	(%)	subtype	WC binaries N	(%)
WN2					
WN3	3	(60)	WC3		
WN4	6	(33)	WC4	2	(40)
WN5	7	(28)	WC5	5	(50)
WN6	13	(50)	WC6	6	(46)
WN7	9	(56)	WC7	11	(61)
WN8	7	(44)	WC8	6	(55)
WN9	2	(25)	WC9	6	(20)
subtotal	47	(37)	subtotal	37	(43)

Table 2. WR period characterization and distribution

period (d)		characterization	N_{WN}	N_{WC}
$P < 1\,d$	:	very-short-period binary	3	1
$1\,d < P < 10\,d$	:	short-period binary	14	9
$10\,d < P < 100\,d$	:	medium-period binary	8	5
$100\,d < P < 1000\,d$	:	long-period binary	3	3
$1000\,d < P < 10000\,d$	:	very-long-period binary	2	7
$10000\,d < P$	:	extremely-long-period binary	1	1

non-thermal radio excesses like WR 140 (Williams *et al.* 1990, 1994), WR 146 and WR 147 (Setia Gunawan *et al.* 2000a,b);
(f) extremely-long-period binaries deduced from high-spatial-resolution non-thermal radio and IR/optical imaging, like WR 146 and WR 147 (Dougherty *et al.* 1996; Williams *et al.* 1997; Niemela *et al.* 1998);
(g) binaries tentatively inferred from composite spectra like, *e.g.*, WR 19, WR 27, WR 50, WR 69, WR 77, WR 104, WR 125, WR 137, and WR 146 (see, *e.g.*, Williams & van der Hucht 1996, 2000); and
(h) binaries tentatively inferred from diluted emission lines, as compared to single stars of the same subtype (van der Hucht 2000).
Ideally, one would like to have sufficient observations to diagnose each binary as a SB2. But a binary observed pole-on will never allow a RV-solution, although it may still be discernable in catagories *(c)–(h)*.

3. Wolf-Rayet Masses

19 WR double-line spectroscopic binaries (SB2) have RV solutions and masses. The 13 WN components have $\overline{M_{\rm WN}} = 22 \pm 17\,{\rm M}_\odot$ in the range 2.3–55 $M_\odot$. Three WN5–7 stars (WR 22, WR 47 and WR 141) have $M_{\rm WN} > 40\,{\rm M}_\odot$. The 6 WC components have $\overline{M_{\rm WC}} = 12 \pm 3\,{\rm M}_\odot$ in the range 9–16 $M_\odot$. In agreement with

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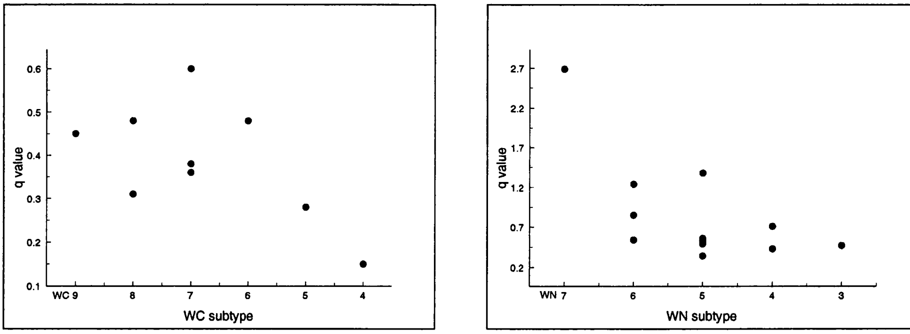

Figure 1. $q_{WR} = M_{WR}/M_{OB}$ per WR subtype

current evolutionary scenarios which state that WN stars evolve into WC stars, $\overline{M_{WC}} < \overline{M_{WN}}$. For these WR binaries the mass ratios $q = M_{WR}/M_{OB}$ range as $q_{WN} = 0.2$–3 (four WN stars have $q > 1$), $q_{WC} = 0.3$–0.6, and $q_{WO} = 0.15$. Figure 1 displays these q-values for WN and WC binaries, respectively. It appears that both q_{WN} and q_{WC} display a decreasing trend going from WRL to WRE subtypes, as demonstrated earlier by Moffat *et al.* (1990) and Moffat (1995). The latter argued that the quantity q represents a measure of the evolution from WRL to WRE phases due to mass loss.

4. More Wolf-Rayet Binaries?

There are at least two reasons to suspect that more WR binaries must be hiding among the $(227 - 84 =)$ 143 presumably single WR stars in the *VIIth Catalogue*:

One reason, given by Langer & Heger (1999), argues that most SNe Ib/c occur in post-mass-transfer close binaries. However, the observed galactic binary frequency is as yet $< 50\,\%$. Thus, although supernova statistics show that there should be many more WR+OB binaries than single WR stars, many of those binaries have apparently not been detected yet.

Another reason stems from direct observational evidence for WCL subtypes. As indicated in the *VIIth WR Catalogue*, sixteen WC9 stars, four WC8 stars, three WC7 stars and one WC4 star display persistent or episodic/periodic thermal IR excesses indicative of heated circumstellar amorphous carbon dust formation (Williams 1999). Of the episodic/periodic cases it has been established that their heated dust is being formed in the wake of the colliding wind cones of WC+OB binaries. Of this phenomenon WR 140 is the prototype (Williams *et al.* 1990). With IR image-masking interferometry Tuthill *et al.* (1999) and Monnier *et al.* (1999) resolved the circumstellar dust shells of two WC stars. They derived from the observed rotation of their pinwheel images the orbital periods (243 d and 565 d) of the low-inclination WR+OB binaries revolving within those dust shells. Such discoveries make it very likely that also all other apparently single WC9d and WC8d stars owe their heated circumstellar dust signatures to colliding WC+OB wind effects, as suggested earlier by Williams *et al.* (1995). Thus the majority ($> 80\,\%$) of the known WC9 stars and WC8 stars could ac-

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tually be WC+OB binaries. A subsequent suggestion could be that such a high binary frequency might also apply to all other WR subtypes. This inturn could imply that the Population I massive star Wolf-Rayet phenomenon is associated to binarity, after all, through mass exchange during the progenitor O+O-binary phase, and that WR stars hold the clues to massive binary formation.

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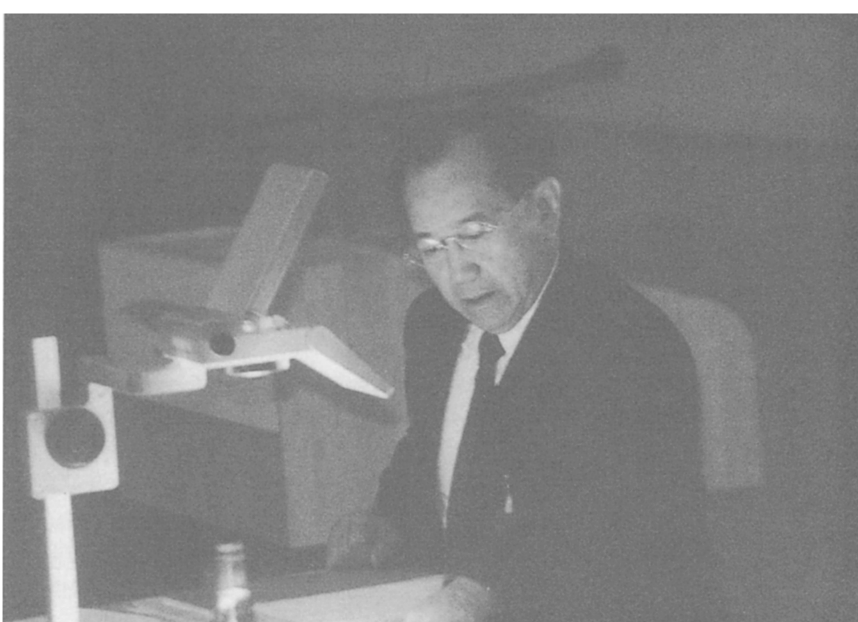

Bambang Hidayat, without his companion

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