WOLF–RAYET BINARIES: EVOLUTIONARY CAUSES FOR THEIR DISTRIBUTION IN THE GALAXY* **

BAMBANG HIDAYAT and A. GUNAWAN ADMIRANTO
Observatorium Bosscha of the Institut Teknologi Bandung, Lembang, Indonesia

and

KAREL A. VAN DER HUCHT
Space Research Laboratory of The Astronomical Institute, Utrecht, The Netherlands

(Received 22 August, 1983)

Abstract. On the basis of the most recent data, the fraction of known Wolf–Rayet binaries is 0.22. In the solar neighbourhood ($d < 2.5$ kpc) this fraction is 0.34

In order to assess the relative importance of massive binary evolution as one of the ways to produce WR stars, the galactic distribution of WR binaries is compared with that of single WR stars using improved intrinsic parameters and new data for the fainter WR stars.

In the galactic plane the increase of the binary frequency with galactocentric distance is confirmed.

In a direction perpendicular to the galactic plane it is demonstrated at all distances from the Sun that the single-line spectroscopic WR binaries with small mass functions have definitely larger $|z|$-distances than the 'single' WR stars and the WR binaries with massive companions. This is consistent with the evolutionary scenario for massive binaries summarized by van den Heuvel (1976). Among the 'single' WR stars the fraction of those with large $|z|$-distances is increasing with galactocentric distance, like the fraction of the known binaries. This implies that among the high-$|z|$ 'single' WR stars as well as among the WR stars with lower $|z|$-values many binaries are still to be discovered.

The total WR binary frequency in the Galaxy could be well above 50 %.

1. Introduction

Population I WR stars are evolved massive stars, primarily in their core He-burning phase, their progenitors being O-type stars (e.g., Conti, 1982). Due to removal of their outer hydrogen layers by mass loss and mass transfer, these stars reveal in their emission spectra overabundances of nucleosynthesis products like He + N (WN stars), He + C (WC stars) or He + C + O (WO stars), as elaborated on by Smith and Willis (1982) and Barlow and Hummer (1982).

Before the importance of mass loss was realized, it was thought that only mass transfer in a binary system could remove sufficient material from a massive star to reveal core H-burning and core He-burning products at its surface. And thus it was thought that all WR stars were produced in binary systems. In recent years

* Contribution from the Bosscha Observatory No. 79.
** Invited paper presented at the Lembang-Bamberg IAU Colloquium No. 80 on 'Double Stars: Physical Properties and Generic Relations', held at Bandung, Indonesia, 3–7 June, 1983.

Astrophysics and Space Science **99** (1984) 175–190. 0004–640X/84/0991–0175$02.40.

it has been shown (e.g., Maeder, 1982) that mass loss and internal mixing can cause a single O-type star with $\mathcal{M} \geqslant 23\,\mathcal{M}_\odot$ (Maeder and Lequeux, 1982) to evolve into a WR star, and that generally an O $\rightarrow$ (RSG $\rightarrow$)WN $\rightarrow$ WC scheme can be expected. During the O-phase the mass loss rate is of the order of $\dot{\mathcal{M}} = 5 \times 10^{-6}\,\mathcal{M}_\odot$; during the WR phase $\dot{\mathcal{M}} = 2.8 \times 10^{-5}\,\mathcal{M}_\odot$ (Abbott, 1982). In the latter phase this mass is lost in a dense, optically thick stellar wind with typically $T_{\text{eff}} = 2\text{–}6 \times 10^4$ K and $n = 10^{12}\text{–}10^{14}\,\text{cm}^{-3}$ (e.g., van der Hucht, 1982). Due to this mass loss a massive star is stripped of its outer layers. This process can be accompanied by internal mixing of various kinds (Maeder, 1982), which makes it even easier to bring N, C, and O to the surface and thus to cause the WR phenomenon.

WR star masses in binary systems have been determined between 5 and 50 $\mathcal{M}_\odot$ (Massey, 1981b).

The WR lifetime is of the order of $3\text{–}6 \times 10^5$ yr (Maeder and Lequeux, 1982).

In the past few years, there has been an increasing interest in the study of the galactic distribution of Wolf–Rayet stars, in response to the recognition that WR stars are descendants of massive early-type stars, and that their distribution may give clues to their origin and evolution.

Recent studies by Moffat and Isserstedt (1980), Hidayat *et al.* (1982), Garmany *et al.* (1982), and Conti *et al.* (1983) each used improved parameters over previous work.

Thanks to the work of Lundström and Stenholm (1983), Hidayat *et al.* (1984) could use improved intrinsic parameters and new colours and spectral types for many of the fainter stars, in order to reinvestigate the galactic distribution of Population I Wolf–Rayet stars. In the present paper emphasis is put on the binaries versus the single stars.

2. Known WR Binaries

In our Galaxy, 159 Population I Wolf–Rayet stars are known (van der Hucht *et al.*, 1981; Hidayat *et al.*, 1984). Table I gives the distribution between single WR stars, single WR stars with intrinsic absorption lines, double-line spectroscopic binaries, and single-line spectroscopic binaries. Stars are called single if no orbit solution is known. Duplicity is published of 35 WR stars, i.e., 22%.

Double-line spectroscopic WR binaries (SB2) have been discussed extensively by Massey (1982), single-line spectroscopic WR binaries (SB1) have been discussed extensively by Moffat (1982). Since then a few more cases have been discovered. Table II lists the WR SB2's arranged by spectral type, Table III lists the WR SB1 systems also arranged by spectral type, and subdivided between SB1's with small mass functions ($f(\mathcal{M}) < 0.3\,\mathcal{M}_\odot$), henceforth labeled as lmSB1, and SB1's with large mass functions ($f(\mathcal{M}) > 0.3\,\mathcal{M}_\odot$), henceforth labeled as mSB1.

In these tables the absolute visual magnitude M_v, the heliocentric distance d, the galactocentric distance r, and the separation from the galactic plane z are from Hidayat *et al.* (1984) and based on the intrinsic parameters given in Table IV

TABLE I

Distribution of galactic Wolf–Rayet stars in subclasses

WR	Single		Double		Total
Subclass	Single	Single + abs.	SB2	SB1	
WN2	1				1
WN3	3	1	1		5
WN4	8		3	1	12
WN4.5	5		1		6
WN5	4		2	1	7
WN6	13		2	6	21
WN7	9	3		4	16
WN8	7			4	11
WN9	1				1
WN10	1				1
unclassified WN	1				1
Subtotal WN	53	4	9	16	82
WC4	3				3
WC5	12		1		13
WC6	11	3	2		16
WC7	4	2	3		9
WC8	5	1	2		8
WC8.5	5				5
WC9	13			1	14
WC10	1				1
Subtotal WC	54	6	8	1	69
WO1	1				1
WO2	1				1
WN + WC	2			1	3
unclassified WR	2	1			3
Grand total	113	11	17	18	159

(see next section). For the SB2 systems the M_v values of the individual binary components have been determined from data in the literature (see notes to Table II).

It should be noted that some of the more recent duplicity determinations would be served by confirmative studies. At least one case, i.e., WR 140 in Table II, is subject to controversy: Conti (1983, private communication) did not find an orbit solution from his data.

Among the 18 SB1 systems in Table III are 13 lmSB1's, in which the unseen component may be a compact star. The listed masses are calculated by assuming that $i = 60°$ and $\mathcal{M}$ (unseen companion) = $1.6\,\mathcal{M}_{\odot}$, following Moffat (1982).

Both the SB2 and SB1 systems can be identified with links in the evolutionary

TABLE II

Double-line spectroscopic Wolf–Rayet binaries (SB2) (17)

WR	HD/Name	Spectral type	Period (days)	$\mathcal{M}_{WR} \sin^3 i$ ($\mathcal{M}_\odot$)	$\mathcal{M}_{WR}/\mathcal{M}_O$	i	$\mathcal{M}_{WR}$ ($\mathcal{M}_\odot$)	Refs.	$(b-v)_0$ (system)	M_v (WR)	M_v (O)	M_v (system)	d (kpc)	r (kpc)	z (pc)
97	E320 102	WN3+O5–7	8.83	1.8	0.33	30°	11	1	−0.33	−3.6	−5.1	−5.3	2.95	7.07	−58
21	90 657	WN4+O4−6	8.2	8–11	0.52	50°	18	2	−0.33	−4.0	−5.2	−5.5	3.51	9.70	−55
31	94 546	WN4+O7	4.9	8	0.34	–	⩾8	3	−0.33	−4.0	−4.9	−5.3	4.96	9.65	+2
127	186 943·	WN4+O9.5V	9.5548	9–11	0.52	70°	13	4	−0.21	−3.6	−4.0	−4.6	4.41	8.99	+133
133	190 918	WN4.5+O9.5 Ia	112.8	0.7	0.26	25°	9	5	−0.33	−4.3	−6.0	−6.2	2.09	9.59	+75
139	193 576	WN5+O6	4.21238 (e)	9.3	0.40	55°	17	6, 7	−0.30	−4.8	−5.1	−5.7	1.74	9.74	+43
151	CX Cep	WN5+O8V	2.1267 (e)	5	0.43	⩾ 50°	5–11	8	−0.33	−4.6	−4.6	−5.4	5.08	12.17	+123
47	E311 884	WN6+O5V	6.34	40	0.84	70°	50	9	−0.30	−5.3	−5.1	−6.0	3.80	8.61	−15
153	211 853	WN6+O	6.6884 (e)	–	⩾ 0.22	⩾ 50°	10–25	4	−0.33	−5.3	−4.8	−6.2	3.56	11.33	−40
9	63 099	WC5+O7	27.63	17	0.16	–	–	1	−0.33	−4.0	−4.5	−5.0	2.08	10.91	−174
30	94 305	WC6+O6–8	18.82	15	0.48	–	–	10	−0.33	−4.4	−5.0	−5.5	8.99	11.00	−410
48	113 904	WC6+O9.5I	18.34	–	–	–	–	11	−0.33	−4.4	−6.0	−6.2	1.59	9.19	−69
42	97 152	WC7+O7V	7.886	3.6	0.59	35°	20	12	−0.33	−4.7	−4.9	−5.6	3.47	9.34	−30
79	152 270	WC7+O5–8	8.893	1.8	0.36	25°	20	13	−0.35	−4.7	−5.6	−6.0	2.00	8.10	+40
140	193 793	WC7+O4–5	1085	11	0.22	74°	13	14	−0.33	−4.7	−5.5	−5.9	1.43	9.88	+104
11	68 273	WC8+O9I	78.5002	17	0.54	70°	20	15	−0.32	−4.9	−6.4	−6.6	0.48	10.07	−64
113	168 206	WC8+O8–9III–V	29.707	11	0.48	70°	13	16	−0.39	−4.8	−4.8	−5.5	2.00	8.13	+61

Note: (e) = eclipsing system.

References:

(1) Niemela (1982).
(2) Niemela and Moffat (1982).
(3) Niemela (1980).
(4) Massey (1981a).
(5) Fraquelli and Horn (1983).
(6) Ganesh *et al.* (1967).
(7) Münch (1950).
(8) Massey and Conti (1981).
(9) Niemela *et al.* (1980).
(10) Niemela *et al.* (1983).
(11) Moffat and Seggewiss (1977).
(12) Davis *et al.* (1981).
(13) Seggewiss (1974).
(14) Lamontagne *et al.* (1983b).
(15) Niemela and Sahade (1980).
(16) Massey and Niemela (1981).

Notes to the SB2 systems in Table II:

WR9: M_v(system) and M_v(WR) = −4.0 from Turner (1982, private communication). This results in M_v(O) = −4.5, corresponding to an O9V star on the scale of Conti *et al.* (1983). Assuming $(b-v)_0 = -0.33$ for the system yields the distance $d = 2.08$ kpc, much closer than the 'HD63077 group' of McCarthy and Miller (1974).

WR11: M_v(system) and M_v(WR) = −4.9 from Turner (1982, private communitation). Distance from Abt *et al.* (1976). Consequently the system has $(b-v)_0 = -0.32$.

WR21: M_v(WR) from Table IV, M_v(O) = −5.2 from scale of Conti *et al.* (1982). Assumption $(b-v)_0 = -0.33$ yields the distance.

WR30: M_v(WR) from Table IV, M_v(O) = −5.0 from scale of Conti *et al.* (1983). Assumption $(b-v)_0 = -0.33$ yields the distance.

WR31: M_v(WR) from Table IV, M_v(O) = −4.9 from scale of Conti *et al.* (1983). Assumption $(b-v)_0 = -0.33$ yields the distance.

WR42: Spectral types and $\Delta M_v = 0.2$ from Davis *et al.* (1981). M_v(O) = −4.9 from Conti *et al.* (1983) results into M_v(WR) = −4.7, in agreement with Table IV.

WR47: Cluster distance $d = 3.80$, colour excess, and M_v(system) from Lundström and Stenholm (1983). According to Niemela *et al.* (1980) the O star is 3 times fainter than WR star, corresponding to M_v(O) = −4.5 and M_v(WR) = −5.6. If we take M_v(WR) = −5.2 from Table IV, then M_v(O) = −5.1, corresponding to O6V, in reasonable agreement with the O-spectral type determined by Niemela *et al.* (1980).

WR48: M_v(WR) from Table IV, M_v(O) from Conti *et al.* (1983). Assumption $(b-v) = -0.33$ yields the distance, somewhat smaller than d(Cen OB1) = 1.9 kpc (Humphreys, 1978).

WR79: Cluster distance, colour excess and M_v(system) from Lundström and Stenholm (1983). M_v(WR) from Table IV implies M_v(O) = −5.6, which corresponds with an O5V or an O7III companion according to the scale of Conti *et al.* (1983).

WR97: Spectral types from Niemela (1982), M_v(WR) from Table IV, M_v(O6V) = −5.1 from the scale of Conti *et al.* (1983). Assumption $(b-v)_0 = -0.33$ we find the distance.

WR113: Distance from Ser OB2 (Humphreys, 1978). $\Delta M_v = 0$ from Massey and Niemela (1981). With M_v(WR) from Table IV, this implies an O8.5V companion on the scale of Conti *et al.* (1983). This yields $(b-v)_0 = -0.39$.

WR127: Distance Vul OB2 and M_v(system) from Turner (1980). Taking M_v(O) = −4.0 from the scale of Conti *et al.* (1983) we find M_v(WR) = −3.6 and a ΔM_v not far from $\Delta M_v = 1.3$ found by Massey (1981a). This yields $(b-v)_0 = -0.21$.

WR133: Distance, reddening and M_v(system) from Lundström and Stenholm (1983). With M_v(O) = −6.0 from the scale of Conti *et al.* (1983) this implies M_v(WR) = −4.3, in agreement with Table IV.

WR139: Distance, reddening and M_v(system) from Lundström and Stenholm (1983). With M_v(WR) from Table IV, we find M_v(O) = −5.1, consistent with an O6V companion on the scale of Conti *et al.* (1983). Distance in reasonable agreement with d (Cyg OB1) = 1.82 (Humphreys, 1978).

WR140: Spectral type from Lamontagne *et al.* (1983b), M_v(WR) from Table IV, M_v(O4–5V) = −5.5 on the scale of Conti *et al.* (1983). This, with the assumption $(b-v)_0 = -0.33$, yields the distance.

WR151: Spectral types and $\Delta M_v = 0$ from Massey and Conti (1981). M_v(O) from Conti *et al.* (1983) implies M_v(WR) = −4.6. Assumption $(b-v)_0 = -0.33$ yields a distance far beyond d(Cep OB2) = 0.83 kpc (Humphreys, 1978).

WR153: Quadrupole system, for which Massey (1981) gives M_v(pair B) = −4.9, $M_v(O_A)$ = −4.8 (i.e., O7.5–8V on the scale of Conti *et al.* (1983)). M_v(WR) from Table IV. This, with the assumption $(b-v)_0 = -0.33$ we obtain a distance, somewhat smaller than d(S132) = 4.95 (Crampton, 1971), but beyond Cep OB2 (Humphreys, 1978).

TABLE III

Single-line spectroscopic Wolf–Rayet binaries (SB1) with small and large mass functions (18)

WR	HD/Name	Spectral type	Period (days)	$f(\mathcal{M})$ ($\mathcal{M}_\odot$)	$\mathcal{M}_{WR}$ ($\mathcal{M}_\odot$)	Refs.	Ring nebula	d (kpc)	r (kpc)	z (pc)
128	187 282	WN4	3.85	0.003	28	1	S84	4.90	8.29	−324
6	50 896	WN5	3.763	0.015	12	2	S308	0.91	10.55	−160
43	97 950	WN6 + abs	3.7720	0.15	2.6	3		7.0	9.87	−63
71	143 414	WN6	7.690	0.0074	17	4		7.08	6.08	−937
134	191 765	WN6	7.44	0.0055	20	5	S109	2.05	9.62	+55
136	192 163	WN6	4.5	0.00024	104	6	NGC6888	1.57	9.73	+67
138	193 077	WN6 + abs	2.3238	0.0009	53	7		1.92	9.69	+37
148	197 406	WN7	4.3174	0.255	1.6	8, 9		6.52	11.95	+735
16	86 161	WN8	10.73	0.00024	104	10		2.48	9.83	−110
40	96 548	WN8	4.1584	0.00052	70	11	RCW58	2.48	9.34	−209
123	177 230	WN8	1.7616	0.0019	36	12		6.06	5.68	−502
124	209BAC	WN8	2.3583	0.0005	71	13	S80	3.33	8.27	+192
103	164 270	WC9	1.7556	0.00146	41	14		2.84	7.16	−242
141	193 928	WN6	21.64	4.9	–	15		1.86	9.70	+3
12	CD–45°4482	WN7	23.9	5.5	–	16		5.75	11.95	−198:
22	92 740	WN7 + abs	80.35	1.67	–	17, 18	NGC3372	2.10	9.59	−31
155	214 419	WN7	1.64 (e)	5.08	–	19		3.77	11.58	−85
145	AS422	WN + WC	22	7.7:	–	20		–	–	–

Notes: (e) = eclipsing system. $\mathcal{M}_{WR}$ calculated by assuming $i = 60°$ and a mass of the unseen companion of $1.6\,\mathcal{M}_\odot$.

References:

(1) Antokhin *et al.* (1982b).
(2) Firmani *et al.* (1980).
(3) Moffat (1982).
(4) Isserstedt *et al.* (1983).
(5) Antokhin *et al.* (1982a).
(6) Koenigsberger *et al.* (1980).
(7) Lamontagne *et al.* (1982).
(8) Bracher (1979).
(9) Moffat and Seggewiss (1980a).
(10) Moffat and Niemela (1982).
(11) Moffat and Isserstedt (1980).
(12) Lamontagne *et al.* (1983a).
(13) Moffat *et al.* (1982).
(14) Isserstedt and Moffat (1981).
(15) Moffat and Seggewiss (1980b).
(16) Niemela (1982).
(17) Moffat and Seggewiss (1978).
(18) Conti *et al.* (1979).
(19) Leung *et al.* (1983).
(20) Pesch *et al.* (1960).

https://doi.org/10.1017/S0252921100088540 Published online by Cambridge University Press

scenario for massive binary systems summarized by van den Heuvel (1976):

$$O_1+O_2 \underset{w+o}{\rightarrow} O_1+WR_2 \underset{s.n.}{\rightarrow} O_1+c_2 \underset{w+o}{\rightarrow} WR_1+c_2 \underset{s.n.}{\rightarrow} c_1+c_2$$

(WR SB2) (WR lmSB1)

(w+o: mass loss and Roche lobe overflow; s.n.: supernova explosion).

The second phase is visible as a WR SB2 system, the fourth phase is visible as a WR lmSB1 system, the last phase is visible as a double pulsar.

Maeder (1982) has pointed out that, next to the binary channel, there are various channels to produce WR stars from single massive stars, depending on mass loss and internal mixing, and that these other channels depend on galactic location, notably on metallicity. It is of great interest to know the relative importance of each of the channels producing WR stars. Therefore it is of importance to determine the exact percentage of WR binaries. As noted above, the percentage of observed binaries is 22%. It should be realized that many of the fainter WR stars listed as single have not yet been investigated for duplicity. In the next chapters we shall look for evidence for more WR binaries by investigating the relative distribution of the known WR binaries in the Galaxy as well as that of the 'single' WR stars.

3. WR Distribution in the Galactic Plane

Recently, Lundström and Stenholm (1983) have reexamined many of the faint WR stars and found new colours and spectral types. In addition Massey and Conti (1983) published some new spectral types. Lundström and Stenholm also re-evaluated the cases of WR stars in open clusters and associations and determined improved intrinsic parameters for these WR stars. We list them in Table IV, with some interpolations and extrapolations. Hidayat *et al.* (1984) used these values to calculate photometric distances for the 142 of the 159 galactic WR stars for which sufficient data are available.

The distribution of these WR stars projected on the galactic plane is given in Figure 1, where the filled symbols represent the known binaries. The galactic center is indicated at 8.7 kpc from the Sun (Oort and Plaut, 1975), but the heliocentric distances r, given in this paper, are calculated as if the galactic center is at 10 kpc from the Sun. This is because we would like to compare our statistics with other published star counts, e.g. by Maeder (1982), where usually the galactic center is put at 10 kpc.

We confirm that the distribution of the WR stars looks similar to that of the more massive ($\mathcal{M} > 40\,\mathcal{M}_\odot$) O-type stars, as found by Conti *et al.* (1983).

Of the 47 WR stars (21 WN and 26 WC) with $d \leqslant 2.5$ kpc, 16 are known binaries (8 SB2, 2 mSB1 and 6 lmSB1), i.e., 34%, quite similar to the 36% known binaries of the 424 O-type stars in the same volume (Conti *et al.*, 1983). This corresponds to a density projected on the galactic plane of $N(O) = 21.6$ kpc^{-2} and $N(WR) = 2.39$ kpc^{-2} within $d \leqslant 2.5$ kpc, where we can expect that the observations

TABLE IV

Adopted intrinsic parameters for the WR subclasses *

	$(b-v)_0$	M_v
WN2	−0.30	−2.0
WN3	−0.30	−3.6
WN4	−0.25	−4.0
WN4.5	−0.25	−4.3
WN5	−0.20	−4.8
WN6	−0.25	−5.3
WN7	−0.27	−6.4
WN8	−0.30	−5.8
WN9	−0.33	−6.0
WN10	−0.33	−6.0
WC4	−0.25	−2.7
WC5	−0.25	−3.9
WC6	−0.30	−4.4
WC7	−0.35	−4.7
WC8	−0.42	−4.8
WC8.5	−0.42	−5.0
WC9	−0.42	−5.1
WC10	−0.42	−5.0
WO1	−0.33	−2.6
WO2	−0.33	−2.6

* *Note*: These values are based on the recent work of Lundström and Stenholm (1983) complemented with assumed values by Conti *et al.* (1983).

are complete. For the binaries the densities are $N(O_{SB}) = 7.8\,\mathrm{kpc}^{-2}$ and $N(WR_{SB}) = 0.82\,\mathrm{kpc}^{-2}$.

Although it seems attractive to compare statistics in a restricted volume around the Sun, there is a danger here. In Figure 1 it appears immediately that in the inner region of the Galaxy the density of the WR stars is larger than in the outer region. This effect is already visible within $d \leqslant 2.5$ kpc: of the 47 WR stars only 6 are outside the solar circle. This galactic star density gradient forces us to do star counts and statistics as a function of galactocentric distance, and we will do this in the observable $\pm 90°$ sector of the Galaxy (see Figure 1).

From Figure 1 it also appears that the relative density of WR binaries is smaller in the inner region, as noted earlier by Maeder (1982). We show this quantitatively in Table V, where we list the relative distribution of WR subtypes as a function of galactic distance. Following Maeder we also list the metallicity Z and LMC and SMC values, and confirm, with our improved data and values, a strong upward gradient of the WN/WC and WR_{SB}/WR_{total} number ratios with galactocentric distance, and the correlation with a downward metallicity gradient. It could very well be that of the various ways of reaching the WR phase, the channels depending on mass

https://doi.org/10.1017/S0252921100088540 Published online by Cambridge University Press

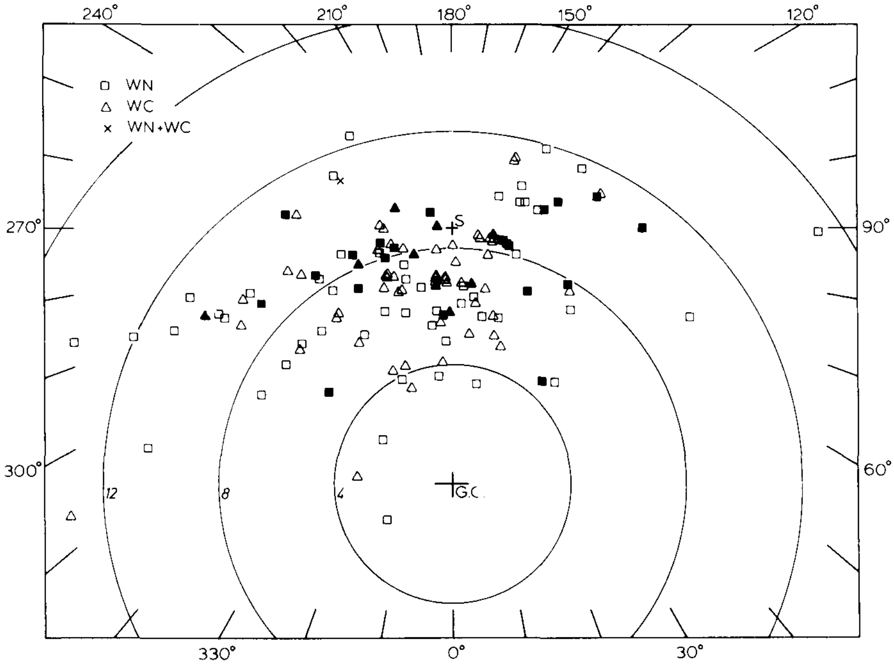

Fig. 1. The (d, l^{II})-distribution of the 141 WR stars for which sufficient photometric and spectroscopic data are available, projected on the galactic plane. The filled-in symbols are spectroscopic binaries.

loss and mixing depend on galactocentric distance (metallicity), while the binary channel is less or not dependent on location. So, if indeed the mass loss/mixing channels operate better in a relative high metallicity environment, this would explain that the relative number of WR binaries between 7 and 9 kpc is smaller (by a factor of 2 in our data) than that between 11 and 13 kpc from the galactic center.

An alternative explanation for more binaries (of all types) in the outer region of the Galaxy is offered by Zinnecker (1982), who argues for a decreasing value

TABLE V

WR heliocentric statistics

r (kpc)	Z	Numbers						Densities (kpc^{-2})	
		WR_{total}	WN	WC	$\frac{WN}{WC}$	WR_{SB}	$\frac{WR_{SB}}{WR_{total}}$	WR	WR_{SB}
7–9	0.03	49	25	23	1.09	8	0.16	1.95	0.32
9–11	0.02	47	14	23	1.04	18	0.38	1.50	0.57
11–13	0.01	20	15	4	3.75	6	0.30	0.53	0.16
LMC	0.01	100	82	18	4.6	50	0.50	0.15	0.07
SMC	0.002	8	7	1	7	8	1.00	0.05	0.05

of the local mean magnetic field strength with increasing galactocentric distance, in the context of binary formation in general.

In the next section we shall use the observed gradient in the relative number of *known* binaries, to indicate that among *single* WR stars many binaries may be awaiting discovery.

4. WR Distribution Perpendicular to the Galactic Plane

Hidayat *et al.* (1982) discussed the z-distribution of galactic WR stars, in order to check the suggestion by Moffat and Isserstedt (1980) that the large z-values of some WR stars are due to large kick-velocities caused by the first supernova explosion in the evolutionary scenario for massive binaries (given in Section 2), and thus that these stars are binaries (lmSB1). With the now available improved data in Hidayat *et al.* (1984), it is worthwhile to consider the z-distribution in more detail.

Figure 2a shows the (l^{II}, z)-distribution of the 142 galactic WR stars for which sufficient data are available. The fact that this distribution shows less scatter and is more confined to the galactic plane than the one shown in Figure 3 of Hidayat *et al.* (1982) demonstrates that the now used parameters and data are an improvement with respect to earlier values.

We expect Population I objects to be concentrated to the galactic plane within, let us say, $|z| \leqslant 200$ pc. However 28 WR stars (i.e., 20%) have values of $|z| > 200$ pc. In Figure 2b, where we show only the WR binaries, it appears that most of the SB2 system are well confined to the galactic plane, while among the SB1 systems many have large $|z|$-distances. Table VI gives a breakdown of the $|z|$-distribution vs. distance from the Sun. It appears that among the stars with $|z| > 200$ pc 21%

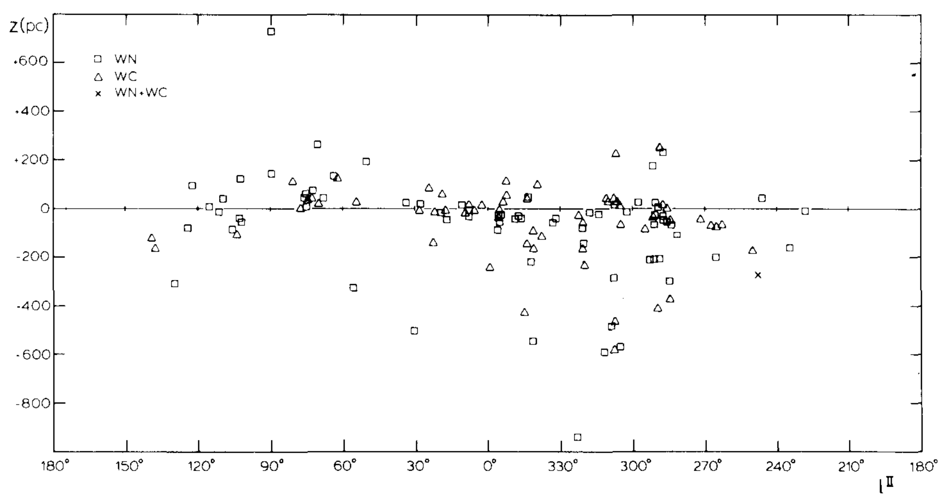

Fig. 2a. The (z, l^{II})-distribution of WR stars.

https://doi.org/10.1017/S0252921100088540 Published online by Cambridge University Press

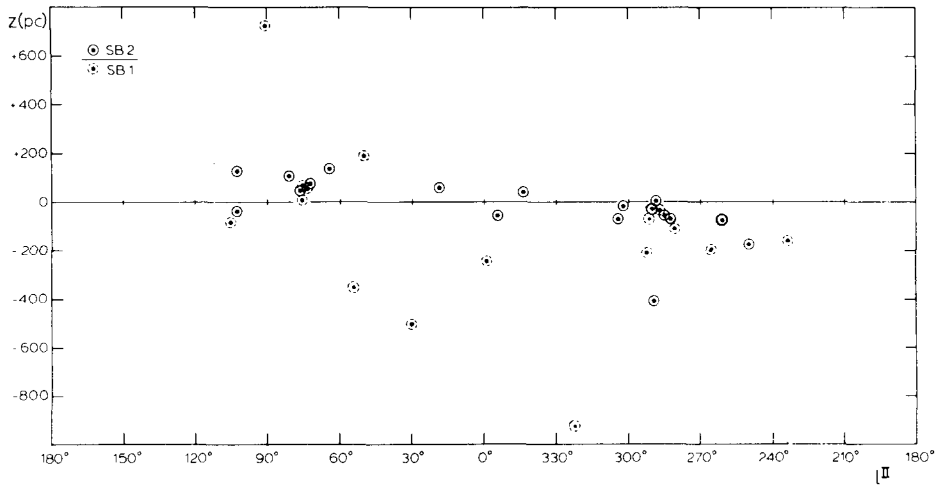

Fig. 2b. The (z, l^{II})-distribution of known WR binaries.

are lmSB1, while among the stars with $|z| < 200$ pc only 6% are lmSB1. This enforces the probability that the WR stars with large $|z|$-values were ejected out of the plane with supernova-induced kick-velocities.

When we consider the average $\overline{|z|}$-values for single WR stars, for mSB1 and SB2 WR systems and for lmSB1 WR systems, as given in Table VI, we note:

$\overline{|z|}$ (SB2+mSB1) = 86 pc, quite reasonable for Population I stars;

$\overline{|z|}$ ('single') = 109 pc, about 25% larger than the value for the binaries with massive components; and

$\overline{|z|}$ (lmSB1) = 279 pc, a very large value and explainable by large supernova-induced kick-velocities.

The fact that a difference exists between the $\overline{|z|}$-value for 'single' WR stars and that for WR binaries with massive companions can be explained by assuming that among the 'single' WR stars are many as yet undiscovered binaries (lmBS1's). We shall find evidence for this below. First we shall discuss observational selection effects.

In the breakdown in Table VI in distances from the Sun, we note that only beyond $d > 4$ kpc from the Sun large values of $\overline{|z|}$ (single WR) are reached. This is caused by two observational effects. Firstly, nearby stars have been better investigated for duplicity, so most lmSB1 systems are already known there. Secondly, as correctly pointed out by Garmany *et al.* (1982), at large distances from the Sun, stars in the galactic plane are obscured by interstellar matter, so we will find in general larger $|z|$-values there, as demonstrated in Figure 3. The first observational selection effect reduces $\overline{|z|}$ (single WR) at small distances from the Sun; the second observational selection effect increases $\overline{|z|}$ (single WR) at large distances from the Sun. If we take the average $|z|$ (single WR) over all distances, then these effects may balance out to a certain degree.

https://doi.org/10.1017/S0252921100088540 Published online by Cambridge University Press

TABLE VI

z-distribution WR stars vs distance from the Sun

d (kpc)	Area (kpc^2)	Numbers ($\lvert z\rvert < 200$ pc)		Numbers ($\lvert z\rvert > 200$ pc)		$\overline{\lvert z\rvert}$ (pc) ($\lvert z\rvert < 200$ pc)		$\overline{\lvert z\rvert}$ (pc) ('single')		(SB2+mSB1)		(lmSB1)		(all)	
			(lmSB1)		(lmSB1)		(N)		(N)		(N)		(N)		(N)
0–1.8	10	21	(2)	0	(0)	46	(21)	31	(15)	70	(4)	113	(2)	46	(21)
1.8–2.5	10	25	(3)	1	(1)	48	(25)	39	(16)	64	(6)	103	(4)	55	(26)
2.5–3.1	10	14	(0)	3	(1)	36	(14)	60	(15)	58	(1)	242	(1)	71	(17)
3.1–3.6	10	14	(1)	0	(0)	72	(14)	69	(10)	42	(3)	192	(1)	72	(14)
3.6–4.0	10	7	(0)	0	(0)	50	(7)	50	(5)	50	(2)	–	(0)	50	(7)
4.0–4.4	10	1	(0)	2	(0)	145	(1)	242	(3)	–	(0)	–	(0)	242	(3)
4.4–5	18	13	(0)	1	(1)	64	(13)	63	(11)	68	(2)	324	(1)	82	(14)
5–10	236	16	(1)	16	(3)	83	(16)	217	(25)	244	(3)	559	(4)	262	(32)
10–17	594	2	(0)	5	(0)	90	(2)	266	(7)	–	(0)	–	(0)	266	(7)
0–17	908	113	(7)	28	(6)	58	(113)	109	(107)	86	(21)	279	(13)	121	(141)

Note: mSB1: SB1 with massive unseen companion; lmSB1: SB1 with low mass unseen companion.

In the region $d \leqslant 4$ kpc we have:
$\overline{|z|}$ (single WR) = 48 pc, so these may be the real singles;
$\overline{|z|}$ (SB2+mSB1) = 59 pc; and
$\overline{|z|}$ (lmSB1) = 134 pc.

The latter value is in reasonable agreement with $\overline{|z|}$ (OB runaway stars) = 150 pc (Moffat and Isserstedt, 1980).

Thus, already within $d \leqslant 4$ kpc there is a definite case of difference in $\overline{|z|}$-distances between single WR stars and lmSB1 WR systems, and this effect is persistent even when the data are subdivided by distance within 4 kpc from the Sun as shown in Table VI, contrary to statements by Garmany *et al.* (1982).

Since, as mentioned above, the percentage of known lmSB1's at $|z| > 200$ pc is large (21 %) and since the existence of these large $|z|$-values can be best explained by assuming that these stars arrived there after suffering large supernova-induced kick-velocities, it is encouraged to investigate all WR stars with large $|z|$-values for duplicity. In addition, proper motion studies with the HIPPARCOS satellite and radial velocity studies of these stars could give conclusive clues about the supernova dynamics. The stars with $|z| > 200$ pc are listed in Table VII.

Additional evidence can be given for the large probability that among the WR stars with large $|z|$-values more binaries with low-mass companions may be present.

In Section 3, Table V, we have confirmed the finding of Maeder (1982) that known WR binaries are relatively more frequent in the outer than in the inner galactic regions. When we now consider in Table VIII only the 'single' WR stars in their

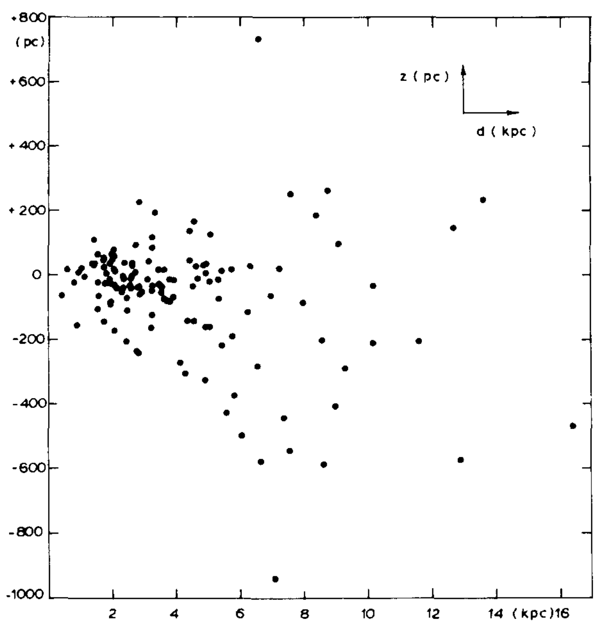

Fig. 3. The (z, d)-distribution of WR stars.

galactocentric distribution, then we note a similar gradient: the fraction of 'single' WR stars with large $|z|$-values is increasing with galactocentric distance. Therefore, among the 'single' WR stars with large $|z|$-values, *and* thus also among the 'single' WR with smaller $|z|$-values (because supernova-induced kick-velocities will have no directional preference), many WR binaries (lmSB1) may yet be waiting to be discovered.

TABLE VII

WR stars with $|z| > 200$ pc (from Hidayat *et al.*, 1984)

WR	Name	Sp. type	v	$b-v$	d (kpc)	r (kpc)	z (pc)
3	HD9974	WN3+abs	10.79	0.00	4.29	13.14	−309
8	HD62910	WN6+WC4	10.56	0.43	4.12	12.21	−272
17	HD88500	WC5	11.11	0.04	5.81	10.24	−374
20	BS1	WN4.5	14.60	0.74	9.29	11.82	−298
26	MS1	WN5+WC	14.64	0.72	13.60	14.38	+230
29	MS3	WN7	12.65	0.64	11.58	12.66	−204
30	HD94305	WC6+O6–8V	11.73	0.27	8.99	11.00	−410
33	HD95435	WC5	12.34	0.20	7.57	10.45	+250
34	LS5	WN4.5	14.50	0.76	8.55	10.70	−207
35	MS6	WN6	13.83	0.75	10.14	11.56	−209
40	HD96548	WN8(lmSB1)	7.85	0.11	2.48	9.34	−209
49	LSS2979	WN5	13.87	0.56	12.88	10.82	−571
52	HD115473	WC5	9.98	0.15	2.81	8.63	+223
54	LSS3111	WN4	12.99	0.46	6.54	7.97	−285
56	LS8	WC6	13.97	0.26	16.40	13.01	−466
57	HD119078	WC7	10.11	−0.18	6.65	7.91	−582
58	LSS3162	WN4	13.08	0.42	7.36	7.87	−448
61	LSS3208	WN4.5	12.56	0.28	8.66	7.79	−590
69	HD136488	WC9	9.43	0.14	2.80	8.08	−235
71	HD143414	WN6(lmSB1)	10.22	0.06	7.08	6.08	−937
82	LS11	WN8	12.42	0.81	5.42	5.13	−219
83	He3–1344	WN6	12.79	0.65	7.59	3.69	−544
92	HD157451	WC9	10.60	0.06	5.58	4.80	−430
103	HD164270	WC9(lmSB1)	9.01	0.03	2.84	7.16	−242
123	HD177230	WN8(lmSB1)	11.27	0.47	6.06	5.68	−502
128	HD187282	WN4(lmSB1)	10.56	0.02	4.90	8.29	−324
131	IC14–52	WN7+abs	12.40:	0.73:	8.71:	10.77:	+260:
148	HD197406	WN7(lmSB1)	10.50	0.42	6.52	11.95	+735

TABLE VIII

Galactocentric statistics of 'single' WR stars

r (kpc)	N ('single' WR)	N ('single' WR ($|z| > 200$ pc))	N ('single' WR ($|z| > 200$ pc)) / N ('single' WR)
7–9	41	7	0.17
9–11	29	6	0.21
11–13	14	4	0.29

5. Conclusions

Because various channels to produce WR stars may be operational (Maeder, 1982), it is important to assess for what fraction the binary channel is responsible.

The fraction of known WR binaries is 22%. This fraction is 34% in the solar neighbourhood ($d < 2.5$ kpc).

The distribution of WR stars projected on the galactic plane shows that in the inner region of the Galaxy the binary channel is relatively less important. This implies that other channels (mass loss, mixing) which require the conditions of the inner region (larger metallicity) are more active there.

The presence of many lmSB1 WR systems at large distances from the galactic plane indicates that these binaries have received large supernova-induced kick-velocities; this is consistent with the evolutionary scenario summarized by van den Heuvel (1976) for massive binaries.

The presence of many 'single' WR stars at large z-distances indicates that they also may have a binary origin. That these 'single' WR stars with large z-values are in addition relatively more frequent at larger galactocentric distances, like the known WR binaries, improves their chances for duplicity. The total WR binary frequency in the Galaxy could be well above 50%.

Acknowledgement

One of us (KAvdH) greatfully acknowledges financial support for this study from the Dutch Ministery of Education and Science and from the Leids Kerkhoven-Bosscha Fund, as well as warm hospitality by the Institut Teknologi Bandung, to work at the Observatorium Bosscha.

References

Abbott, D. C.: 1982, *Astrophys. J.* **263,** 723.
Abt, H. A., Landolt, A. U., Levy, S. G., and Mochnacki, S.: 1976, *Astron. J.* **81,** 541.
Alter, G., Balász, B. and Ruprecht, J.: 1970, *Catalogue of Star Clusters and Associations*, Prague.
Antokhin, I. I., Aslanov, A. A., and Cherepashchuk, A. M.: 1982a, *Pis'ma Astron. Zh.* **8,** 290 (*Soviet Astron. Letters* **8,** 156.
Antokhin, I. I., Aslanov, A. A., and Cherepashchuk, A. M.: 1982b, *Pis'ma Astron. Zh.* **8,** 734 (*Soviet Astron. Letters* **8,** 395).
Barlow, M. J. and Hummer, D. G.: 1982, in C. de Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars, Observations, Physics, and Evolution', *IAU Symp.* **99,** 387.
Bracher, K.: 1979, *Publ. Astron. Soc. Pacific* **91,** 827.
Conti, P. S.: 1982, in C. de Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars, Observations, Physics, and Evolution', *IAU Symp.* **99,** 3.
Conti, P. S. and Smith, L. J.: 1972, *Astrophys. J.* **172,** 623.
Conti, P. S., Niemela, V. S., and Walborn, N. R.: 1979, *Astrophys. J.* **228,** 206.
Conti, P. S., Garmany, C. D., de Loore, C., and Vanbeveren, D.: 1983, *Astrophys. J.*, (in press).
Crampton, D.: 1971, *Monthly Notices Roy. Astron. Soc.* **153,** 303.
Davis, A. B., Moffat, A. F. J., and Niemela, V. S.: 1981, *Astrophys. J.* **244,** 528.
Firmani, C., Koenigsberger, G., and Bisiacchi, G. F.: 1980, *Astrophys. J.* **239,** 607.
Fraquelli, D. A. and Horn, J.: 1982, in preparation.

Ganesh, V. S., Bappu, M. K. V., and Natajaran, V.: 1967, *Kodaikanal Observatory Bull., Ser.* **A184.**
Garmany, C. D., Conti, P. S., and Chiosi, C.: 1982, *Astrophys. J.* **263,** 777.
Hidayat, B., Supelli, K., and van der Hucht, K. A.: 1982, in C. de Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars, Observations, Physics, and Evolution', *IAU Symp.* **99,** 27.
Hidayat, B., van der Hucht, K. A., Suppelli, K. R., and Admiranto, A. G.: 1984, *Astron. Astrophys.* (to be submitted).
Humphreys, R. M.: 1978, *Astrophys. J. Suppl.* **38,** 309.
Isserstedt, J. and Moffat, A. F. J.: 1981, *Astron. Astrophys.* **96,** 133.
Isserstedt, J., Moffat, A. F. J., and Niemela, V. S.: 1983, in preparation.
Koenigsberger, G., Firmany, C., and Bisiacchi, G. F.: 1980, *Rev. Mexicana Astron. Astrof.* **5,** 45.
Lamontagne, R., Moffat, A. F. J., Koenigsberger, G., and Seggewiss, W.: 1982, *Astrophys. J.* **253,** 230.
Lamontagne, R., Moffat, A. F. J., and Seggewiss, W.: 1983a, *Astrophys. J.* **269,** 596.
Lamontagne, R., Moffat, A. F. J., and Seggewiss, W.: 1983b, *Astrophys. J.*, in press.
Leung, K.-C., Moffat, A. F. J., and Seggewiss, W.: 1983, *Astrophys. J.* **265,** 961.
Lundström, I. and Stenholm, B.: 1983, in preparation.
Maeder, A.: 1982, *Astron. Astrophys.* **105,** 149.
Maeder, A. and Lequeux, J.: 1982, *Astron. Astrophys.* **114,** 409.
Massey, P.: 1981a, *Astrophys. J.* **244,** 157.
Massey, P.: 1981b, *Astrophys. J.* **246,** 153.
Massey, P.: 1982, in C. de Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars, Observations, Physics, and Evolution', *IAU Symp.* **99,** 251.
Massey, P. and Conti, P. S.: 1981, *Astrophys. J.* **244,** 169.
Massey, P. and Conti, P. S.: 1983, *Publ. Astron. Soc. Pacific* **95,** 440.
Massey, P. and Niemela, V. S.: 1981, *Astrophys. J.* **245,** 195.
McCarthy, C. D. and Miller, E. W.: 1974, *Astron. J.* **79,** 1396.
Moffat, A. F. J.: 1974, *Astron. Astrophys.* **34,** 29.
Moffat, A. F. J.: 1982, in C. de Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars, Observations, Physics, and Evolution', *IAU Symp.* **99,** 263.
Moffat, A. F. J. and Isserstedt, J.: 1980, *Astron. Astrophys.* **91,** 147.
Moffat, A. F. J. and Niemela, V. S.: 1982, *Astron. Astrophys.* **108,** 326.
Moffat, A. F. J. and Seggewiss, W.: 1977, *Astron. Astrophys.* **54,** 607.
Moffat, A. F. J. and Seggewiss, W.: 1978, *Astron. Astrophys.* **70,** 69.
Moffat, A. F. J. and Seggewiss, W.: 1980a, in M. J. Plavec, D. M. Popper, and R. K. Ulrich (eds.), 'Close Binary Stars', *IAU Symp.* **88,** 181.
Moffat, A. F. J. and Seggewiss, W.: 1980b, *Astron. Astrophys.* **86,** 87.
Moffat, A. F. J., Lamontagne, R., and Seggewiss, W.: 1982, *Astron. Astrophys.* **114,** 135.
Münch, G.: 1950, *Astrophys. J.* **112,** 266.
Niemela, V. S.: 1980, in M. J. Plavec, D. M. Popper, and R. K. Ulrich (eds.), 'Close Binary Stars', *IAU Symp.* **88,** 177.
Niemela, V. S.: 1982, in C. de Loore and A. J. Willis (eds.), 'Wolf–Rayet Stars, Observations, Physics, and Evolution', *IAU Symp.* **99,** 299.
Niemela, V. S. and Moffat, A. F. J.: 1982, *Astrophys. J.* **259,** 213.
Niemela, V. S. and Sahade, J.: 1980, *Astrophys. J.* **238,** 244.
Niemela, V. S., Conti, P. S., and Massey, P.: 1980, *Astrophys. J.* **241,** 1050.
Niemela, V. S., Méndez, R., and Moffat, A. F. J.: 1983, *Astrophys. J.* **272,** 190.
Oort, J. H. and Plaut, L.: 1975, *Astron. Astrophys.* **41,** 71.
Pesch, P., Hiltner, W. A., and Brandt, J. C.: 1960, *Astrophys. J.* **132,** 513.
Seggewiss, W.: 1974, *Astron. Astrophys.* **31,** 211.
Smith, L. J. and Willis, A. J.: 1982, *Monthly Notices Roy. Astron. Soc.* **201,** 451.
Turner, D. G.: 1980, *Astrophys. J.* **235,** 146.
van den Heuvel, E. P. J.: 1976, in P. Eggleton, S. Mitton, and J. Whelan (eds.), 'Structure and Evolution of Close Binary Systems', *IAU Symp.* **73,** 35.
van der Hucht, K. A.: 1982, in S. D'Odorico, D. Baade, and K. Kjär (eds.), 'The Most Massive Stars', *Proc. ESO Workshop*, 23–25 November, 1981, Garching, p. 157.
van der Hucht, K. A., Conti, P. S., Lundström, I., and Stenholm, B.: 1981, *Space Sci. Rev.* **28,** 227.
Zinnecker, H.: 1982, in Z. Kopal and J. Rahe (eds.), 'Binary and Multiple Stars as Tracers of Stellar Evolution', *IAU Colloq.* **69,** 115.