Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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The VIIth Catalogue of Galactic Wolf-Rayet stars

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Abstract. The VIIth catalogue of Galactic Population I Wolf-Rayet stars provides improved coordinates, spectral types and b, v, K photometry of known WR stars, and it adds 62 new WR stars to the previous WR catalogue. The present census of Galactic WR stars stands at 218, including 117 WN stars, 87 WC stars, 11 WN/WC stars and 3 WO stars.

1. Introduction

The first five catalogues of Galactic Population I Wolf-Rayet stars have been presented by Campbell (1884), Fleming (1912), Payne (1930), Roberts (1962), and Smith (1968), respectively. Those catalogues, listed in Table 1, were discussed by van der Hucht *et al.* (1981). With the appearance of the *VIth Catalogue of Galactic Wolf-Rayet Stars* (van der Hucht, Conti, Lundström & Stenholm 1981, 159 stars) almost two decades ago, time and opportunity have come for a *VIIth Catalogue*, giving credit to new discoveries since 1981 of 62 new galactic WR stars, and bringing the number of known WR stars to 218.

Table 1. The catalogues for Galactic Population I Wolf-Rayet stars.

	author(s)	$N_{\rm WR}$	reference
I	Campbell, W.W.	55	1884, *Astronomy & Astrophysics* **13**, 448 (Northfield, Minnesota: Goodsell Observatory)
II	Fleming, W.P.	108	1912, *Harvard College Obs. Ann.* **56**, 165
III	Payne, C.H.	92	1930, The Stars of High Luminosity, *Harvard Obs. Monographs* No. **3**, p. 19
IV	Roberts, M.S.	123	1962, *Astron. J.* **67**, 79
V	Smith, L.F.	127	1968, *MNRAS* **138**, 109
VI	van der Hucht, K.A., Conti, P.S., Lundström, I., Stenholm, B.	157	1981, *Space Science Reviews* **28**, 227
VII	van der Hucht, K.A.	218	1999, *New Astronomy Reviews* to be submitted

Comprehensive general reviews on the WR phenomenon have been presented by, *e.g.*, Abbott & Conti (1987), van der Hucht (1992), Maeder & Conti

(1994) and in the proceedings of IAU Symposium No. 143 (van der Hucht & Hidayat 1991), in IAU Symposium No. 163 (van der Hucht & Williams 1995), and in the 33^{rd} Liège International Astrophysics Colloquium (Vreux *et al.* 1996).

It is useful to discover and monitor WR stars since each one of them is a unique physics laboratory, a tracer of star-formation in spiral arms, and a representative of an evolved phase in the evolution of massive stars to be followed up, most likely, by a Type Ib/Ic supernova event (Woosley *et al.* 1993; Maeder & Conti 1994; Langer & Woosley 1996; García-Segura *et al.* 1996). And since statistically the next Galactic supernova is already overdue, it is of paramount importance to gather detailed knowledge about its potential progenitor.

2. Spectral classification

Spectral classification of WR stars, as well as of O-type stars, was reviewed extensively by van der Hucht (1996). As an extension of the late WN subtypes, L.J.Smith *et al.* (1994, 1995) and Crowther *et al.* (1995a) introduced the WN10-11 subtypes, following earlier, tentative, suggestions by Walborn (1977). Crowther *et al.* (1998) introduced a revised quantitative classification scheme for the carbon and oxygen sequences of the WR stars, based on excitation only. In that way they ignore possible abundance effects, of importance in appreciating the evolutionary status of WR stars.

3. Galactic Wolf-Rayet star inventory

The VIth Galactic Wolf-Rayet star inventory by van der Hucht *et al.* (1981) has been succeeded by:
- the deletion of three stars from the VIth Catalogue (Table 2);
- the renumbering of WR 29a to WR 30a;
- the deletion of three supposedly new WR stars (Table 3); and
- the discovery of 62 new WR stars (Tabel 4), which we include in the WR numbering system of van der Hucht *et al.* (1981), to compile the VIIth Catalogue of Galactic Wolf-Rayet Stars.

Table 2. Stars deleted from the VIth Galactic Wolf-Rayet Catalogue.

WR	other design.	old type	ref.	v	$b-v$	RA (1950)	Dec (1950)	new type	ref.
72	Sand 3	WC4pec	a	(14.24)	(0.21)	16 03 12.6	−35 37 10	PN [WOI]	d,e
99	DA 2	WN	b	(16.0)	...	17 36 08.8	−28 13 30	symbiotic	f
122	NaSt 1	WN10	c	15.4	1.5	18 49 44.8	+00 56 03	hidden WRE	g,h

References: (a) van der Hucht *et al.* 1981; (b) Allen 1979; (c) Massey & Conti 1983; (d) Barlow & Hummer 1982; (e) Crowther *et al.* 1998; (f) Mikolajewska *et al.* 1997; (g) van der Hucht *et al.* 1997; (h) Crowther & Smith 1999 and these Proceedings.

Table 3. Stars found after 1981 but later rejected.

star	suggested type	ref.	v	$b-v$	RA (1950)	Dec (1950)	type	ref.
M1-13, PK 232−1° 1	WC	a	10.	....	07 19 01.2	−18 02 51	PN	d,e
Pe1-7, PK 337+1° 1	[WC9]/WC9	b	16.43	1.12	16 26 48.1	−45 56 22	PN [WC9]	d,f
LSS 4005, WRA 1656	WN11	c	14.05	1.12	17 12 36.8	−38 12 22	O[e]/B[e]	g

References: (a) Gyul'budagyan *et al.* 1984; (b) Lundström & Stenholm 1984; (c) Lundström & Stenholm 1983; (d) van der Hucht & Williams 1987; (e) Acker *et al.* 1992; (f) Tylenda *et al.* 1993; (g) van der Hucht *et al.* 1997.

The discovery of the 62 new WR stars comprises many efforts:
- Danks *et al.* (1983) discovered a faint new WC8 star with variable IR emission (WR 48a);
- Acker & Stenholm (1990) reclassified the alleged planetary nebula Th3-28 (Thé 1964) as a new WN2.5-3 star (WR 93a);
- Panov & Seggewiss (1990) found that the quadruple system WR 153 (GP Cep) harbours two WN+O systems, while L.J.Smith *et al.* (1990) classify the object WN6o/WCE+O6I;
- Cohen *et al.* (1991) classified IRAS 17380-3031 as a new WC8-9 star (WR 98a);
- Shara *et al.* (1991) discovered in a dedicated survey 13 new WR stars (11 WN and 2 WC);
- Crawford & Barlow (1991) classified the emission-line star We 21 (Weaver 1974) as a new WN8 star (WR 47a);
- van Kerkwijk *et al.* (1992, 1993, 1996) discovered that Cygnus X-3 has in the IR K-band a variable WN4–7 spectrum (WR 145a);
- Mereghetti *et al.* (1994) identified the X-ray source 1E 1024.0-5732 with the emission-line star Th35-42 (Thé 1966) and classified it as WN6+O (WR 21a);
- Hofmann *et al.* (1995) resolved with speckle observations four individual WN stars in WR 43, the central object of cluster and H II region NGC 3603, three of which were confirmed by Drissen *et al.* (1995);
- Smith *et al.* (1994) reclassified two LBV or WN/Of-type objects into WN11 subtypes;
- Krabbe *et al.* (1995) discovered six, Blum *et al.* (1995) discovered one, and Figer *et al.* (1995, 1996, 1999a) discovered eight new WR stars near the Galactic Center;
- Najarro *et al.* (1997) reclassified GC IRS 7W, one of the WN9/Ofpe stars of Krabbe *et al.* (1995), as WN9-10 (WR 101c);
- Shara *et al.* (1999) continued their dedicated optical survey to discover 18 new WR stars (12 WN (including the known We 21, Crawford & Barlow 1991), 5 WC, 1 WN/WC);
- Pereira *et al.* (1998 and these Proceedings) discovered one new WN/WC star (WR 7a);
- Blum *et al.* (1999) discovered one new WN star (WR 121a) in the main stellar cluster of the giant H II region W 43 (W 43 #1);
- Bohannan & Crowther (1999) reclassified the extreme Of stars HD 152408 (O8:Iafpe) and HD 152386 (O6:Iafpe) as WN9ha (WR 79a, WR 79b);
- Figer *et al.* (1999b) found very close to FMM96-3 another so-called $<$WC8 star (WR 102e).

Near the Galactic Center many more new WR stars may be found, *e.g.*, among 14 Galactic Center stars resolved in NHSSK-17 (Nagata *et al.* 1993, 1995); among 13 Galactic Center stars (Of or WNL) in the cluster G 012+0.02 near the Arched Filaments (Cotera *et al.* 1996, 1999); among the other 10 WN9/Ofpe stars found by Krabbe *et al.* (1995, see also Najarro *et al.* 1997); among the five extremely dusty enigmatic Quintuplet-proper stars noted by Figer *et al.* (1996, 1999a). In addition, many more new WR stars may be found in star-formation regions like W49A, where De Pree *et al.* (1997) note that W49A/M is the more obvious one of thirteen 3.6cm-continuum sources with strong He92α emission. Narrow-band near-IR surveys for detecting more WR

Table 4. New Galactic Wolf-Rayet stars since 1981, discoveries and/or re-classifications.

new WR number(s)	other designations(s)	type(s)	reference(s)
7a	MP 1, SPH 2	WN/C	Pereira *et al.* 1998, these Proceeding
19a,20ab,31c,35ab, 38ab,42abcd,44a	SMSP series	11 WN, 2 WC	Shara *et al.* 1991
21a	Th35-42 = 1E 1024.0-5732	WN6	Mereghetti *et al.* 1994
31ab	AG Car, He3-519	2 WN11	L.J.Smith *et al.* 1994
43abc	WR 43 in NGC 3603	3 WN	Drissen *et al.* 1995
45abc,46a,47bc,48bc 56a,62ab,68a,70a, 75ab,102j,107a	SMSPN series	11 WN, 5 WC, 1 WN/WC	Shara *et al.* 1998
47a	We 21 = SMSPN 5	WN8	Crawford & Barlow 1991
48a	Danks 1	WC8	Danks *et al.* 1983
79ab	HD 152408, HD 152386	WN9ha	Bohannan & Crowther 1999
93a	Th3-28 = PK 359+03 1	WN2.5-3	Acker & Stenholm 1990
98a	IRAS 17380-3031	WC8-9	Cohen *et al.* 1991
101a	BSD 1	WC9	Blum *et al.* 1995
101bcdefgh	Kr series	5 WC9, 2 WN9-10	Krabbe *et al.* 1995; Najarro *et al.* 1997
102bf	FMM95 series	WN9, WC9	Figer *et al.* 1995
102acdghi	FMM96 series	3 WN, 3 WC	Figer *et al.* 1996, 1999a
102e	FMM99-1	WC	Figer *et al.* 1999b
121a	W 43#1	WN7	Blum *et al.* 1998
145a	Cyg X-3	WN4-7	van Kerkwijk *et al.* 1992
153ab	WR 153	2× WN+O	Panov & Seggewiss 1990

stars are being carried out (*e.g.*, Blum & Damineli, these Proceedings) or are being planned (Shara 1998, priv. comm.).

The new discoveries are summarized in Table 4. This brings the number of known Galactic WR stars to 218, comprising 117 WN types, 11 WN/WC types, 87 WC types, and 3 WO types. The WR subtype distribution is listed in Table 5.

The format of the VIIth Galactic WR Catalogue is:
column 1: running number from the VIth Catalogue of Galactic Wolf-Rayet Stars and intermediate numbers;
column 2: star name;
columns 3, 4, 5: cross-correlation of various catalogue numbers;
column 6: J2000.0 equatorial coordinates;
column 7: galactic coordinates;
column 8: correlation with open clusters and OB associations;
column 9: correlation with H II regions, ring nebulae, and H I bubbles;
column 10: source for finding charts;
column 11: spectral classification;
column 12: visual *vb* photometry ;
column 13: *K*-band infrared photometry; and
column 14: period or periodicity.

The VIIth Catalogue of Galactic Wolf-Rayet Stars will be submitted to New Astronomy Reviews.

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Table 5. Subtype distribution of the known Galactic Wolf-Rayet stars, progress in one decade.

subtype	number of WR stars in HH88					number of WR stars in this study					
	single		double		total	single		double			total
		+a	SB1	SB2			+a	SB1	SB2	VB	
WN2	1				1	1					1
WN3	4	1		1	6	2		2	1		5
WN4	7		1	3	11	13		3	2		18
WN4.5	5			1	6						
WN5	3		1	2	6	19		1	5	2	27
WN6	13		5	3	21	12	6	3	2		23
WN7	12	4	3		19	11	3		2		16
WN8	8		2		10	7	1	7			15
WN9	1				1	9	1				10
WN11						2					2
subtotal WN	54	5	12	10	81	76	11	16	12	2	117
WN/WC	3		1		4	6		3	2		11
WC4	4			1	5	4			1		5
WC5	10			1	11	8		1	1		10
WC6	10	2		2	14	8	1	1	3		13
WC7	6	1		5	12	7	2		6		15
WC8	7			2	9	10	1		3		14
WC9	16		1	1	18	26		1	3		30
WC10	1				1						
subtotal WC	54	3	1	12	70	63	4	3	17		87
WO1	1				1	1					1
WO2	1				1	1					1
WO5									1		1
subtotal WO	3				3	2			1		3
grand total	113	8	14	22	157	147	15	22	32	2	218

Note: HH88 : van der Hucht *et al.* 1988

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Discussion

Massey: Could you comment on the completeness issue?

van der Hucht: Shara *et al.* (1991, 1998) claim that 25% of the number of the WR stars in the solar neighborhood is still hiding.

Vanbeveren: The observed period distribution of WR+OB binaries shows a gap between 100 days and > 1000 days. Do you think that this is due to observational bias, indicating that there is still a significant number of WR+OB binaries to be discovered?

van der Hucht: Yes, observational bias indeed.

Shara: A comment: Karel has been one of the strongest supporters of our decade-long survey for new Galactic WR stars. He accurately refers to this as 'the work of monks'. In fact, we performed photometry on 100 000 000 stars to find 1 000 candidates, and eventually confirm 31 new WR stars. This will surely be supplanted by near-IR surveys in the next decade.

van der Hucht: Thanks again, Mike & co-workers!

Peimbert: To obtain the number ratio of WR stars to O stars we need to know the completeness factors for WR stars and O stars. Can you comment on this problem?

Garmany, referred to by van der Hucht: Although we went through this exercise a long time ago, I think the work in Magellanic Cloud associations as well as recent work on Galactic associations (Massey *et al.*) has shown how incomplete the early catalogues were. In addition, the *Hipparcos* distances, to OB associations raise the possibility that the entire M_V scale for galactic OB stars needs re-examination.

Walborn: As we focus on WR stars as a class, and even statistically, it's good to keep in mind that the class contains qualitatively different kinds of objects which display the WR phenomena for different physical reasons. At IAU Symposium No. 49 in 1971 it was still possible to hold the view that all WR stars were likely due to mass transfer in binary systems. Jacques mentioned that about 10% of LMC WRs are known SB1/2 objects. How many of the current Galactic WR census are known short-period binaries such that mass transfer may have caused or enhanced their WR phenomena? Allan mentioned that HD 93131 has moving narrow-absorbtion components in its wind profiles, similar to what is seen in many O stars; it's important to note that this star is a high-luminosity WNL type in a giant H II region, which subclass is most directly related to massive (single) O stars in terms of its origin. Finally, Allan also reported that 15% of all WRs observed for line de-polarisation show evidence of asymmetrical winds. What other properties, if any, does this effect correlate with, *e.g.*, subclass, line-width, line-strength (which are independent variables in WR spectra)? Or binarity?

van der Hucht: The percentage of WR binaries in the Galaxy in the volume limited sample with $R < 2.5$ kpc stands at about 50%.