Spectral analysis and model atmospheres of WR type central stars

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Abstract. Wolf-Rayet type spectra of central stars are compared with spectra from Pop. I objects. Non-LTE models for expanding atmospheres are applied for analyzing these spectra quantitatively.

Key words: Central stars, Wolf-Rayet stars, stellar winds, mass-loss

1. Introduction

Wolf-Rayet (short: WR) stars are characterized by the bright and broad emission lines which dominate their spectra. "Normal" WR stars are young, massive and very luminous ($10^{4.5}...10^{6} M_{\odot}$) and form a nitrogen (WN) and carbon (WC) sequence according to the ions dominating their line spectrum. However, Wolf-Rayet (especially WC) type spectra with very similar characteristics are also shown by a number of central stars of planetary nebulae, although these stars obviously belong to an older population and are less massive and less luminous than their Pop. I relatives.

Wolf-Rayet spectra of the carbon subclass are arranged in a subtype sequence from WC2 to WC12, considering the strength of selected carbon and, as secondary criteria, oxygen emission lines (van der Hucht *et al.* 1981 – abbreviated HCLS in the following, Méndez & Niëmela 1982, Hu & Bibo 1990). Subtype numbers up to WC6 are comprehensively termed as "early" (short: WCE), the rest as "late" (WCL). We follow HCLS in typing the spectral classification of central stars in brackets.

2. Model atmospheres for Wolf-Rayet stars

Radiative transfer calculations for WR atmospheres must account for the extreme non-LTE situation and for the velocity field. Adequate models have been developed during the last years by Hillier (see e.g. Hillier 1990) and by the "Kiel group" (now in Potsdam; cf. Hamann & Wessolowski 1990). The so-called *standard model* is based on the idealizing assumptions of spherical symmetry, stationarity and homogeneity. The velocity field is pre-specified ("β law"). Present models can handle very complex model atoms (e.g. He, C, N, O) with together a few hundred energy levels and more than thousand explicitely treated line transitions. These models have been used with some success to analyze Pop. I WR stars, and their application to WR-type central stars is reported here (cf. also Crowther *et al.*, these proceedings).

3. Central stars of subclass [WCE]

The compilation by Tylenda *et al.* (1993) lists some 23 CPN with early-type [WC] spectra. Except of one [WC2], they are all of [WC3] or [WC4] subtype, while [WC5] and [WC6] are missing. This statistical distribution differs completely from the Pop. I WC stars. Among the 70 Galactic WC stars in HCLS, there are only six stars of subtype WC4 or earlier, but very many WC5, WC6 and WC7. Those [WCE] stars which are presently under study by the Kiel/Potsdam group are compiled in Table I.

TABLE I

Our [WCE] program stars (observations done). WR numbers in brackets (second column) refer to the list of Wolf-Rayet type central stars in van der Hucht *et al.* (1981). Note that Sanduleak 3 was formerly in the list of Pop. I WR stars in the same catalogue (WR number without brackets).

Name	HCLS alias	Spectral Type	Analyzed by
NGC 5189	[WR 13]	[WC2]	
NGC 6905	[WR 39]	[WC2-3]	
NGC 7026	[WR 40]	[WC3]	
PB6	-	[WC3]	
Sand 3	WR 72	[WC3]	Koesterke & Hamann (1995b)
IC 1747	[WR 03]	[WC4]	
NGC 1501	[WR 06]	[WC4]	
NGC 5315	[WR 15]	[WC4]	
NGC 6369	-	[WC4]	
NGC 6751	[WR 28]	[WC4]	Hamann & Koesterke (1993)

One representative spectrum for each [WCE] subtype is shown in Fig. 1 and compared to spectra of Population I WC stars. The gradual change of ionization from C IV to C III can be nicely seen. In parallel, the dominant oxygen lines change from O VI to O V when going from [WC2] to [WC4]. Note that the [WCE] spectra can be contaminated with nebular emission (e.g. He I 5876 Å).

Among the spectra of the few earliest Pop. I WC stars (WO1, WO2, WC4) we find no close counterparts to the [WCE] representatives. However, the spectrum

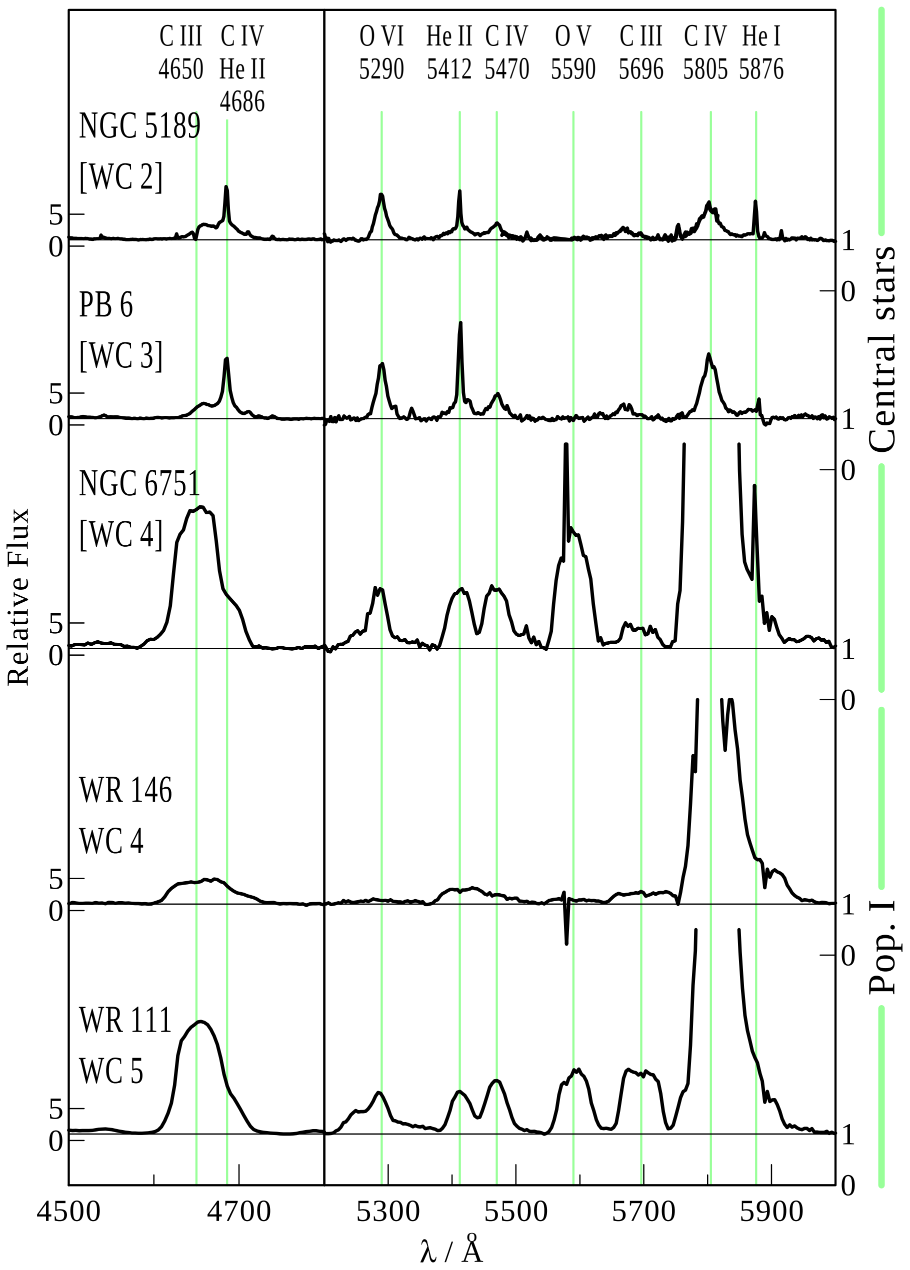

Fig. 1. Comparison between Pop. I Wolf-Rayet stars and central stars with early-type WC spectra

of the WC5 prototype WC 111 (Pop. I) is very similar to the spectrum of the CPN NGC 6751, except of its slightly later subtype reflected by the somewhat stronger C III 5696Å line. Thus it seems that [WCE] spectra do not differ in principle from

WCE spectra, and we are encouraged to apply the same type of models developed for the Pop. I WC stars to analyze the central stars. But obviously, the observed representatives of these two classes populate different regions in the space of atmospheric parameters which have only partial overlap.

TABLE II

Results of [WCE] analyses with the *Standard Model*

		T_* [kK]	$\log L$ $[L_\odot]$	R_* $[R_\odot]$	$\log \dot{M}$ $[\frac{M_\odot}{\mathrm{yr}}]$	v_∞ [km/s]	β_{He} [%]	β_{C} [%]	β_{N} [%]	β_{O} [%]
Sand 3	[WC3]	140	3.7	0.12	-6.2	2200	61.5	26	0.5	12
NGC 6751	[WC4]	105	3.7	0.22	-5.2	2000	61.5	27	1.5	10

Only two [WCE] stars have been analyzed so far by means of the detailed non-LTE models (cf. Table I for the references). The results are compiled in Table II. The carbon-to-helium ratio is estimated as approximately 1:2 by mass. Oxygen is enhanced with a mass fraction of about 10%, but the abundances of N and O are due to relatively large error margins (factor of two). Note that the spectral analysis yields the quantity $R_*/\dot{M}^{2/3}$. In order to determine the dimensions of the star (i.e. R_*, which then implies $\dot{M}$ and L) one of these absolute parameters must be determined independently. As for the two studied [WCE] stars the distance is not known, the luminosity has been set to the value of $10^{3.7} L_\odot$ as favored from evolutionary arguments.

4. Central stars of subclass [WC]-PG 1159

This spectral subclass, which is alternatively termed Of-WR(C) after Méndez (1991), shows mass-loss features but otherwise resembles the very hot PG 1159 stars composed mainly of carbon, oxygen and helium (cf. Dreizler *et al.* 1995). Only a handful of [WC]-PG 1159 stars is known so far. Spectra of our four program stars from this class are plotted in Fig. 2. The fifth spectrum in this figure belongs to Longmore 4, normally a PG 1159 star which was fortuitously observed in January 1992 when suddenly showing a [WC]-PG 1159 spectrum (Werner *et al.* 1992) with emission lines closely resembling the spectrum of Abell 30. The emissions declined within a few days, and the star returned to its normal state within two weeks.

Results from analyses of [WC]-PG 1159 stars are compiled in Table III (Abell 30: from Leuenhagen *et al.* 1993; Abell 78: from Hamann & Koesterke 1993; Longmore 4: Werner *et al.* 1993). The few detectable wind lines were analyzed with

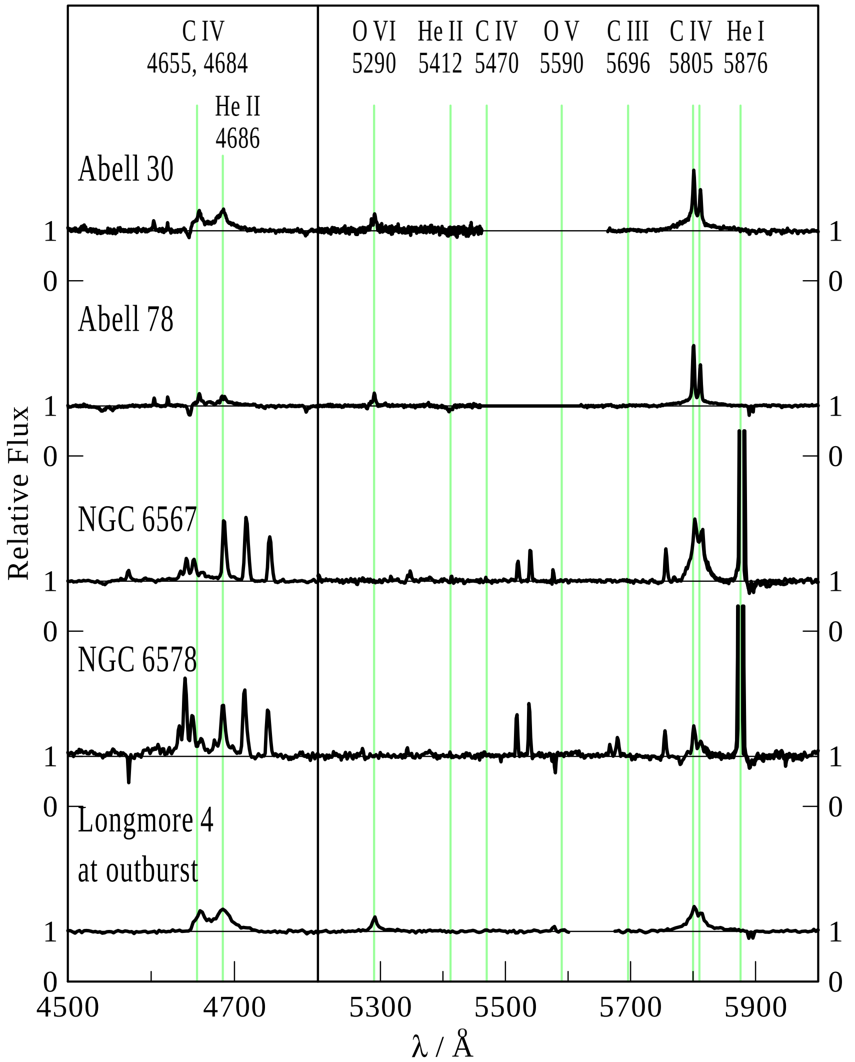

Fig. 2. Observed spectra of [WC]-PG 1159 type central stars

Wolf-Rayet models, while the weak photospheric absorption profiles could be fitted with static, plane–parallel non-LTE calculations. The latter yield a surface gravity of $\log g = 5.5$ [cgs units] in all three cases. The surface composition as reported in Table III was consistently found with both methods. Note that the carbon-to-helium ratio is about unity (by mass), which is also the typical value for PG 1159 stars. The quoted mass-loss rate for Longmore 4 refers to the outburst spectrum from January 27, 1992. In the quiet state the mass-loss rate is lower by at least a factor of five. Thus the only obvious difference between [WC]-PG 1159

TABLE III

Results of spectral analyses of [WC]-PG 1159 type central stars. Wind (emission) lines are compared with the *Standard Model* for WR stars, while static non-LTE models are applied for the photospheric (absorption) lines. The data for Longmore 4 refer to the outburst state. As the distances of these stars are unknown, the luminosities are set to 5000 $L_{\odot}$ and the other absolute quantities are scaled accordingly.

	T_* [kK]	$\log L$ [$L_{\odot}$]	R_* [$R_{\odot}$]	$\log \dot{M}$ [$\frac{M_{\odot}}{\mathrm{yr}}$]	v_∞ [km/s]	β_{He} [%]	β_{C} [%]	β_{N} [%]	β_{O} [%]
Abell 30	115	3.7	0.18	-7.2	4000	41	40	4	15
Abell 78	115	3.7	0.18	-7.4	3750	33	50	2	15
Longmore 4	120	3.7	0.16	-7.3	4000	46	43	?	11

TABLE IV

Our [WCL] program stars (observations done)

Name	HCLS alias	Spectral type	Analyzed by
NGC 40	[WR 1]	[WC8]	Leuenhagen *et al.* (1996)
He 2-99	[WR 14]	[WC9]	*ditto*
BD+30°3639	[WR 31]	[WC9]	*ditto*
CPD-56°8032	[WR 19]	[WC11]	*ditto*
M 4-18	[WR 7]	[WC11]	*ditto*
He 2-113	[WR 17]	[WC11]	*ditto*
K 2-16	-	[WC11]	*ditto*
V 348 Sgr	[WR 25]	[WC12]	Leuenhagen & Hamann (1994)
SwSt 1	[WR 23]	[WC10]	
PM 1-188	-	[WC11]	
He 2-459	-	[WC9]	
IRAS 21282+5050	-	[WC11]	
M 2-43	-	[WC8]	
MA 17 (LMC)	-	[WC7]	Koesterke *et al.* (in prep.)
MG 08 (LMC)	-	[WC8?]	

stars and PG 1159 stars concerns the strength of the mass-loss, and Longmore 4 demonstrates that this parameter can vary with time.

5. Central stars of subclass [WCL]

Our program stars (cf. Table IV) are selected from the list by Tylenda *et al.* (1993), who identify nine [WCL] stars, and from a few other sources. Representative spectra for the subclasses [WC8], [WC9], [WC11] and [WC12] are shown in Fig. 3. (The subclass [WC10] is perhaps not necessary in the classification sequence.) From [WC8] to [WC9] there is only a gradual decrease of C IV in favor of C III. Spectra of corresponding Pop. I stars, included in Fig. 3 for comparison, look very similar. While the latest subtype found among Pop. I stars is WC9, a great fraction of the [WCL] central stars is even "later". [WC11] and [WC12] spectra look entirely different from the earlier subtypes, because He II and C IV lines do not show up, and all lines are rather narrow (low wind velocities).

A variety of [WCL] stars have been analyzed so far (references given in Table IV), and the results are compiled in Table V. The effective temperatures T_* form a sequence correlated with the subtype number, stretching from about 100 kK ([WC7]) to as low as 20 kK ([WC12]).

TABLE V

Results of spectral analyses of [WCL] type central stars by application of the *standard model* for WR stars. Absolute parameters (i.e. L, R_*, $\dot{M}$) are based on (nebular) distances if available, otherwise $\log L/L_\odot = 3.7$ is adopted.

	T_* [kK]	v_∞ [km/s]	$\log L$ [$L_\odot$]	R_* [$R_\odot$]	$\log \dot{M}$ [$\frac{M_\odot}{\mathrm{yr}}$]	β_{He} [%]	β_{C} [%]	β_{O} [%]	β_{H} [%]
MA 17 (LMC)	100	900	3.8	0.3	-5.8	60	25	15	-
NGC 40	78	1000	3.6	0.3	-5.6	40	50	10	<2
He 2-99	49	900	3.7	1.0	-5.6	50	40	10	<2
BD+30°3639	47	700	4.7	3.3	-4.9	45	50	5	<7
CPD-56°8032	32	240	4.1	3.4	-5.6	42	50	8	<0.5
M 4-18	31	350	3.7	2.3	-6.0	46	50	4	<10
He 2-113	30	200	4.5	6.5	-5.5	44	50	6	≈7
K 2-16	30	300	3.7	2.6	-6.4	45	50	5	<1
V 348 Sgr	20	190	3.7	6.0	-6.5	40	56	1	4

The stellar distance which is needed to determine L, R_* and $\dot{M}$ (cf. the discussion at the end of Sect. 3) is known in some cases (e.g. for MA 17 because it belongs to the LMC, and for BD+30°3639 from the measured angular growth of its

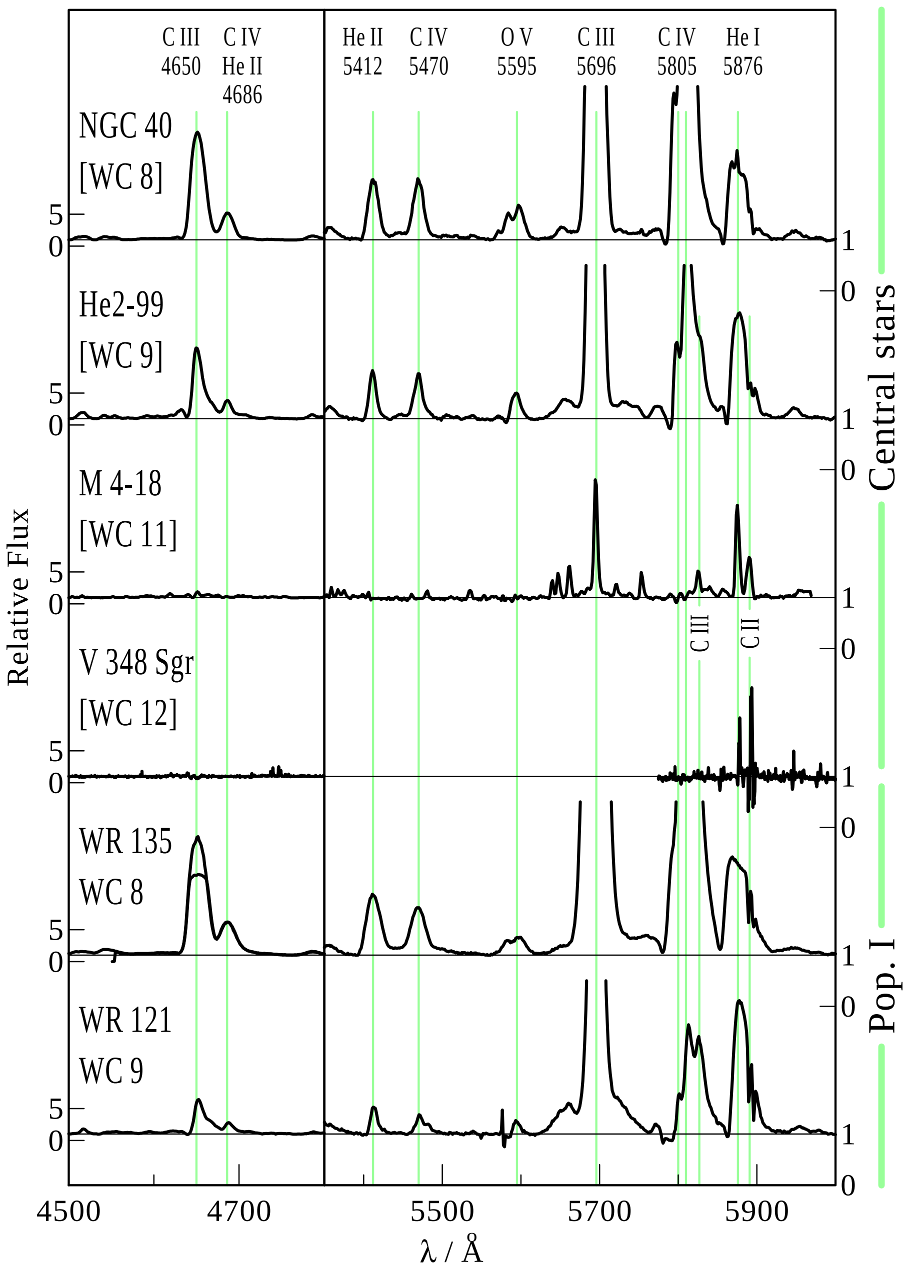

Fig. 3. Comparison between Pop. I Wolf-Rayet stars and central stars with late-type WC spectra

nebula). Otherwise $\log L/L_{\odot} = 3.7$ is assumed (K 2-16, V 348 Sgr). The obtained mass-loss rates for the [WCL] stars are of the order of $10^{-6} M_{\odot}\,\mathrm{yr}^{-1}$. The chemical composition is similar to the PG 1159 stars (roughly equal mass fractions of carbon and helium). As a strange result, V 348 Sgr exhibits a small amount of hydrogen (4% by mass) in its atmosphere which otherwise shows the products of helium burning. The possible detection of hydrogen in He 2-113 is not definite, while for the other [WCL] stars more or less sharp upper limits for the hydrogen abundance are established (cf. Table V).

6. Central stars of subclass [WN]?

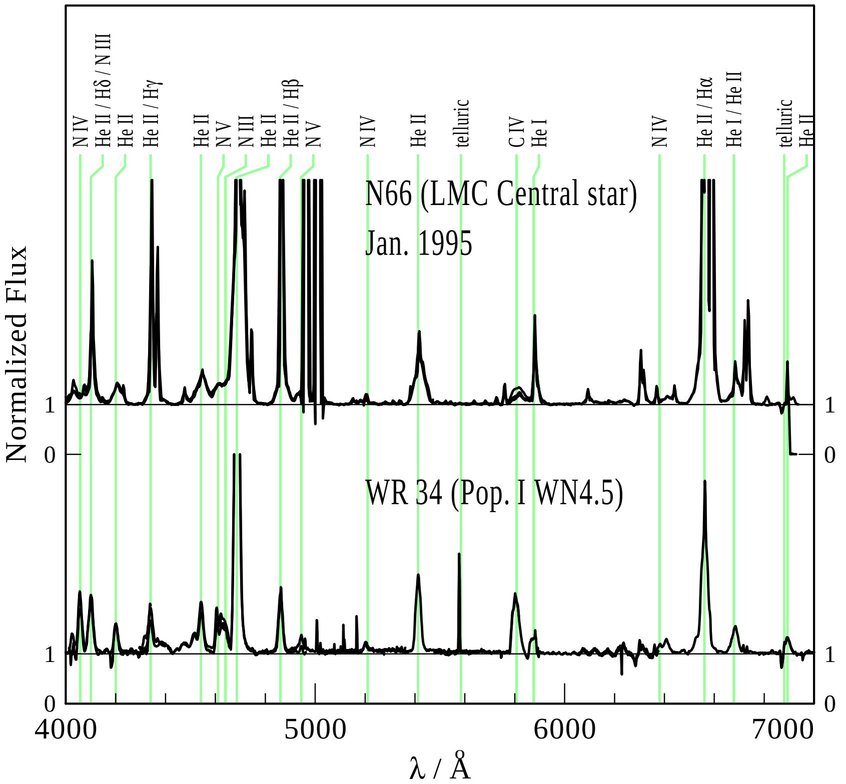

Fig. 4. Spectrum of the central star N66 in the LMC as observed by us in January 1995, compared with the Galactic Pop. I Wolf-Rayet star WR 34 (spectral subtype WN4.5)

The Wolf-Rayet stars of Pop. I form two spectroscopic sequences dominated by nitrogen lines (WN subtypes) and by carbon lines (WC sequence), respectively. Central stars of planetary nebula, however, when showing a Wolf-Rayet spectrum are always of the WC type. The only exception known yet is the LMC object N66. As a further peculiarity, this central star developed his WN-type spectrum only recently since the year 1990 (Peña *et al.* 1994, 1995). Its present spectrum may be compared with a Pop. I WN4.5 star (cf. Fig. 4). However, the lines of N66 are broader than in the galactic comparison star (higher wind velocity). Note that the sharp lines in the shown N66 spectrum are emissions of the surrounding planetary nebula. All C and N lines are weaker in N66, probably reflecting the smaller metallicity in the LMC. The effective temperature of N66 might be considerably hotter than in the Pop. I comparison, as there is probably no stellar He I 5876 Å emission hidden under the corresponding nebular line.

7. Discussion

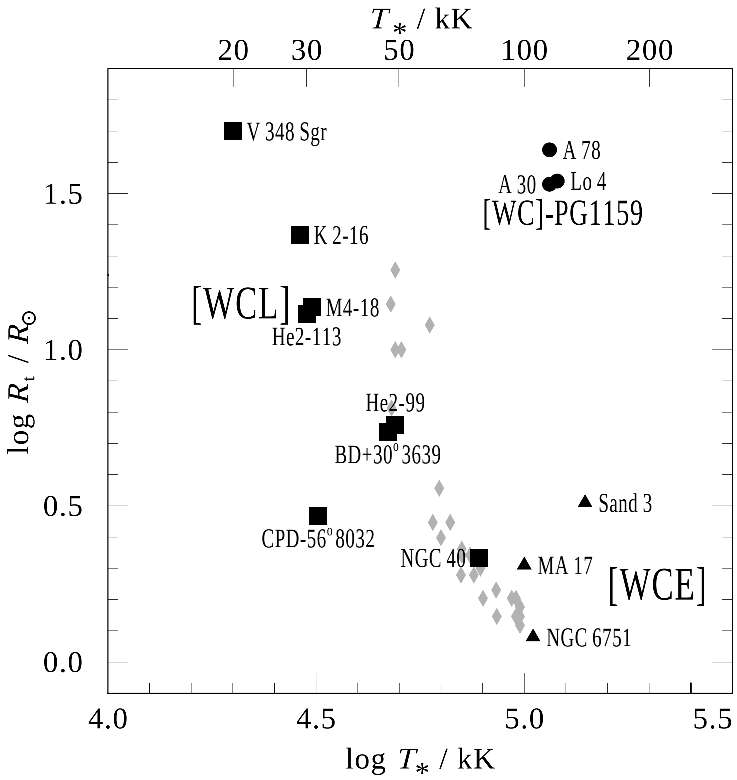

Fig. 5. Central stars of Wolf-Rayet type in the $R_t - T_*$–diagram. [WCL], [WCE] and [WC]-PG 1159 subtypes are represented by squares, triangles and circles, respectively. Shaded diamonds indicate Pop. I WC stars of intermediate subtype (WC5 ... WC7) (analyzed by Koesterke & Hamann 1995a).

A purely spectroscopic parameter we obtain from the spectral analysis is the "transformed radius" R_t which we define by

$$R_t = R_* \left(\frac{v_\infty / 2500\,\mathrm{km\,s^{-1}}}{\dot{M}/10^{-4}\,M_\odot\,\mathrm{yr^{-1}}} \right)^{2/3} . \qquad (1)$$

R_t is independent from the adopted distance of the star and thus plays in expanding atmospheres the role of $\log g$ in the static case. In Fig. 5 $\log R_t$ is plotted versus $\log T_*$ for all WC-type central stars analyzed so far. The [WCL] stars form a nice sequence which continues to higher temperatures and lower R_t with the [WCE] object NGC 6751. The group of [WC]-PG 1150 stars lies apart, being as hot as [WCE] stars but with higher R_t (thinner wind). Sand 3 has an intermediate R_t. Note the coincidence of the [WCL]-[WCE] sequence with Pop. I WC stars of intermediate subtype also shown in the figure for comparison.

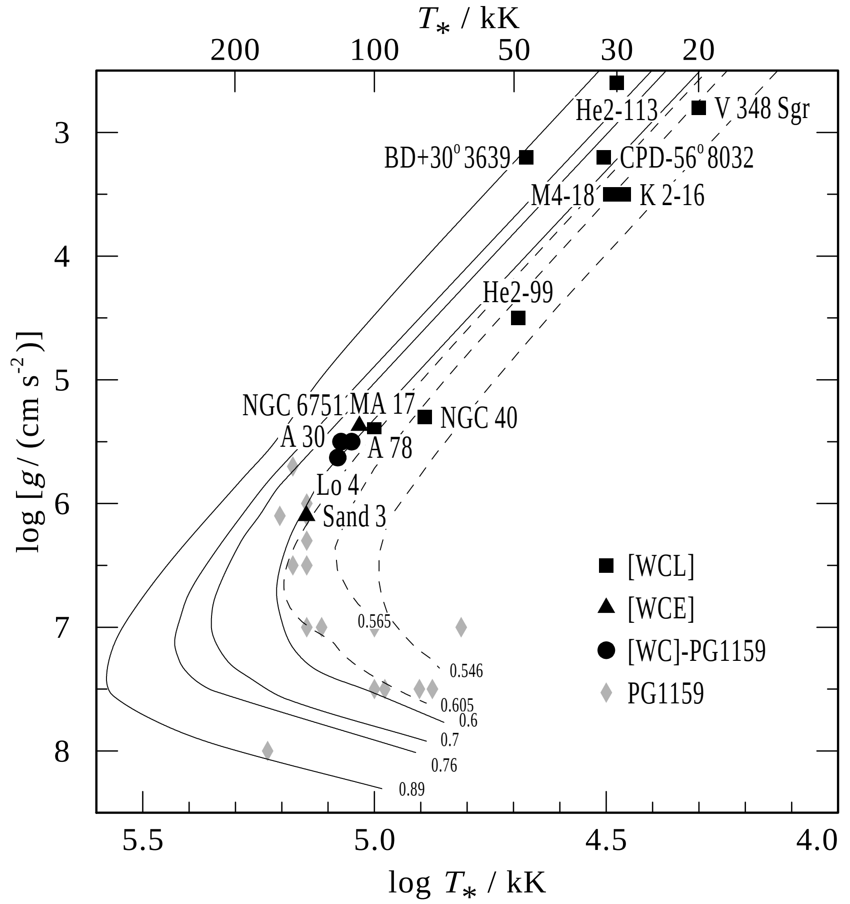

Fig. 6. Central stars of Wolf-Rayet type in the $\log g - \log T_*$–diagram. [WCL], [WCE] and [WC]-PG 1159 subtypes are represented by squares, triangles and circles, respectively. Shaded diamonds indicate "normal" PG 1159 stars without strong mass-loss (after Dreizler *et al.* 1995). The tracks for post-AGB evolution taken from Schönberner (1983) or Wood & Faulkner (1986) (labels: mass in $M_\odot$) and are only shown for rough comparison; they are not really adequate for the considered objects, as they predict normal surface abundances.

In order to visualize possible evolutionary connections we employ the $\log g - \log T_{\rm eff}$–diagram (Fig. 6). Surface gravities $\log g$ are directly obtained from photospheric absorption lines in the case of [WC]-PG 1159 stars. For the [WCE] and [WCL] stars we take the spectroscopic radii R_* (Tables II and V) and assume a mass of $0.6M_\odot$. "Normal" PG 1159 stars (photospheric spectra analyzed with static model atmospheres) are also shown. The evolutionary tracks included in the figure are not claimed to be adequate in detail for the type of stars under consideration, but shall indicate roughly an evolution at constant luminosity finally turning into the white dwarf cooling sequence. The diagram suggests an evolutionary sequence from the coolest [WCL] stars (highest subtype numbers) to the hottest [WCE] types. At its hot end we find stars with different mass-loss rates ([WCE], [WC]-PG1159, PG 1159) at the same place of that diagram, while only the PG 1159 class extends further to higher gravities. The only contradiction to the suggested evolutionary sequence [WCL] $\rightarrow$ [WCE] $\rightarrow$ [WC]-PG 1159 $\rightarrow$ PG 1159 is the slightly different chemical composition found for the two analyzed [WCE] stars (carbon-to-helium $\approx$ 1:2) compared to the ratio 1:1 found for the other types. The significance of this problem must be investigated further. Anyhow, special evolutionary scenarios must be employed in order to explain the peculiar chemical compositions observed in the atmospheres of these stars.

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