Wolf-Rayet stars of high and low mass

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Abstract. The quantitative analysis of Wolf-Rayet type spectra requires non-LTE models for expanding atmospheres which are available now. They were extensively applied to study the "classical", massive Wolf-Rayet stars of Population I. The obtained results are briefly reviewed and discussed. Wolf-Rayet type spectra are also shown by a subgroup of central stars of planetary nebulae. Recent spectral analyses of these low-mass stars yielded their parameters and atmospheric abundances, providing the empirical basis for discussing their evolutionary status. Hydrogen deficiency and strong mass-loss are the common features of both, high- and low-mass stars showing Wolf-Rayet type spectra.

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 ($10^{4.5}...10^{6} L_{\odot}$) 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.

The WN spectra are arranged in a subtype sequence (Smith 1968) according to the degree of ionization of nitrogen as reflected by the ratios between the strength of characteristic emission lines. Subtypes WN2 to WN6 are called "early" (WNE), while WN7 to WN9 are "late" (WNL). For WNE stars it is useful to distinguish between spectra with strong (WNE-s) and weak (WNE-w) emission lines. Analogously, Wolf-Rayet spectra of the carbon subclass form a subtype sequence from WC2 to WC12, depending on 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). Following HCLS we type the spectral classification of central stars in brackets.

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 explicitly treated line transitions. These models have been used extensively to analyze Pop. I WR stars (cf. Sect. 2), and a number of WR-type central stars (cf. Sect. 3).

Although the *standard model* can explain the observed Wolf-Rayet spectra in general, there is increasing evidence for its limitations. E.g. some observed spectra show lines from three or even four different ionization stages of the same element, while the model spectra can only reproduce two subsequent ionization stages simultaneously. Time variations in line profiles, and the emission of X-rays are other phenomena which are not explained by the *standard model.* Probably the assumptions of stationarity and homogeneity are violated to some degree, and the stellar wind is actually structured with clumps and shocks.

2. Wolf-Rayet stars of high mass

The Sixth Galactic WR Catalogue (by HCLS, updated by van der Hucht *et al.* 1988) comprises about 140 Wolf-Rayet stars, when leaving aside binaries with luminous companions (i.e. with composite spectra). An uniform atlas of WC spectra has been published by Torres & Massey (1987), while an almost complete set of WN spectra is made accessible by Hamann *et al.* (1995b). Almost all of the Galactic WN stars have been analyzed quantitatively by comparing their spectra with *standard model* calculations (cf. Hamann *et al.* 1995a, and references therein). For the determination of their atmospheric parameters helium-hydrogen models are sufficient in general, but more elaborate analyses accounting for nitrogen, carbon *etc.* were performed for a couple of objects as well.

A purely spectroscopic parameter that can be obtained from a spectral analysis of an expanding atmosphere is the "transformed radius" R_t which we define by

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

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 order to establish the stellar radius, mass-loss rate and luminosity, additional knowledge of the distance (or, equivalently, the absolute visual brightness or another absolute quantity) is prerequisite. Fortunately, for many of the Galactic WN stars their distance is known from their membership in open clusters or associations. For the rest of them suitable calibrations can be suggested. Thus an empirical HRD of the WN stars can be constructed (Fig. 1).

The WNL stars arrange themselves in a vertical strip at 30 ... 35 kK, which is continued towards lower luminosities by the WNE-w subclass. However, the few WNE-w stars of earliest subtype (cf. WR 3 and WR 46, subtype WN3-w) form their own class at very high temperatures. The WNE-s stars populate a wide temperature range from 50 ... 90 kK and intermediate luminosities.

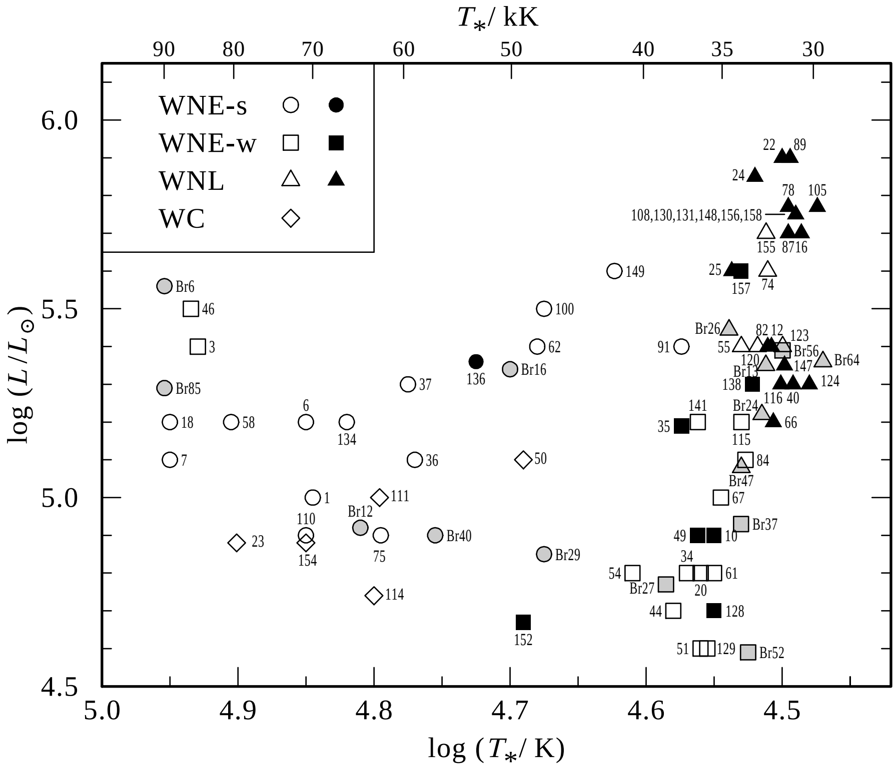

Figure 1. Empirical Hertzsprung-Russel diagram of Pop. I Wolf-Rayet stars. The effective temperature T_* chosen for the abscissa refers to the core radius (cf. Hamann 1994). Different subclasses are distinguished by different symbol shapes (see inlet). Filled symbols indicate WN stars with detectable hydrogen, while open symbols stand for hydrogen-free atmospheres. The Galactic stars are identified by their WR number (HCLS catalogue). Additionally, WN stars from the LMC (identified by "Br" numbers according to Breysacher 1981) are represented by shaded symbols because their hydrogen abundance has not yet been determined.

A couple of WN stars in the LMC has been analyzed with pure-helium models (Koesterke *et al.* 1991). Their distribution in the HRD is not obviously different from the Galactic WNs. Especially, they are not more luminous on the average – contrary to the prediction of standard evolutionary calculations.

25 Galactic WC stars of intermediate subtype (WC5 ... WC7) were analyzed by Koesterke & Hamann (1995a) using helium-carbon models. Only a subset of these stars can be included in the HRD (Fig. 1), because the others have unknown distance and a reliable calibration of their absolute brightness is not obvious. The shown WC stars have similar temperatures as WNE-s stars, but are significantly less luminous.

Abundance determinations confirmed that all WN stars are hydrogen-deficient (Hamann *et al.* 1995a). In fact, 53% (33 out of 62 studied stars) are even free of hydrogen within the detection limits. The occurrence of hydrogen

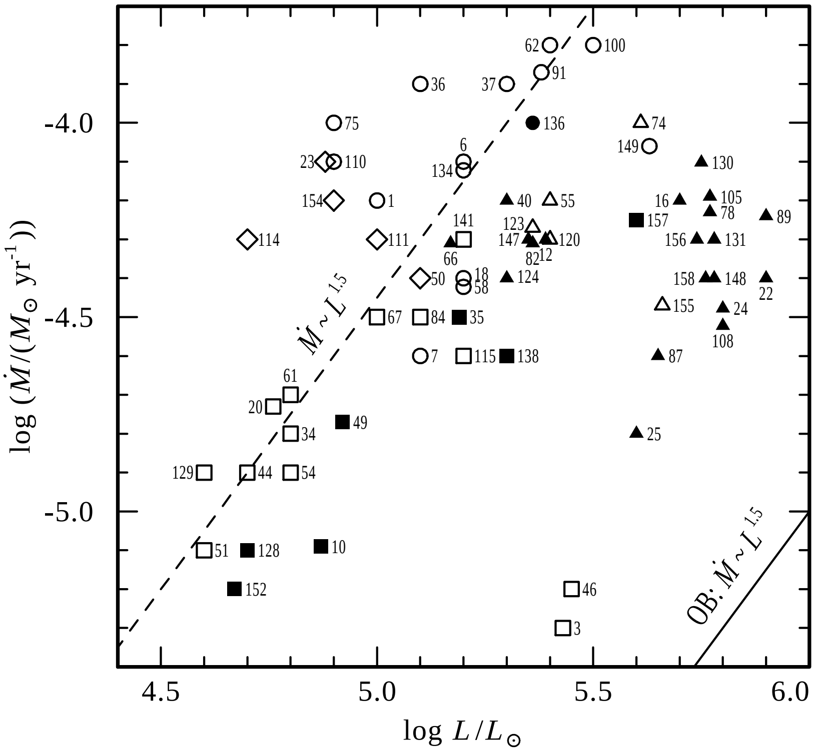

Figure 2. Mass-loss rates of Galactic WR stars versus luminosity. The individual stars are labeled by their WR number. Triangles, squares and circles refer to WNL, WNE-w and WNE-s stars, respectively. Five WC stars with well-established data are also represented (diamonds). Filled and open symbols indicate whether hydrogen is detectable or absent, respectively. The dashed line gives a tentative fit to the mass-loss rates of *hydrogen-free* WN stars, while those WN stars *with hydrogen* lie to the lower-right of that relation. The corresponding relation for OB stars is indicated at the lower-right corner. (After Hamann *et al.* 1995a)

is restricted to those WN stars with lowest stellar temperatures (30 ... 38 kK, with two exceptions), comprising most WNL stars and part of the WNE-w subgroup (filled symbols in Fig. 1). For those WN stars showing hydrogen the typical abundance ranges between 10% and 30% (hydrogen mass fraction). A small group of four WN7 stars (WR 22, 24, 25, 87) with very high luminosity ($> 10^{5.6} L_\odot$) has outstandingly high hydrogen mass fractions (40 ... 53%).

The mass-loss rates of the *hydrogen-free* WN stars and the WC stars follow a tentative relation $\dot{M} \propto L^{1.5}$ (cf. Fig. 2). The corresponding relation established for OB stars has the same slope, but $\dot{M}$ is lower by a factor of 100, roughly, grazing only the lower right corner of Fig. 2. Most remarkably, those WN stars with some atmospheric hydrogen are lying between the $\dot{M}$-L-relation for hydrogen-free WR stars and for the OB stars with their (more or less) normal surface composition. Even quantitatively, those WN stars with highest hydrogen mass fractions approach closest to the OB relation. Note that the two analyzed WN3 stars – WR 3 and WR 46 – form again a separate group in this Fig. 2. Mass-loss rates from WC stars gather above the dashed relation.

The clear empirical correlation between hydrogen deficiency and mass-loss rate might provide a key to understand the mass-loss mechanisms theoretically. Either, the chemical compositions directly affects the driving mechanism (radiation pressure? pulsational instabilities?), or mass-loss rate and surface abundances change synchronously in the course of stellar evolution (e.g. caused by changing surface gravity or pulsational properties).

Standard evolutionary theory for very massive stars can in principle explain the formation of Wolf-Rayet stars when mass-loss is accounted for. However, the theoretical calculations (e.g. Schaller *et al.* 1992) are in conflict with various empirical facts. In particular, the standard tracks cannot produce those many WN stars with relatively low luminosities, fail generally to explain the observed hydrogen-helium abundances in O, Of, LBV and WN stars, and yield hydrostatic stellar radii drastically smaller than the observed photospheric radii of WR stars. Furthermore, stellar models along parts of the standard tracks have been found to be pulsationally unstable. These arguments motivated Langer *et al.* (1994) to present a new evolutionary scenario relating O stars, LBVs and Wolf-Rayet stars, based on the assumptions of strong mass-loss in phases of pulsational instability. The presented track for a star of initially $60\,M_\odot$ can better account for some observational facts that the standard calculations. However, modelling the evolution of massive stars consistently to the observation obviously needs new physical input, most likely concerning internal mixing processes.

3. Wolf-Rayet stars of low mass

Among the central stars of planetary nebulae (CPN) a considerable fraction exhibits emission line spectra of Wolf-Rayet type, more definitely of type [WC]. The compilation by Tylenda *et al.* (1993) lists some 23 CPN with early-type (i.e. [WCE]) spectra. If definitely classified, they are all of [WC3] or [WC4] subtype, while [WC5], [WC6] and [WC7] are missing. Eleven late-type (i.e. [WCL]) central stars are identified in the quoted list, their subtypes ranging from [WC8] to [WC11].

In comparison, the subtype distribution of Pop. I WC stars is completely different. Among the 70 Galactic WC stars in HCLS there are only six stars of subtype WC4 or earlier, while the bulk is WC5 to WC9, and the latest subtype is WC10 with only one member. The subtypes [WC11] and [WC12] had to be defined exclusively for central stars.

Are Population I WC-spectra principally different from the spectra of [WC] central stars? Some of the spectral subtypes occur only in the one or in the other group. For instance, among the spectra of the few earliest Pop. I WC stars (WO1, WO2, WC4) we find no close counterparts to the earliest [WCE] representatives. But for spectral subtypes which are found in both object classes, very similar spectra can be encountered. This is demonstrated in Fig. 3.

Thus it seems that [WC] spectra do not differ in principle from WC 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 repre-

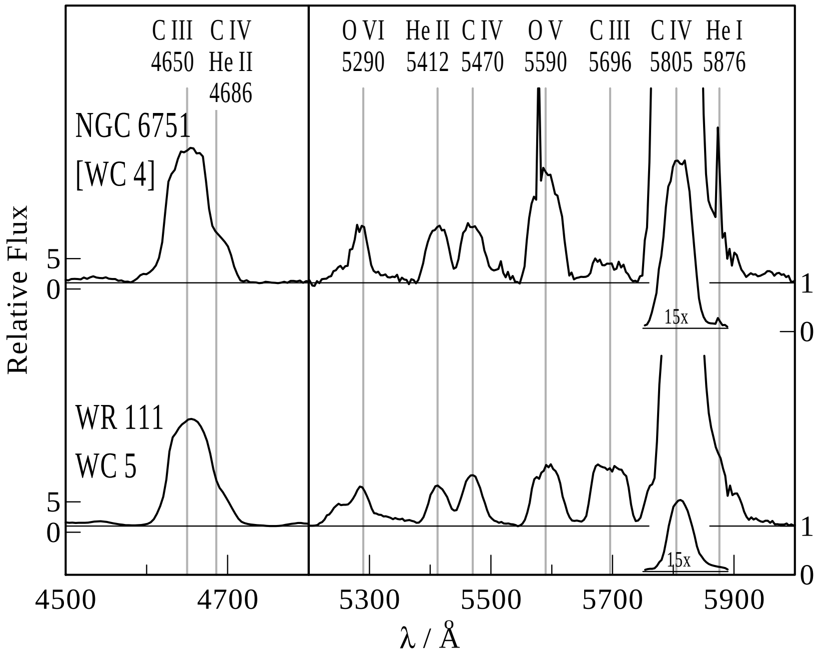

Figure 3. Spectrum of the WC5 prototype WC 111 (Pop. I), compared with the spectrum of the central star NGC 6751 ([WC4]). Despite of the slightly different subtype (reflected by the strength of the C III 5696Å line), both spectra look rather similar. Note that the sharp emissions in the CPN spectrum are of nebular origin.

sentatives of these two object classes populate different regions in the space of atmospheric parameters which have only partial overlap.

An example for these analyses is illustrated in Fig. 4. With the suitable choice of the model parameters most observed lines are well reproduced by the theoretical spectrum. As a peculiarity in this extremely hot [WC] star, the spectrum shows a couple of lines from ultra-high ionization stages (C V, C VI, O VII, O VIII). These ions can not be explained by any atmospheric models in radiative equilibrium and reasonable effective temperatures. Similar lines from ultra-high ions have been detected recently in the spectra of a few hot white dwarfs (Werner *et al.* 1995, Dreizler *et al.* 1995b).

3.1. Results from spectral analyses of [WC] stars

Representatives of the different [WCL] subtypes have been analyzed recently with *standard model* calculations by Leuenhagen & Hamann (1994 – V 348 Sgr) and Leuenhagen *et al.* (1996 – other [WCL]). The only two [WCE] stars analyzed so far are Sanduleak 3 (Koesterke & Hamann 1995b) and NGC 6751 (Hamann & Koesterke 1993). The results are compiled in Table 1.

Regarding the effective temperatures T_*, the [WCL] and [WCE] stars form a sequence correlated with the subtype number, starting with 20 kK ([WC12]) and reaching 140 kK for the [WC3] subtype. The terminal velocity of the stellar wind, v_∞, increases along that sequence almost monotonically. A further

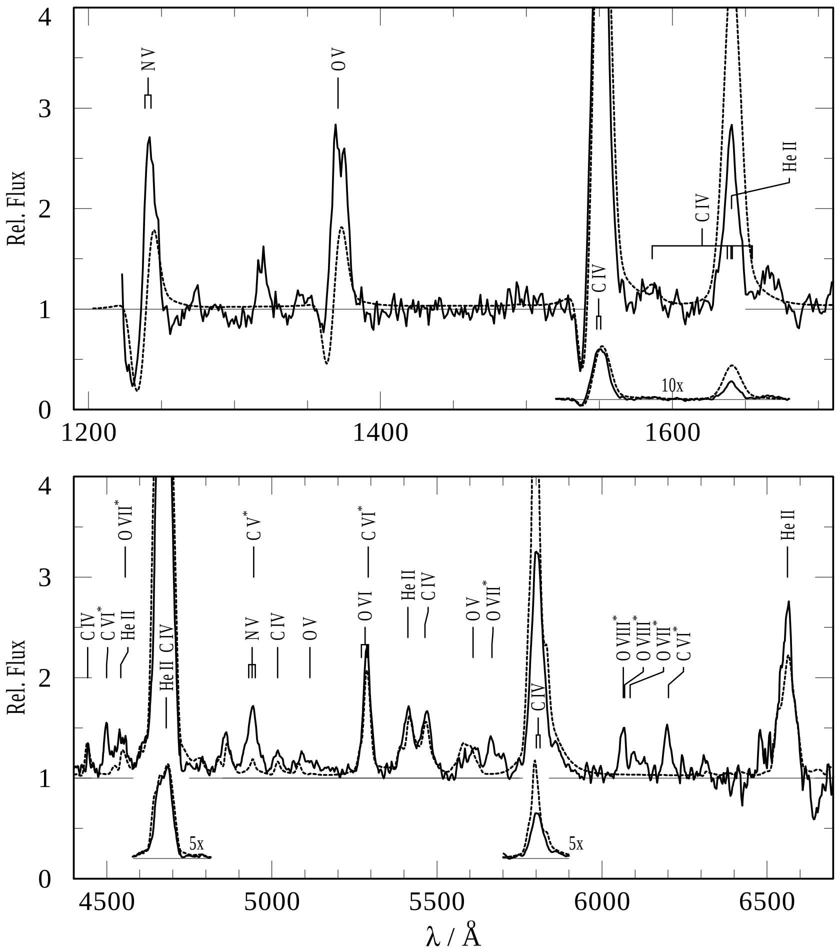

Figure 4. Spectral fit of Sanduleak 3. The theoretical spectrum (dashed; model parameters as given in Table 1) is compared with the observation (solid line). Line identifications marked with an asterisk refer to lines from ultra-high ionization stages (see text).

spectroscopic parameter for expanding stellar atmospheres is the "transformed radius" (cf. Sect. 2, Eq. 1). Figure 5 reveals that [WCL] and [WCE] stars populate a continuous strip when plotting $\log R_{\rm t}$ versus $\log T_*$, which for intermediate subtypes coincides with the Pop. I WC stars as analyzed by Koesterke & Hamann (1995a).

While the spectral analysis yields the quantity $R_{\rm t}$, one of the absolute parameters must be entered independently in order to determine the dimensions of the star (i.e. R_*, which then implies $\dot{M}$ and L). Fortunately the stellar distance 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 nebula). Otherwise $\log L/L_\odot = 3.7$ is assumed (for K 2-16, V 348 Sgr, NGC 6751, Sand 3) as favored from evolutionary arguments. The obtained mass-loss rates for the [WC] stars are of the order of $10^{-6} M_\odot\,{\rm yr}^{-1}$.

Table 1. Results of spectral analyses of [WC] 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. In the case of [WC]-PG 1159 type central stars static non-LTE models are applied for the photospheric (absorption) lines additionally. The data for Longmore 4 refer to the outburst state. The given abundances are to be complemented to 100 % by a corresponding nitrogen mass fraction (only studied yet for NGC 6751, Sanduleak 3, Abell 30, Abell 78). As a very puzzling exception, V 348 Sgr shows a significant trace of hydrogen in its atmosphere (4 % by mass).

	Sub-type	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} [%]
Late type:									
V 348 Sgr	[WC12]	20	190	3.7	6.0	-6.5	40	55	≤1
K 2-16	[WC11]	30	300	3.7	2.6	-6.4	45	50	5
He 2-113	[WC11]	30	200	4.5	6.5	-5.5	44	50	6
M 4-18	[WC11]	31	350	3.7	2.3	-6.0	46	50	4
CPD-56°8032	[WC11]	32	240	4.1	3.4	-5.6	42	50	8
BD+30°3639	[WC9]	47	700	4.7	3.3	-4.9	45	50	5
He 2-99	[WC9]	49	900	3.7	1.0	-5.6	50	40	10
NGC 40	[WC8]	78	1000	3.6	0.3	-5.6	40	50	10
MA 17 (LMC)	[WC7]	100	900	3.8	0.3	-5.8	60	25	15
Early type:									
NGC 6751	[WC4]	105	2000	3.7	0.22	-5.2	62	27	10
Sanduleak 3	[WC3]	140	2200	3.7	0.12	-6.2	62	26	12
[WC]-PG 1159 type:									
Abell 30		115	4000	3.7	0.18	-7.2	41	40	15
Abell 78		115	3750	3.7	0.18	-7.4	33	50	15
Longmore 4		120	4000	3.7	0.16	-7.3	46	43	11

About equal mass fractions of carbon and helium constitute the atmospheres of the [WCL] stars, while in the two [WCE] stars the carbon-to-helium ratio seems to be smaller, which is a somewhat disturbing result. Oxygen contributes a mass fraction of about 10%, increasing with the stellar temperature. Very puzzling is the detection of hydrogen (4 % by mass, Leuenhagen & Hamann 1994) in the atmosphere of in V 348 Sgr, which otherwise shows the products of helium burning. The possible detection of ≈ 7% 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. Leuenhagen *et al.* 1996).

3.2. 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

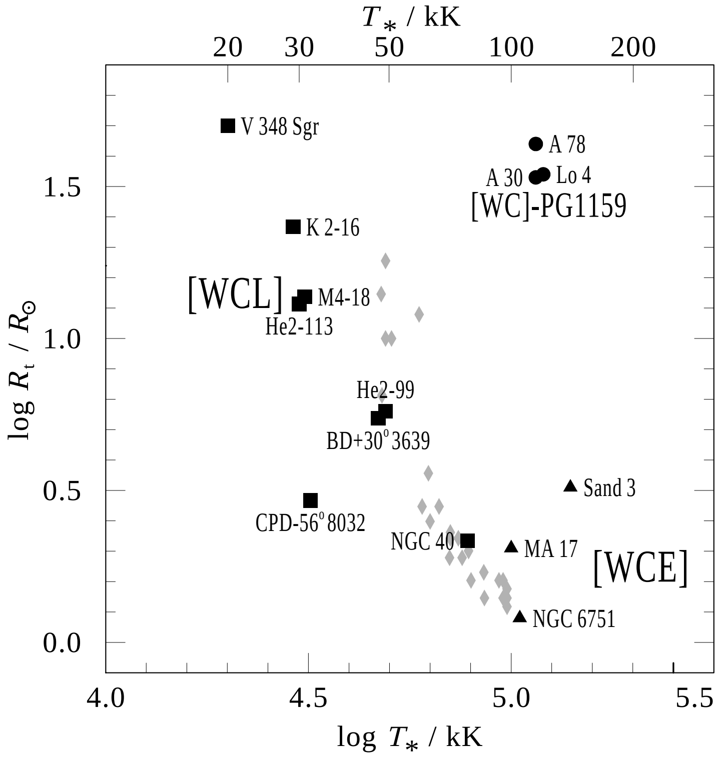

Figure 5. Central stars of Wolf-Rayet type in the $R_t - T_*$–diagram. [WCL], [WCE] and [WC]-PG 1159 subtypes are represented by squares, triangles and circles, respectively. Shaded diamonds indicate Pop. I WC stars of intermediate subtype (WC5 ... WC7) analyzed so far.

stars composed mainly of carbon, oxygen and helium (cf. Dreizler *et al.* 1995a). 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. 6. 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 (cf. Fig. 7).

Results from analyses of [WC]-PG 1159 stars are included in Table 1 (sources: Abell 30 – Leuenhagen *et al.* 1993; Abell 78 – Werner & Koesterke 1992; Longmore 4 – Werner *et al.* 1993). The few detectable wind lines were analyzed with 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 1 was consistently found with both methods. Note that the carbon-to-helium ratio is about unity (by mass) as found for the [WCL] subtypes, 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.

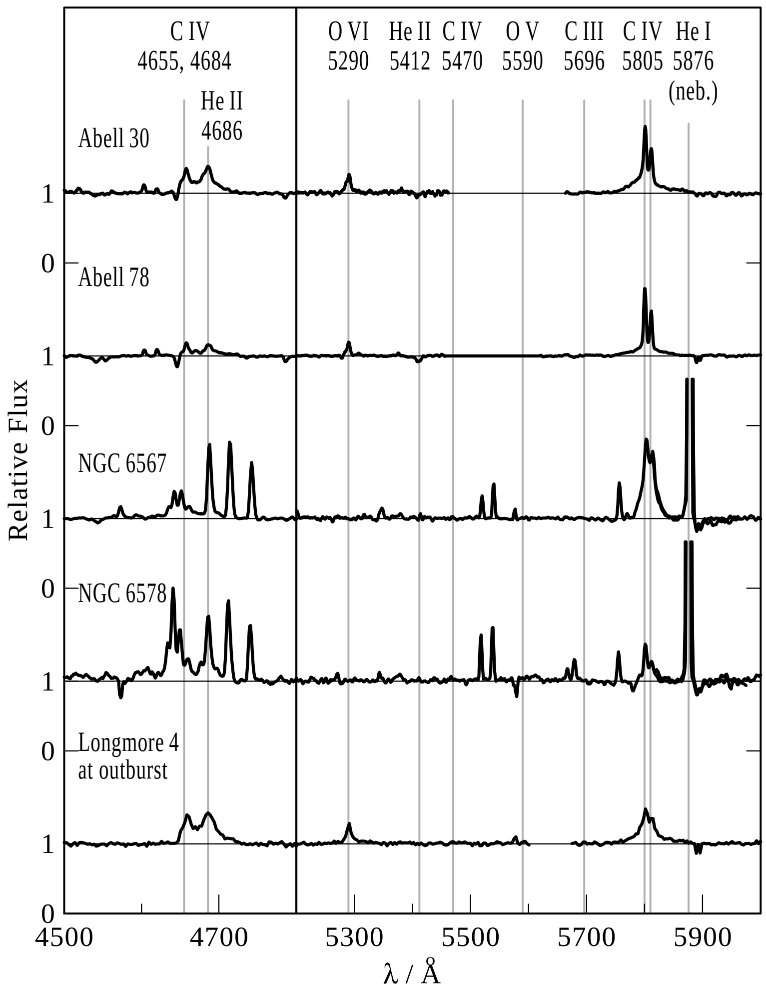

Figure 6. Observed spectra of [WC]-PG 1159 type central stars. NGC 6567 and NGC 6578 are contaminated by nebular emissions.

Thus the only obvious difference between [WC]-PG 1159 stars and PG 1159 stars concerns the strength of the mass-loss, and Longmore 4 demonstrates that this parameter can vary with time.

In Fig. 5, where $\log R_{\mathrm{t}}$ is plotted versus $\log T_*$ for all WC-type central stars analyzed so far, the group of [WC]-PG 1159 stars lies apart from the [WCL]-[WCE] strip, being as hot as [WCE] stars but with higher R_{t} (thinner wind). Sand 3 has an intermediate R_{t}.

3.3. Central stars of subclass [WN]?

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 nebulae, however, are always of the WC type when showing a Wolf-Rayet spectrum at all. The only exception known yet is the

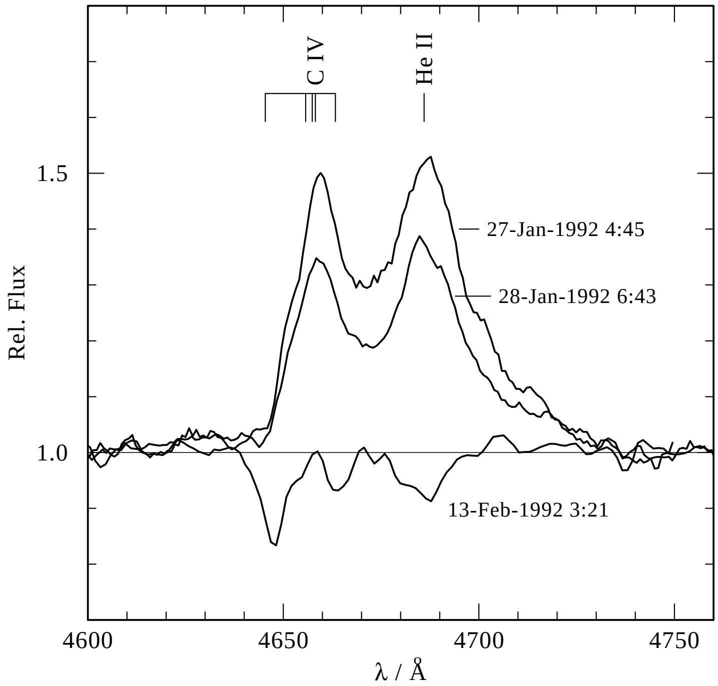

Figure 7. The spectacular outburst of Longmore 4: spectral change of the 4686 Å complex

LMC object N66. Even more peculiar, 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. 8). However, the lines of N66 are broader than in the Galactic comparison star (higher wind velocity). 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.

3.4. Evolutionary status

In order to visualize possible evolutionary connections we employ the $\log g - \log T_{\rm eff}$−diagram (Fig. 9). 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_* (Table 1) and assume a mass of $0.6\,M_\odot$. "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 contradic-

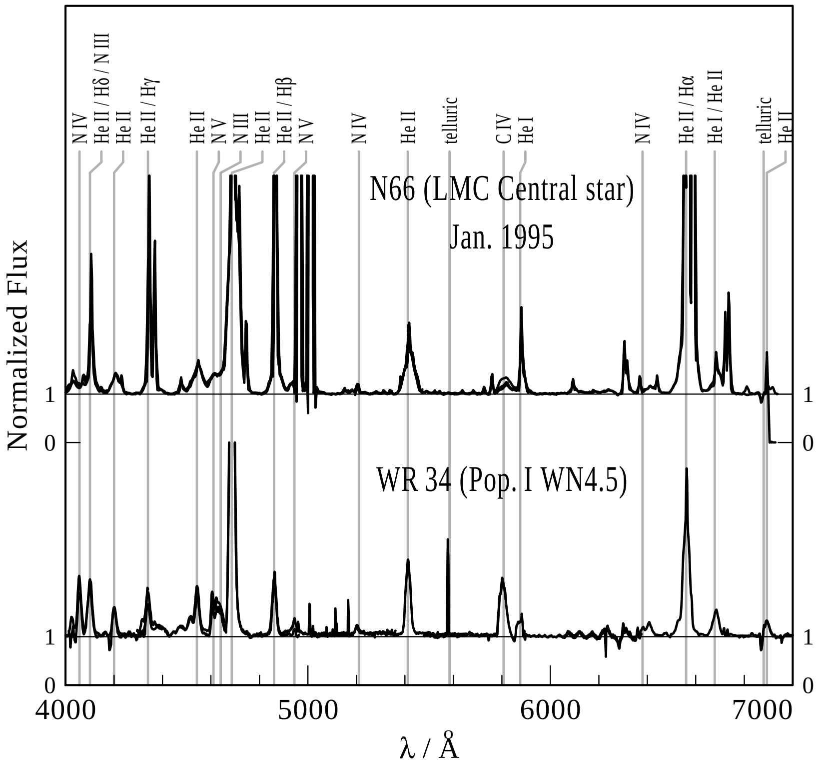

Figure 8. Spectrum of the central star N66 in the LMC as observed by us in January 1995, compared with the Galactic Pop. I Wolf-Rayet star WR 34 (spectral subtype WN4.5). The sharp emission lines in the N66 spectrum are of nebular origin.

tion 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.

4. Concluding remarks

Wolf-Rayet type spectra indicating strong mass-loss are shown not only by the “classical”, massive Wolf-Rayet stars of Population I, but also by a considerable fraction of central stars from planetary nebulae. In both object classes the atmospheric composition is hydrogen-deficient. Inversely, the occurrence of very strong mass-loss seems to be restricted to hydrogen-deficient stars.

Although ranging in different domains of luminosity and mass, both object classes with WR-type spectra result from stellar evolution with strong mass loss. Additionally, internal mixing processes which are not yet understood must be invoked in order to explain the observed surface abundances. Pulsational

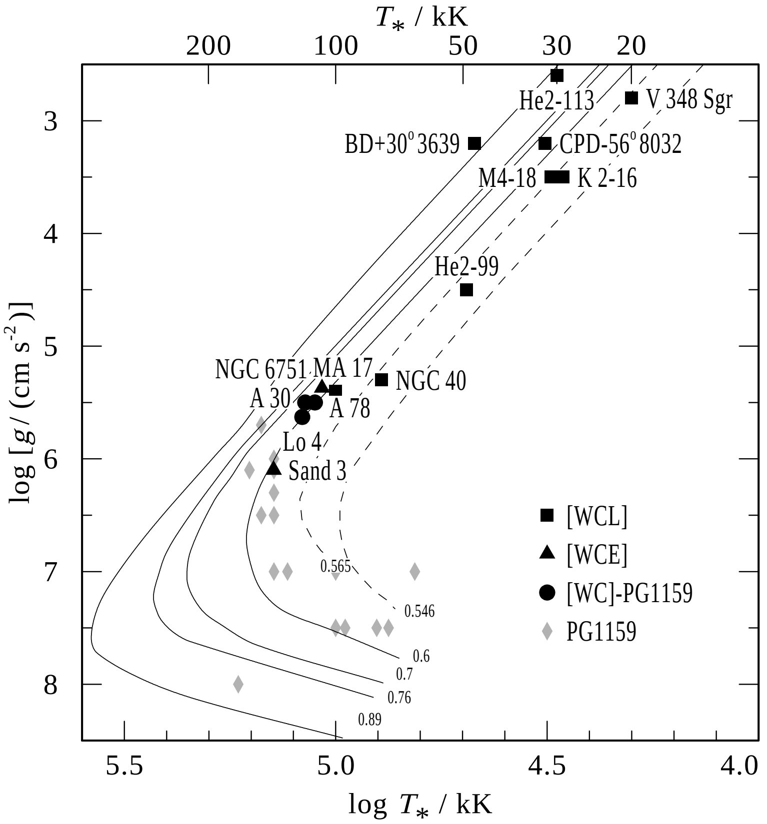

Figure 9. Central stars of Wolf-Rayet type in the $\log g$-$\log T_*$-diagram. [WCL], [WCE] and [WC]-PG 1159 subtypes are represented by squares, triangles and circles, respectively. Shaded diamonds indicate "normal" PG 1159 stars without strong mass-loss (after Dreizler *et al.* 1995a). The tracks for post-AGB evolution taken from Schönberner (1983) or Wood & Faulkner (1986) (labels: mass in $M_\odot$) are only shown for a rough comparison; they are not really adequate for the considered objects, as they predict normal surface abundances.

instabilities might play a role for the mass-loss mechanism, additionally to the well-known radiation driving.

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