SPECTRAL ANALYSES OF WR-TYPE CENTRAL STARS OF PLANETARY NEBULAE

L. KOESTERKE
Institut für Physik, Universität Potsdam, Germany

Abstract. So far, the evolution of post-AGB stars is not fully understood. In particular the formation of hydrogen-deficient and hydrogen-free Central Stars of Planetary Nebulae (CSPN) is unsettled. New evolution models, which allow for the consistent treatment of the physics of late thermal pulses, promise new insights to the formation of these stars. In this paper we summarize the results of non-LTE analyses of CSPN with wind. By comparing these results with the predictions of the new evolution models, open questions concerning the evolution of the stars might be answered. In addition we discuss the driving mechanism of the winds of Wolf-Rayet CSPN. New models, which account for millions of iron lines, support the assumptions that these winds are driven by radiation.

1. Introduction

The stellar evolution of AGB and post-AGB stars is still not fully understood. In particular the formation of hydrogen-deficient post-AGB stars was not sufficiently explained by stellar evolution theory. As one possible explanation the born-again scenario was proposed by Iben (1984) and Iben & Mac Donald (1995). A post-AGB star which has already evolved to a white dwarf suffers from a very late thermal pulse and is thrown back to the AGB regime. During this pulse, the hydrogen is mixed downwards and burned and a hydrogen-deficient or hydrogen-free post-AGB star is formed, respectively. Because of numerical difficulties, this pioneering work by Iben and co-workers was not based on fully consistent but rather on semi-analytic calculations.

Nowadays new numerical techniques were applied which allow for a consistent treatment of mixing and burning processes (Herwig, these proceedings; Blöcker, these proceedings). In contrast to other phases of stellar evolution, in which the time scales for mixing and burning processes are different by orders of magnitudes, these time scales are equal during the very late thermal pulse because protons from the surface are mixed downwards and are instantaneously burned in hot regions near the helium burning shell. Therefore the equations of mixing and burning have been solved simultaneously in a numerically expensive scheme.

In addition, it was found by Herwig et al. (1997) that an improved treatment of the convective boundary is also very important because it affects the chemical composition of the intershell (i.e. the layer between the hydrogen and helium burning zone). Motivated by hydrodynamical models for convection (Freytag et al. 1996), they included diffusive overshoot at the boundaries of the convection zones in AGB and post-AGB stars. Note that after a late thermal pulse this intershell becomes visible at the surface.

From the first models three different scenarios have been derived. The models as well as the scenarios are well described in Herwig (these proceedings) and Blöcker (these proceedings).

LTP Late Thermal Pulse : The thermal pulse occurs while the star has already left the AGB and hydrogen burning is still going on. The star is approximately located in the regime of the Central Stars of Planetary Nebulae (CSPN). During the pulse the hydrogen at the surface remains unchanged and no convective hydrogen burning takes place. By dredge-up during the 2^{nd} AGB phase, hydrogen at the surface is decreased down to a very few percent by mass.

VLTP Very Late Thermal Pulse : This scenario is similar to the LTP but the star has already turned around the knee (in the HRD) and entered the white dwarf cooling sequence. The hydrogen burning has already ceased. During the pulse the hydrogen at the surface is efficiently mixed downwards into hot regions and a hydrogen free star is formed by convective hydrogen burning. As in the first case the star is thrown back to the AGB. This scenario is nearest to the born-again scenario proposed by Iben and co-workers and provides almost perfect hydrogen free precursors of non-DA white dwarfs.

AFTP Asymptotic giant branch Final Thermal Pulse : This is like an ordinary thermal pulse at the AGB but with a particular small envelope mass. As in the first case, the hydrogen burning ceases and the hydrogen is mixed (but not burned) with the intershell. The remaining hydrogen abundance is relatively high.

Hydrogen-deficient stars are formed by all of these scenarios but the stars have different properties. In particular from the abundances of hydrogen, helium, carbon and oxygen it might be possible to distinguish whether a star was formed by a LTP, VLTP or AFTP. Therefore we review results of non-LTE analyses of hydrogen deficient CSPN with wind signatures (Sect. 2). A brief overview of related objects (RCrB, extreme He-B-stars, He-sdO and O(He) is given in Werner (these proceedings, his Table 1). A short list of open questions on the evolution of hydrogen-deficient post-AGB stars is presented in Sect. 3. In Sect. 4 a discussion of the driving mechanism of the mass-loss is given.

2. Spectral analyses of hydrogen-deficient CSPNe with wind

In the recent years a large number of CSPN of [WC]-type and related objects have been analyzed by means of sophisticated non-LTE models. Two similar types of models have been applied. De Marco used the code of John Hillier (1990) to investigate three late-type [WC] central stars (De Marco & Crowther 1998, De Marco et al. 1997, De Marco & Crowther 1999). The second code from the Potsdam group was applied to larger samples of late-type (Leuenhagen et al. 1996, Leuenhagen & Hamann 1998) and early-type [WC] central stars (Koesterke & Hamann 1997a,b). In addition, the latter group investigated the mass-loss of four PG 1159 stars (Koesterke et al. 1998, Koesterke & Werner 1999). In the next sections the models are briefly introduced (Sect. 2.1)and complemented by overviews on the analyses of the different groups (sects. 2.2 to 2.5).

2.1. NON-LTE MODELS

Models of John Hillier and the Potsdam group have been applied to CSPNe. Both types of models are based on the so-called standard model for Wolf-Rayet (WR) stars. The atmospheres are assumed to be spherically symmetric and homogeneous. Due to the unsolved driving mechanism of the wind the velocity law is taken *ad hoc*, usually in the form of the β-law with β=1. Five parameters describe such a model: the stellar temperature T_*, the radius of the core R_*, the mass-loss rate $\dot{M}$, the terminal velocity v_∞ and the abundances by mass β_i. The set of parameters can be reduced by introducing the transformed radius

$$R_\mathrm{t} = R_* \left[\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \bigg/ \frac{\dot{M}\sqrt{D}}{10^{-4}\,M_\odot\,\mathrm{yr}^{-1}} \right]^{2/3} \quad ,$$

which can be understood as the wind density of the model. The smaller R_t the larger the wind density. Note that in this formula also the clumping factor D is introduced (Hamann 1998), which was set to unity in all studies described here.

2.2. [WC]-CSPN (LATE-TYPE)

TABLE 1. Analyses of late-type [WC]-CSPN: Stellar parameters. Entries in columns 3 to 5 are distance independent while entries in columns 6 to 8 depend on the distance.

Star	type	T_* [kK]	R_t [$R_\odot$]	v_∞ [km/s]	R_* [$R_\odot$]	log L [$L_\odot$]	log $\dot{M}$ [$M_\odot/yr$]	ref.
NGC 40	[WC 8]	78	2.16	1000	0.33	3.58	-5.62	5
He 2-459	[WC 8]	77	2.15	1000	0.84	4.37	-5.01	6
M 2-43	[WC 8]	65	4.04	850	0.32	3.24	-6.08	6
He 2-99	[WC 9]	49	5.76	900	0.97	3.72	-5.59	5
BD+30°3639	[WC 9]	47	5.46	700	3.32	4.71	-4.87	5
SwSt 1	[WC 9]	35	25.9	400	1.03	3.27	-6.90	6
PM 1-188	[WC 11]	35	7.07	360	1.88	3.70	-5.70	6
CPD-56°8032	[WC 11]	32	7.92	240	3.40	4.06	-5.57	5
— " —	[WC 11]	34.5	3.45	225	2.0	3.72	-5.4	1
M 4-18	[WC 11]	31	13.7	350	2.30	3.67	-6.01	5
— " —	[WC 11]	31	8.27	160	2.4	3.72	-6.0	3
He 2-113	[WC 11]	30	13.0	200	6.49	4.51	-5.54	5
— " —	[WC 11]	31.2	10.0	160	2.5	3.72	-6.1	1
K 2-16	[WC 11]	30	20.9	300	2.56	3.70	-6.36	5
IRAS 21282	[WC 11]	28	52.0	180	<3.12	<3.75	<-6.98	6
V 348 Sgr	[WC 12]	20	50.0	190	5.75	3.70	-6.53	4,5

1: De Marco & Crowther 1998
2: De Marco et al. 1997
3: De Marco & Crowther 1999
4: Leuenhagen & Hamann 1994
5: Leuenhagen et al. 1996
6: Leuenhagen & Hamann 1998

The spectral analyses of late-[WC] stars started in 1994 by Leuenhagen & Hamann (1994). They investigated V 348 Sgr and found a relatively high amount of hydrogen (about 0.04 by mass). This pioneering work was followed by two papers (Leuenhagen et al. 1996, Leuenhagen & Hamann 1998) on larger samples. Again they claimed that they definitely found hydrogen in some of the stars. The other group, led by De Marco, concentrated on three late-[WC] CSPN (De Marco et al. 1997, De Marco & Crowther 1998, De Marco & Crowther 1998). In contrast to the work of Leuenhagen and co-workers, they found significantly lower hydrogen abundances (cf. Table 2).

Due to two reasons the determination of the hydrogen abundance is generally difficult in Wolf-Rayet central stars. The separation of about 123 km/s of He II lines and the corresponding H I lines is smaller than the line width due to the high terminal velocity (200 - 1000 km/s) and therefore hydrogen lines are always blended with He II lines. The second point is that the embedding nebula also shows H I emission lines. These

TABLE 2. Analyses of late-type [WC]-CSPN: Abundances. Uncertain values are marked by colons.

Star	type	β_{H}	β_{He}	β_{C}	β_{N}	β_{O}	β_{Ne}	β_{Si}	ref.
		mass fraction							
NGC 40	[WC 8]	$\leq$2	40	50		10			5
He 2-459	[WC 8]	$\leq$2:	40	50		10			6
M 2-43	[WC 8]	$\leq$2:	40	50		10			6
He 2-99	[WC 9]	$\leq$2	50	40		10			5
BD+30°3639	[WC 9]	$\leq$7:	45	50		5			5
SwSt 1	[WC 9]	$\leq$10:	44	53	<0.5	3	2-4	$\approx$1	6
PM 1-188	[WC 11]	1	42	50	1	7	2-4	2-3	6
CPD-56°8032	[WC 11]	$\leq$0.5	42	50	<0.1	8		0.5-1	5,6
— " —	[WC 11]	0	34	52		14			1
M 4-18	[WC 11]	$\leq$10:	46	50	<0.5	4		0.5-1	5,6
— " —	[WC 11]	$\leq$4	31	56		13			3
He 2-113	[WC 11]	$\leq$7	44	50	0.5	6		0.5-1	5,6
— " —	[WC 11]	0	34	54		13			1
K 2-16	[WC 11]	$\leq$1	45	50	1	5	>4	0.5-1	5,6
IRAS 21282	[WC 11]	10	43	46	<0.5	1		<0.1	6
V 348 Sgr	[WC 12]	4	40	55	0.5-1	$\leq$1	2	< 0.1	4,5,6

1: De Marco & Crowther 1998 2: De Marco et al. 1997
3: De Marco & Crowther 1999 4: Leuenhagen & Hamann 1994
5: Leuenhagen et al. 1996 6: Leuenhagen & Hamann 1998

emissions cannot be removed completely by the data reduction and large errors are induced. Leuenhagen et al. (1998) fitted the Hα line wings by models with varied hydrogen abundance to the observations. The line core, which is contaminated by the nebula emission, is fitted by a Gaussian of the observed peak height with a widths comparable to the resolution of the observation. This technique remains doubtful because observations with good spectral resolution *and* good S/N ratio are required and because the point spread function of the spectrograph might also induce line wings due to the high contrast of nebula line flux and stellar continuum flux.

2.3. [WC]-CSPN (EARLY-TYPE)

Early-type [WC] stars have been investigated by Koesterke & Hamann in 1997 (1997a,b). They presented models for Sand 3 and NGC 6751 and added later the analyses of 10 [WCE] stars. The fit quality is satisfactory (cf. Fig. 1) for all of these stars except for NGC 6751 which shows C III emission at 5696 Å. The models failed to reproduce this line together with

TABLE 3. Analyses of early-type [WC]-CSPN: Stellar parameters. Entries in columns 3 to 5 are distance independent while entries in columns 6 to 8 depend on the distance. Abundances of C, N and O are given in mass-fraction while the rest is contributed by helium. In contrast to the analyses of the [WCL] stars, no individual distances have been applied but a uniform luminosity of $\log L/\mathrm{L}_\odot$=-3.7 has been assumed. Uncertain values are marked by colons.

Name	Type	T_* [kK]	R_t [$\mathrm{R}_\odot$]	v_∞ [km/s]	R_* [$\mathrm{R}_\odot$]	$\log L$ [$\mathrm{L}_\odot$]	$\log \dot{M}$ [$\mathrm{M}_\odot$/yr]	β_C mass fraction	β_O	β_N
NGC 5189	[WC 2]	135.0	5.0	3000	0.13	3.7	-6.30	0.16	0.08	0.003
PB 6	[WC 2]	140.0	4.5	3000	0.12	3.7	-6.28	0.24	0.14	0.003
NGC 2452	[WC 2]	141.0	4.0	3000	0.12	3.7	-6.20	0.15	0.07	0:
NGC 2867	[WC 2]	141.0	4.0	1800	0.12	3.7	-6.24	0.25	0.09	0:
NGC 6905	[WC 2-3]	141.0	3.4	1800	0.12	3.7	-6.32	0.25	0.15	0
NGC 7026	[WC 3]	130.5	6.3	3500	0.14	3.7	-6.34	0.20	0.10	0:
He 2-55	[WC 3]	128.0	5.2	3000	0.15	3.7	-6.25	0.15	0.06	0:
Sand 3	[WC 3]	140.0	3.0	2200	0.12	3.7	-6.15	0.26	0.12	0.005
IC 1747	[WC 4]	126.0	6.3	1800	0.15	3.7	-6.58	0.25	0.06	0
NGC 1501	[WC 4]	134.5	3.5	1800	0.13	3.7	-6.28	0.35	0.15	0
NGC 6369	[WC 4]	150.0	1.8	1200	0.11	3.7	-6.15	0.30	0.14	+:

high excited O VI lines and the star is consequently omitted in the following presentation (Table 3). In these stars hydrogen is hard to detect since hydrogen is fully ionized over the whole atmosphere and recombination processes are suppressed. An amount of 10% by mass would not affect the emergent spectrum.

As shown in Fig. 1, many of the [WCE]-CSPN show lines of very high excited ions like C V, C VI and O VII. This was reported first by Barlow et al. (1980) for Sand 3. The phenomenon is also known for many PG 1159 stars (Werner 1994) and hot white dwarfs (Werner et al. 1995, Dreizler 1995a). From the high ionization potential of these ions it is clear that they cannot be populated in atmospheres with temperatures as low as 140 kK. Temperatures of at least 500 to 700 kK would be necessary. So one might speculate that lines of these high excited ions are formed in shock-heated regions of the atmospheres of the stars. Due to the lack of consistent hydro-models the hypothesis cannot not be judged in the foreseeable future.

2.4. TRANSITION OBJECTS ([WC]-PG 1159)

Among the hydrogen-deficient post-AGB stars there are three objects which are supposed to be the evolutionary link between the [WCE]-type CSPN and the PG 1159 stars. They show clear signatures of stellar winds in the UV but resemble in the optical the PG 1159 stars and are consequently

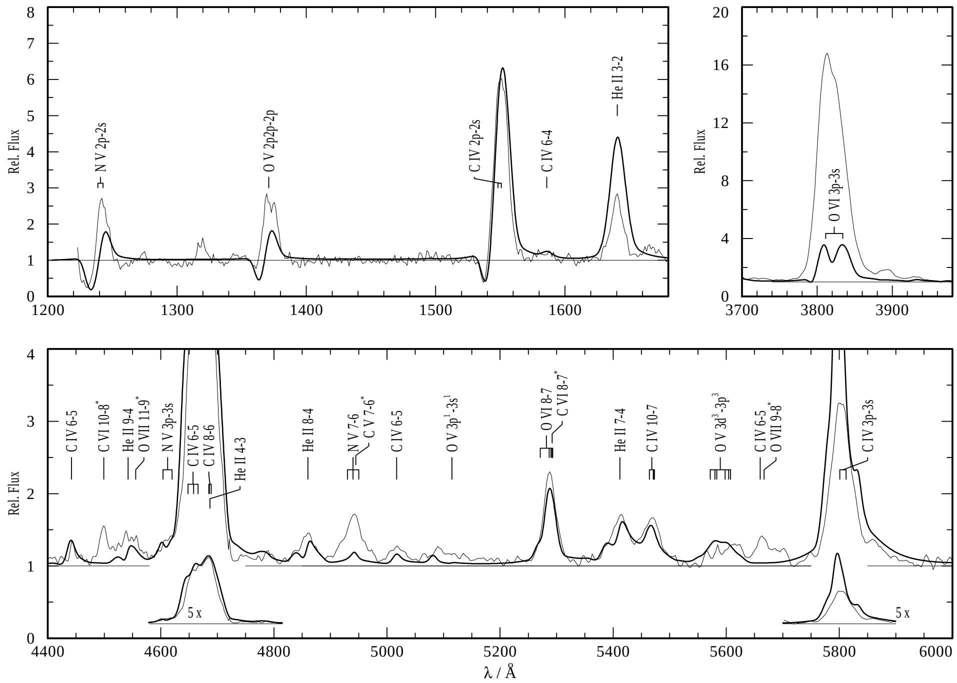

Figure 1. Fit of Sand 3. The observation (thin lines) is shown together with the synthetic spectrum (thick lines). The fit parameters are $T_* = 140\,\mathrm{kK}$, $R_\mathrm{t} = 3.01\,R_\odot$, $R_* = 0.12\,R_\odot$, $\log(\dot{M}/(M_\odot \mathrm{yr}^{-1})) = -6.15$, $v_\infty = 2200\,\mathrm{km/s}$, $\beta_\mathrm{C} = 0.26$, $\beta_\mathrm{O} = 0.12$ and $\beta_\mathrm{N} = 0.005$ (the rest is contributed by helium). Except the strong O VI doublet at 3820 Å, the synthetic spectrum does fairly agree with the observation. Note that the lines from very high excited ions like C V, C VI and O VII (marked with an asterisk) are not formed in the photosphere and cannot be reproduced by the model.

TABLE 4. Analyses of [WC]-PG 1159 stars: Stellar parameters. Entries in columns 2 to 4 are distance independent while entries in columns 5 to 7 depend on the distance. Abundances of C, N and O are given in mass-fraction while the rest is contributed by helium. No individual distances have been applied but a uniform luminosity of $\log L/\mathrm{L}_\odot$=-3.7 has been assumed.

Name	T_* [kK]	R_t [R$_\odot$]	v_∞ [km/s]	R_* [R$_\odot$]	$\log L$ [L$_\odot$]	$\log \dot{M}$ [M$_\odot$/yr]	β_C mass fraction	β_O	β_N
Abell 30	115	34.7	4000	0.16	3.7	-7.3	40	15	4
Abell 78	115	45.2	3750	0.16	3.7	-7.5	50	15	2
Longmore 4	120	34.7	4000	0.16	3.7	-7.3	43	11	

classified as [WC]-PG 1159 objects. Two of the stars (Abell 78 and Abell 30) have been analyzed by Werner & Koesterke (1992) and Leuenhagen et al.

(1993). They combined static models from Werner and co-workers for the absorption features in the optical and models for expanding atmospheres, as described in Sect. 2.1, for the P Cygni profiles in the UV. The third one, Longmore 4, had an outburst in 1992 and its spectral appearance was similar to Abell 78 and Abell 30 during this time. The stellar parameters have been determined by Werner et al. (1992). A compilation of the results is given in Table 4.

2.5. PG 1159 STARS

TABLE 5. Analyses of PG 1159 stars: Stellar parameters. Data taken from Koesterke et al. (1998) and Koesterke & Werner (1998). The transformed radii are derived from mass-loss rates given in column 8. The classification (column 2) refers to low-gravity (lg) PG 1159 stars with emission lines (E) and occasionally with hydrogen (H). Uncertain values are marked by colons.

Star	type	T_* [kK]	R_t [$R_\odot$]	v_∞ [km/s]	R_* [$R_\odot$]	log L [$L_\odot$]	log $\dot{M}^a$ [$M_\odot/yr$]	log $\dot{M}^b$ [$M_\odot/yr$]
NGC 7094	lgEH	110	34.6	3500	0.17	3.6	-7.3	-7.7:
K 1-16	lgE	140	37.0	4000	0.11	3.6	-7.6	-8.1:
NGC 246	lgE	150	20.1	3500	0.19	4.2	-6.9	-6.9:
RXJ2117.1+3412	lgE	170	18.3	3500	0.15	4.2	-7.0	-7.4:

[a] Mass-loss rate from C IV resonance line
[b] Mass-loss rate from O VI resonance line

TABLE 6. Analyses of PG 1159 stars: Abundances. Data taken from Koesterke et al. (1998). Uncertain values are marked by colons.

Star	type	β_H	β_{He}	β_C	β_N	β_O
			mass fraction			
NGC 7094	lgEH	42:	51	5	<1	<1
K 1-16	lgE		38	56		6
NGC 246	lgE		64	30		6
RXJ2117.1+3412	lgE		33	50		17

In the recent years a large sample of PG 1159 stars has been analyzed by Werner and co-workers (Werner, these proceedings; Dreizler et al. 1995b). PG 1159 stars are found around the knee at the hot side of the HRD where the luminosity of the stars drops and the white dwarf cooling sequence starts. Some of the stars have a relatively large hydrogen abundance up to about 40% by mass. The group of PG 1159 stars can be divided into low-gravity and high-gravity objects. Stars of the former group have not turned around the knee yet. They still have high luminosities of about $\log(L/L_{\odot}) \approx 3.7$ and show wind signatures in the UV. Koesterke et al. (1998) and Koesterke & Werner (1998) have investigated the mass-loss rates and terminal velocities of four of these low-gravity objects. They applied the same technique as for the transition objects. The stellar parameters as T_*, R_*, $\log g$ and the chemical composition are derived by comparing optical absorption lines and static non-LTE models. Note that the spectroscopic detection of hydrogen in PG 1159 stars is as difficult as in [WCE] stars. Even for NGC 7094, which has a very high hydrogen abundance of about 0.42 by mass, the exact value remains uncertain. The wind parameters ($\dot{M}$ and v_∞) are derived from the P Cygni resonance lines of C IV and O VI. The results of these analyses are compiled in Tables 5 and 6.

3. Evolutionary status

Low and intermediate mass stars might evolve according to the following scheme: AGB $\rightarrow$ LTP/VLTP/AFTP $\rightarrow$ [WCL] $\rightarrow$ [WCE] $\rightarrow$ [WC]-PG 1159 $\rightarrow$ PG 1159$\rightarrow$ WD, but there are still many open questions left. Some of them are listed below:

- The analyses of [WCE] stars result in much lower C and O abundances than those of [WCL] and PG 1159 stars. Helium is the most abundant element in the atmospheres of [WCE] stars while the others are dominated by carbon. This is in clear contradiction to the idea, that [WCE] stars are the immediate descendants of [WCL] stars.
- Some late-type [WC] CSPN show high silicon abundances. This is not explained by stellar evolution models.
- So far, the branching ratio between normal (i.e. hydrogen rich) evolution and LTP, VLTP and AFTP evolution is not determined. Apparently only the VLTP scenario provides hydrogen-free non-DA progenitors. On the surfaces of LTP and AFTP stars remain sufficiently high fractions of hydrogen and the stars will end up as DA white dwarfs. It is unsettled whether these layers can be removed by mass loss.
- There is no significant difference in nebula ages of hydrogen-rich and hydrogen-deficient CSPN (Gorny, these proceedings). This favors the AFTP scenario to be the most common one. So one might ask whether there is another AFTP-like scenario which provides hydrogen-free post-AGB stars and which has not been identified yet.
- From recent infrared observations of some [WCL] stars it is known that the change from oxygen to carbon rich chemistry in their winds has occurred only some hundred years ago (Waters, these proceedings).

This point in time coincides with the thermal pulse. It favors the AFTP scenario since the time needed for the LTP and VLTP is much longer, respectively.

4. Mass-loss and "Radiation driven wind theory"

Aside from the discussion of the evolutionary status of hydrogen-deficient post-AGB stars, spectral analyses of these stars can also provide information on the driving mechanism of the winds of hot stars. In case of the WR stars this mechanism is not fully identified but it is becoming more and more likely that these winds are accelerated by radiation. One of the hints towards this hypothesis have resulted from the comparison of wind properties of PG 1159 stars and of [WC] stars.

Koesterke et al. (1998) and Koesterke & Werner (1998) argued that the radiation fields of PG 1159 stars are sufficient to drive the stellar winds within the single scattering limit ($\eta = \frac{\dot{M}\,v_\infty}{L\,c}$, $\eta \approx 1$) and speculated that the much higher performance numbers ($\eta \approx 15$) of [WCE] stars might be explained by multi-scattering processes in their atmospheres. They compared the ionization structure of oxygen for a typical PG 1159 and a typical [WCE] star and found changes in ionization only in the [WCE] atmosphere. This favors multi-scattering processes in the wind of the [WCE] stars because, as Lucy & Abott (1993) showed, these processes are stimulated in stratified atmospheres where the leading ionization stage changes.

Two years ago it was only speculation whether iron, which is supposed to yield the main contribution to the driving force, behaves similar because iron opacities still had not been considered, but today first iron line-blanketed models become available and they confirm the difference in ionization structure of PG 1159 and [WCE] stars (Fig. 2).

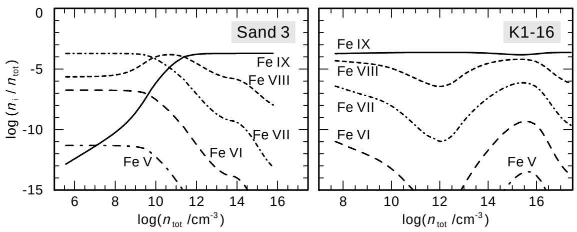

Figure 2. Ground-level non-LTE occupation numbers versus the particle density of iron for Sand 3 (left) and K 1-16 (right). The iron abundance is $2\,10^{-3}$ by mass. While the whole atmosphere of K 1-16 is dominated by Fe IX the leading iron ionization stage changes twice in the atmosphere of Sand 3. This might explain the enhanced mass-loss rates of [WCE] stars by multi-scattering processes.

The stellar evolution in terms of temperature and wind density is sketched in Fig. 3. During the [WCL]-phase the stars evolve from 20 kK towards higher temperatures and reach at about 140 kK the [WCE]-phase. Simultaneously the wind density increases drastically. In these phases the wind efficiency η is greater 1. Then the mass-loss fades abruptly, possibly because their atmospheres become homogeneously ionized and multi-scattering processes vanish, and the star becomes a [WC]-PG 1159 star showing absorption and emission lines in the optical. The optical emission lines vanish when the PG 1159 stage ($\eta \approx 1$) is reached and only weak P Cygni profiles persist in the UV. As before, the wind density increases towards higher temperatures.

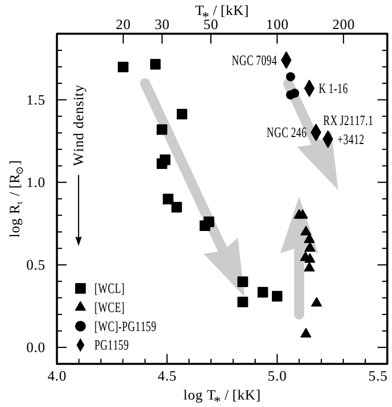

Figure 3. The post-AGB stars in the $\log(R_t)$–$\log(T_*)$–plane. A decreasing R_t can be considered as an increasing wind density. The suggested evolutionary path is indicated by the arrows.

In the discussion of the driving mechanism of the winds of [WC] stars it remains questionable, if multi-scattering processes can induce high wind efficiencies of $\eta \approx 15$ or higher. From this point of view it is noteworthy that recently the mass-loss rates of massive WR stars have been reduced by factors of 2 to 4. Hillier (1984) and Hamann & Koesterke (1998) applied clumped atmospheres to these stars and derived significant lower mass-loss rates, from the comparison of observed and synthetic line wings. The wind efficiencies were also lowered. By now no one has already applied clumped atmospheres to CSPN. Due to the lower wind densities, line wings induced by electron scattering are generally weaker and almost no discrepancies between observations and models are detectable, but the similarity of massive WC stars and CSPN of [WC]-type suggests that the [WC] atmospheres are clumped as well. In case of Sand 3 this would reduce η to approximately 4 to 7.

5. Outlook

A new generation of models has been developed which accounts for clumping and iron line-blanketing. Some aspects are listed below:

- Better concordance of observation and synthetic profiles will reduce uncertainties of the derived parameters.
- The determination of iron abundances will give further constraints to the evolution of low and intermediate mass stars.
- The applied iron opacities will lead to modified emergent fluxes. This will allow more reliable analyses of the nebulae.

ACKNOWLEDGMENT
I thank Klaus Werner and Falk Herwig for helpful discussions.

References

Barlow M.J., Blades J.C., Hummer D.G. 1980, ApJ 241, L27
De Marco O., Storey P.J., Barlow M.J. 1997, MNRAS 297, 999
De Marco O., Crowther P.A. 1998, MNRAS 296, 419
De Marco O., Crowther P.A. 1999, MNRAS 306, 931
Dreizler S., Heber U., Napiwotzki R., Hagen H.J. 1995a, A&A 303, L53
Dreizler S., Werner K., Heber U. 1995b in "White Dwarfs", D. Koester and K. Werner (eds), Lecture Notes in Physics, Springer-Verlag, p. 160
Freytag B, Ludwig H.-G., Steffen M. 1996, A&A 313, 497
Hamann W.-R., Koesterke L. 1998, A&A 335, 1003
Hillier J. 1984, ApJ 280, 744
Hillier J. 1990, A&A231, 111
Herwig F, Blöcker T., Schönberner D. 1997, A&A 324, L81
Iben I.Jr. 1984, ApJ 277, 333
Iben I.Jr., McDonald J. 1995, in "White Dwarfs", D. Koester and K. Werner (eds), Lecture Notes in Physics, Springer-Verlag, p. 160
Koesterke L., Hamann W.-R. 1997a, A&A 320, 91
Koesterke L., Hamann W.-R. 1997b, in *Planetary Nebulae* IAU Symp. 180, H.J. Habing & H.J.G.L.M. Lamers (eds), Kluwer Academic Publishers
Koesterke L., Werner K. 1998, ApJ Letters 500, 55
Koesterke L., Dreizler S., Rauch T. 1998, A&A 320, 1041
Leuenhagen U., Hamann W.-R. 1998, A&A 330, 265
Leuenhagen U., Hamann W.-R., Jeffery C.S. 1996, A&A 312, 167
Leuenhagen U., Hamann W.-R. 1994, A&A 283, 567
Leuenhagen U., Koesterke L., Hamann W.-R. 1993, Acta Astronomica 43, 329
Lucy L.B., Abbott D.C. 1993, ApJ 405, 738
Werner K., Koesterke L. 1992, in "The Atmospheres of Early-Type Stars", Lecture Notes in Physics 401, Springer Verlag, p. 288
Werner K., Heber U., Fleming T.A. 1994, A&A 284, 907
Werner K., Hamann W.-R., Heber U., Napiwotzki R., Rauch T., Wessolowski U. 1992, A&A 259, L69
Werner K., Dreizler S., Heber U. Rauch T., Wisotzki L., Hagen H.-J. 1995, A&A 293, L75
Werner K., Hamann W.-R., Heber U., Napiwotzki R., Rauch T., Wessolowski U. 1992, A&A 259, L69