A&A manuscript no.
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Your thesaurus codes are:
08.09.2 NGC 7094; 08.09.2 NGC 246; 08.09.2 RX J2117.1+3412; 08.09.2 K1-16; 08.13.2;

ASTRONOMY
AND
ASTROPHYSICS
27.10.1997

On the mass-loss of PG 1159 stars ⋆

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Received date; accepted date

Abstract. The winds of the four PG 1159 stars NGC 7094, NGC 246, K 1-16 and RX J2117.1+3412 are investigated by means of non-LTE models for spherically expanding atmospheres. Based on the results of recent plane-parallel non-LTE analyses, several individual models with various mass-loss rates are calculated. Synthetic profiles of the C IV resonance line are compared to high resolution, high quality HST and IUE UV spectra in order to determine mass-loss rates of the stars and terminal velocities of their winds. Complex model atoms of hydrogen, helium, carbon and oxygen are taken into account.

In contrast to previous studies we find from the C IV line at 1550 Å exceedingly high mass-loss rates of $-7.6 \leq \log(\dot{M}\,/[\,M_{\odot}\,\mathrm{yr}^{-1}]) \leq -6.9$ which are, in case of K 1-16, only two times smaller than the mass-loss rates of [WC]-PG 1159 stars. From the comparison with theoretical predictions of line strength and terminal wind velocity it is most likely that the theory of radiation driven winds is appropriate for the PG 1159 stars.

The results are discussed in the light of the evolutionary sequence [WCL]→[WCE]→[WC]-PG 1159→PG 1159→WD, which is suggested for hydrogen deficient post-AGB stars. Similarities between the winds of PG 1159 stars and the exceptional strong winds of [WC]-type stars lead to the assumption that the theory of radiation driven winds might also apply for [WCE] stars. Changes of ionization degrees, which might enhance the mass-loss by multi-scattering processes, are found in the atmospheres of [WCE] stars but not in the atmospheres of PG 1159 stars.

Key words: stars: individual: NGC 7094, NGC 246, RX J2117.1+3412, K 1-16 – stars: mass-loss

1. Introduction

At the time of the detection of the prototype PG 1159-035 (McGraw et al. 1979) our knowledge of hot stars was still in its infancies. Complex models of hot stellar atmospheres were not feasible due to both the poor computer capability and the lack of adequate solution techniques for the coupled equations of radiation transfer and statistic equilibrium under non-LTE conditions. Nowadays both problems have been overcome and realistic atmospheres for hot stars can be modelled.

The development of the so-called Accelerated Lambda Iteration (ALI) method and its application to static plane-parallel (cf. Werner 1986, Dreizler & Werner 1993) and spherically expanding atmospheres (cf. Hamann 1987) has increased the number of non-LTE analyses of post-AGB stars drastically. Reliable stellar parameters and abundances are now established for several groups of these objects. The absorption line spectra of hot White Dwarfs and PG 1159 stars are investigated by static plane-parallel models (Dreizler et al. 1995, Werner et al. 1997) while the emission line spectra of Wolf-Rayet [WR] type Central Stars of Planetary Nebulae (CSPN) are analyzed by spherically expanding atmospheres (Koesterke & Hamann 1997, Hamann 1997). Also few stars, with a spectral appearance intermediate between PG 1159 and [WCE] stars (named [WC]-PG 1159 stars or transition objects), are analyzed with both codes (Werner & Koesterke 1992, Werner et al. 1992, Leuenhagen et al. 1993). These analyses show that agreement between the two types of models, plane-parallel and spherically expanding, is achieved.

Contrary to the well-established stellar parameters and abundances of the stars, the evolutionary link between the different groups of hydrogen deficient stars is still poorly understood. It is assumed that hydrogen deficient CSPN, Wolf-Rayet stars as well as PG 1159 stars and hydrogen deficient White Dwarfs, have progenitors of initial masses less than eight solar masses which have lost their hydrogen-rich envelope during AGB and post-AGB phases. According to the born-again-scenario (Iben et al. 1983) a star which has left already the AGB may suffer a "final helium flash" and the remaining hydrogen envelope is effectively mixed with deeper layers. Anyhow, the evolution of

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⋆ Partly based on observations made with NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555; Partly based on observations obtained with the IUE satellite from VILSPA, Spain, jointly operated by the NASA, ESA, and PPARC.

these objects is not known in detail because adequate tracks are not available so far. Progress can be expected for the near future: Herwig et al. (1997) incorporate diffuse mixing processes in AGB stars and achieve chemical abundances typical for PG 1159 and [WC]-stars in intershell layers of AGB stars. The question how these layers appear at the surface is connected to the mass-loss during AGB and post-AGB phases.

Hamann (1996) assumed from the comparison of the analyses with evolutionary tracks (Schönberner 1983, Wood & Faulkner 1986) the following evolutionary post-AGB sequence: [WCL]→[WCE]→[WC]-PG 1159→PG 1159→WD. Note that these tracks are not really adequate for the objects considered here as they predict normal (hydrogen-rich) surface abundances.

The understanding of the surface abundances of the hydrogen-deficient stars will be based on mass-loss rates of all phases. While the mass-loss rates of [WC] stars of both late and early type are well investigated (cf. Hamann 1997) only rough attempts to determine the mass-loss rates of PG 1159 stars were made so far (Leuenhagen 1994). The prototype itself has been investigated by Fritz et al. (1990) who found no evidence for mass-loss.

In this work we determine mass-loss rates and terminal velocities of four PG 1159 stars which clearly show a P Cygni profile at C IV 1550 Å. Starting from recently published plane-parallel non-LTE analyses, series of models with different mass-loss rates and terminal velocities are calculated for each object. The wind parameters are derived from the best fit between theoretical and observed line profiles.

An overview on the observations is given in Sect. 2, followed by the presentation of the model calculations and the spectral fits (Sect. 3). The results are compiled and discussed in Sects. 4 and 5.

2. Observations

For NGC 7094 we obtained HST data in cycle 6 using the GHRS spectrograph equipped with grating G140L centered on 1294 Å and 1607 Å. Observations were taken through the Large Science Aperture at Sept. 7th 5:30:24 and 7:07:48 UT with total exposure times of 1305.6 sec and 2828.8 sec, respectively. Each exposure was split in four equal pieces slightly shifted on the detector to reduce fixed pattern noise. The final spectrum is a co–addition of the calibrated spectra taking from the standard pipeline reduction.

RX J2117.1+3412 had been observed recently by IUE (Table 1) in high resolution mode (large aperture). The spectra were wavelength calibrated by using interstellar lines and co-added in order to increase to S/N ratio. The resulting spectrum was smoothed with a Savitzky-Golay filter (Press et al. 1992).

The IUE spectrum of the CSPN of NGC 246 was kindly provided by W. Feibelman (9 spectra co-added, Feibelman & Johansson 1995). The HST spectrum of K 1-16 was taken from Patriarchi & Perinotto (1996).

Table 1. Observation log of the IUE spectra of RX J2117.1+3412

Image No.	Exposure time	Date	Observer
SWP 47556	360 min	27-04-93	Leuenhagen
SWP 47563	362 min	28-04-93	Leuenhagen
SWP 55411	363 min	03-08-95	Werner

3. Model calculations and spectral fits

The program stars have been recently analyzed by means of line-blanketed plane-parallel non-LTE atmospheres aiming on the fit of the absorption lines. Detailed descriptions can be found in Rauch & Werner (1997) and Dreizler et al. (1995). The stellar temperatures and surface gravities (cgs) range between 110 and 170 kK and between $10^{5.7}$ and $10^{6.1}$, respectively. All stars are classified as low-gravity PG 1159 stars with emission cores (lgE). Their atmospheres consist of helium, carbon and oxygen while NGC 7094 has additionally a remarkable amount of hydrogen and is consequently classified as *hybrid* star (lgEH). Note that helium is still the most abundant element in the atmosphere of this star. The stellar parameters and abundances are listed in Table 2.

We have calculated several wind models for each star with varied mass-loss rates to achieve a spectral fit of C IV 1550 Å taking the stellar parameters and abundances from the plane-parallel analyses described above. The calculations presented here are based on the so-called standard model for WR-stars assuming a spherically symmetric outflow, homogeneity and stationarity. The radiation transfer is calculated in the comoving frame under non-LTE conditions, accounting for complex model atoms with a total number of 186 non-LTE levels focusing on H I (10 levels), He II (16), C III (40), C IV (19), O IV (25), O V (37), and O VI (15). The consistent solution of the radiation transfer and the statistical equilibrium is achieved by the ALI method. For the velocity field we assume the usual β-law

$$v(r) = v_\infty \left(1 - \frac{r_0}{r}\right)^\beta$$

with $\beta = 0.4$ which reproduces the observed line shapes best. The line strength and therefore the derived mass-loss rate is nearly independent from the choice of β. For a detailed description of the models we refer to Hamann & Wessolowski (1990) and Koesterke & Hamann (1997).

Note that only Doppler broadening is accounted for when the emergent flux is derived. Therefore the strength and shape of absorption lines cannot be reproduced adequately due to neglection of pressure broadening. The mass-loss rate, however, is determined from the observed P Cygni profile of the C IV resonance doublet at 1550 Å which is clearly formed in the wind regions of the atmospheres. The spectra and the synthetic C IV profiles of the program stars are shown in Fig. 1. A summary of the results is included in Table 2.

In addition to the analyses of the C IV resonance line we have also investigated the O VI resonance line at 1033 Å. EUV observations, taken by ORFEUS 1 in 1993 and ORFEUS 2 in

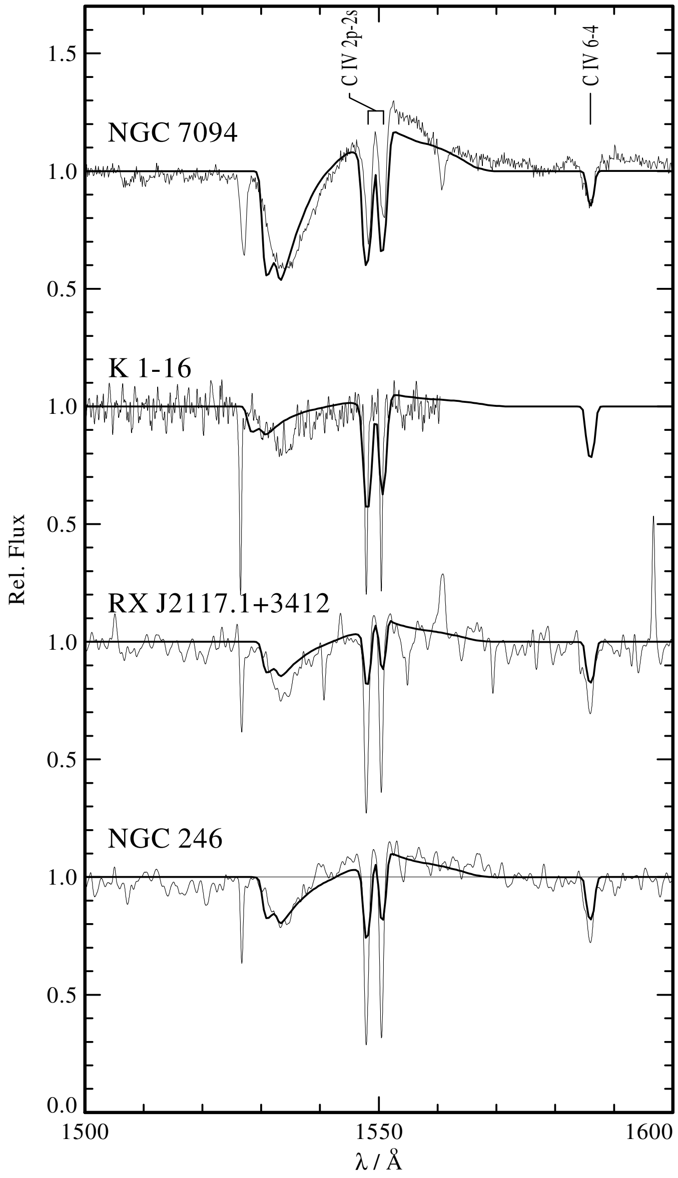

Fig. 1. Fit of the C IV resonance doublet for the program stars. The observation of NGC 7094 is shifted by 1 Å to match the synthetic profile of C IV 6-4.

1996 (NGC 7094, NGC 246 and RX J2117.1+3412) and HUT in 1995 (K 1-16), revealed P Cygni profiles suitable for the analyses by our wind models. Because these analyses are still under way the final results and the appropriate spectral fits will be presented elsewhere (Koesterke & Werner, in prep.). In the present work preliminary values for the mass-loss rate derived from the O VI resonance line are given in Table. 2 and Fig. 2.

Unfortunately the mass-loss rates derived from the C IV and O VI lines are not consistent for three stars. The mass-loss rates of NGC 7094, K 1-16 and RX J2117.1+3412 are significantly lower by factors of two or more when derived from the O VI resonance line. The reason for this is not clear since both ions are members of the same isoelectronic sequence and both lines are emitted by the same region of the atmosphere.

A consistent fit of both lines would be achieved if, instead of decreasing the mass-loss rate, the oxygen abundance is dropped by the factor between the high and the low mass-loss rate. NGC 7094, K 1-16 and RX J2117.1+3412 would then have oxygen abundances of about 0.4, 2.0 and 7.0, respectively, but these values are in strict contradiction with the oxygen abundances derived from the plane-parallel analyses.

4. Results

4.1. Mass-loss rates and terminal velocities

The mass-loss rates of the post-AGB stars considered here are shown in Fig. 2. As expected from the weak P Cygni profiles in the UV and the absorption lines in the optical, the mass-loss rate of K 1-16 is smaller than those of the transition objects. Note that K 1-16 is most suitable for a comparison because it is very similar in mass, luminosity and chemical composition to the [WCE] and [WC]-PG 1159 stars. NGC 7094 has a remarkable amount of hydrogen while both other stars are more massive and therefore more luminous.

Pauldrach et al. (1988) investigated the properties of radiation-driven wind for hot CSPN. Although their model grids up to 100 kK do not cover the temperature of the program stars, the principle effect of stellar mass and chemical composition on the terminal velocity and the mass-loss rate can be studied. The more massive stars (NGC 246 and RX J2117.1+3412) have, as predicted, higher mass-loss rates and slightly lower terminal velocities than K 1-16. Also the terminal velocity of the hybrid star NGC 7094 is slightly lower and its mass-loss rate is slightly enhanced compared to K 1-16. This accordance supports the assumption that the mass-loss of PG 1159 stars is driven by radiation. Additionally the terminal velocity is, as expected from the wind theory, about three times larger than the escape velocity (cf. Table 2). In order to compare absolute values, we extrapolate the results of Pauldrach et al. (1988, their Fig. 6b) to 140 kK ($M = 0.645\,M_{\odot}$) and read off $\dot{M} \approx 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$ which is only about two times smaller than the mass-loss rate of K 1-16 derived from C IV 1550 Å in this work.

4.2. Comparison to other studies

Compared to earlier investigations we find exceedingly high mass-loss rates for the PG 1159 stars. Leuenhagen (1994) estimated mass-loss rates of about $10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$ from a general study of synthetic line profiles in the optical and the UV. This very low value was derived from some weak optical emission features (especially C IV 5805 Å), but not from the much more wind-sensitive UV resonance lines considered in this work.

In a second study the mass-loss rate of K 1-16 was determined by Patriarchi & Perinotto (1996) to $\dot{M} < 2\,10^{-11}\,M_{\odot}\,\mathrm{yr}^{-1}$. Their investigation was based on the same HST observations as presented in Sect. 2., but the P Cygni profile was analyzed by means of Sobolev models. Within this method the internal structure of the atmosphere is not calculated

Table 2. Summary of the model parameters. Two different values for the mass-loss rates are given with respect to the C IV and the O VI line. The latter values are derived from preliminary spectral fits (see text). The stellar masses are taken from evolutionary tracks by Blöcker (1995).

		static analyses										wind analyses			
Star	type	T_* [kK]	$\log g$ [cgs]	H	He	C	O	N	$\log L$ [$L_\odot$]	M [$M_\odot$]	$\dot{M}$ [$\log(M_\odot\,\mathrm{yr}^{-1})$] C IV	O VI	v_∞ [km/s]	v_{esc} [km/s]
					mass fraction									
NGC 7094[a]	lgEH	110	5.7	42:	51	5	<1	<1	3.6	0.63	-7.3	-7.7:	3500	1150
K 1-16[a]	lgE	140	6.1		38	56	6		3.6	0.63	-7.6	-8.1:	4000	1450
NGC 246[b]	lgE	150	5.7		64	30	6		4.2	0.84	-6.9	-6.9:	3500	1200
RX J2117.1+3412[b]	lgE	170	6.0		33	50	17		4.2	0.83	-7.0	-7.4:	3500	1350

: denotes uncertain values
[a] Dreizler et al. (1995)
[b] Rauch & Werner (1997)

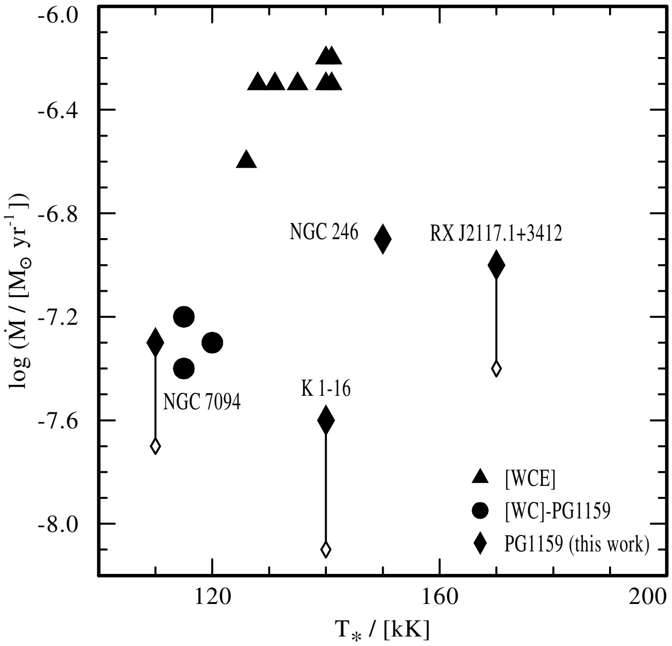

Fig. 2. Post-AGB stars in the $\log \dot{M}$–T_*-plane. The entries for the [WCE] and PG 1159-[WC] stars are taken from Koesterke & Hamann (1997) and Leuenhagen et al. (1993), respectively. Two values are given for the program stars whether the C IV line (filled diamonds) or the O VI (open diamonds, preliminary results) line is fitted. The four quantities mass-loss rate, mass, temperature and luminosity of the stars are connected in the way that the less massive stars (NGC 7094 and K 1-16) are cooler, less luminous and have smaller mass-loss rates. The behavior of the mass-loss rate is principally explained by the theory of radiation driven winds (Pauldrach et al. 1988). The mass-loss rate (derived from the C IV line) of K 1-16, which has the same mass and a similar chemical composition compared to the [WCE] and [WC]-PG 1159 stars, is about two times smaller than those of the transition objects.

consistently and, among other approximations, the occupation number of C IV is arbitrarily chosen. In Fig. 3 it is demonstrated that the population fraction of the C IV ground state is about 10^{-7} which is 10^4 times smaller than the value assumed by Patriarchi & Perinotto (1996).

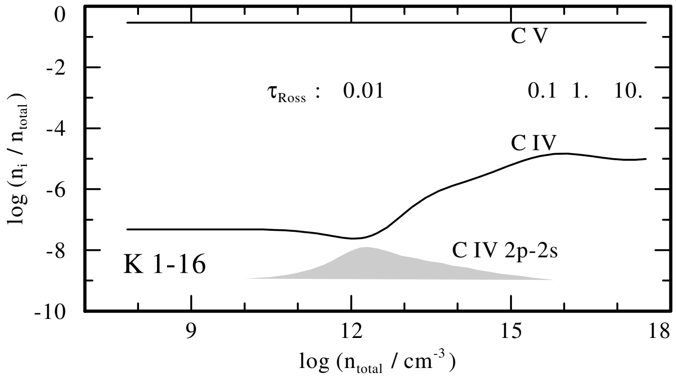

Fig. 3. Non-LTE occupation numbers versus the heavy particle density of C V and C IV ground states for K 1-16. The Rosseland optical depth is indicated. The line emitting region of C IV 1550 Å is shown by the shaded area. C V is the dominant ion at all depths. In the line emitting region the occupation number of C IV is about 10^{-7} relative to total number of heavy particles n_{total}.

5. Discussion

The discussion of the formation of hydrogen deficient stars, especially with respect to the mass-loss rates derived in this work, suffers from uncertainties of the analyses and is therefore not fully conclusive. Nevertheless we try to give clues to the evolution by comparing PG 1159, [WC]-PG 1159 and [WC] stars in the $R_\mathrm{t} - T_*$-plane.

R_t is the so-called transformed radius and can be considered as a density parameter. It connects the stellar radius, the mass-loss rate and the terminal velocity via its definition

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

The empirical fact that models with the same R_t (different combinations of R_* and $\dot{M}$) result in almost identical emission line strengths is known as the "transformation law" for expanding stellar atmospheres (Schmutz et al. 1989). Further explanations can be found in Koesterke & Hamann (1997).

Note that the effective temperature has a different definition in the different model codes applied. In contrast to plane-parallel atmospheres the stellar temperature T_* in spherically expanding atmospheres depends via the Stefan-Boltzmann law on the adopted stellar radius R_*, where a specific $\tau_{\rm Ross}$ ($\approx$20 throughout this work) is reached. Due to the lack of consistent hydrodynamic calculations, basically because the driving force of the wind is not known in detail, the right assignment to the plane-parallel temperature is not fully ensured. This might explain that the stellar temperatures of the [WC]-PG 1159 stars are slightly lower than those of the [WCE] stars while the evolutionary scenario predicts [WCE] stars to be cooler.

In Fig. 4 the transformed radii of the hydrogen deficient post-AGB stars are displayed versus their stellar temperatures. The adopted evolutionary scenario, [WCL]→[WCE]→[WC]-PG 1159→PG 1159→WD, is indicated by arrows. 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. The mass-loss then fades abruptly 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 is reached and only weak P Cygni profiles persist in the UV. As before, the wind density increases towards higher temperatures.

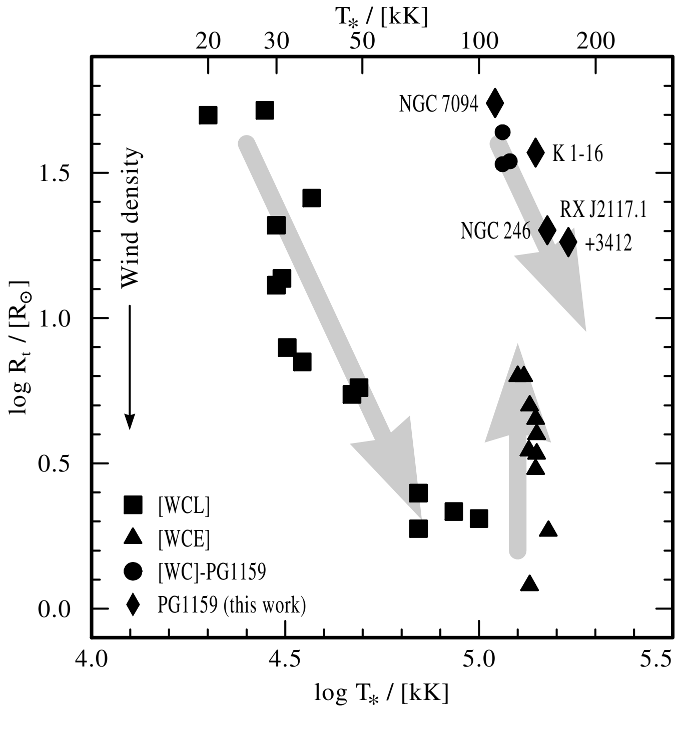

Fig. 4. The post-AGB stars in the $\log(R_{\rm t})$–$\log(T_*)$–plane. The entries for the [WCL], [WCE] and PG 1159-[WC] stars are taken from Leuenhagen & Hamann (1998), Koesterke & Hamann (1997) and Leuenhagen et al. (1993), respectively. The transformed radii of the program stars are calculated from the higher mass-loss rates derived from the C IV resonance lines. A decreasing $R_{\rm t}$ can be considered as an increasing wind density. The suggested evolutionary path is indicated by the arrows.

As shown in Sect. 4.1 the properties of the weak winds of PG 1159-CSPN can be well explained within the radiation-driven wind theory. It is striking that the wind density depends on the temperature with the same slope for both [WC]-type and PG 1159-type (Fig. 4) and so one might conclude that, in principle, the strong wind of [WC]-type Central Stars is driven by the same mechanism, which is efficiently enlarged by a so far not fully identified physical mechanism. We speculate that multi-scattering processes in connection with the chemical surface abundances of carbon, nitrogen and oxygen might be responsible for the enlarged mass-loss rates of [WC]-stars.

In the first place it is generally noticed that there are almost no CSPN with strong mass-loss which show predominantly helium and nitrogen at the surface. While several Central Stars of PG 1159-type composition (helium, carbon and oxygen) have strong mass-loss and are classified as [WC] stars, there is only one star (N66 in the LMC) which is claimed to be of [WN]-type. Moreover, as Peña et al. (1997) have shown, the wind of that star is not stable.

In the second place we stress that the ratio between the mechanical wind momentum and the momentum of the radiation field ($\eta = \frac{\dot{M} v_\infty}{Lc}$) differs considerably for [WCE] and PG 1159 stars. Since the first analyses it is established that the winds of WR stars exceed the single-scattering value by a factor of 5 ... 100. In particular from the wind parameters of Sand 3 (Koesterke & Hamann 1997) $\eta \approx 15$ is derived while the parameters of K 1-16 lead to $\eta \approx 1$. As Owocki & Gayley (1995) emphasized, $\eta \approx 1$ is not a limit to radiation driven winds because photon-plasma interactions can convert momentum of the radiation field several times into mechanical momentum if multi-scattering processes occur. Lucy & Abbott (1993) showed that changes of the degree of ionization would help to stimulate these multi-scattering processes, simply because the total number of lines is increased when different ionization stages are dominant at different depths. The photons are scattered by lines of high ions close to the star *and* again scattered by lines of low ions further in the wind.

From that point of view it is very interesting that the ionization structures of [WCE] and PG 1159 stars are different. In Fig. 5 the ground-level occupation numbers of several oxygen ions are shown for K 1-16 (PG 1159-type) and Sand 3 ([WCE]-type). The whole atmosphere of K 1-16 is dominated by O VII, while the degree of ionization changes in Sand 3. This might indicate that the ionization stratification has influence on the mass-loss rate via the above mentioned multi-scattering mechanism. In case of the PG 1159 stars no ionization changes occur in their atmospheres and consequently η is of the order of 1 while for [WC] stars the efficiency of the driving mechanism is enlarged.

We suppose that the ionization stratification of iron, which is so far not included in the models, is similar to that of oxygen. In case of [WCE] stars the degree of ionization of iron changes and the mass-loss is enhanced by multi-scattering processes. This mechanism fails for the hotter PG 1159 stars investigated here, because their atmospheres show no change of ionization. The cooler star NGC 7094 might be special due to his consid-

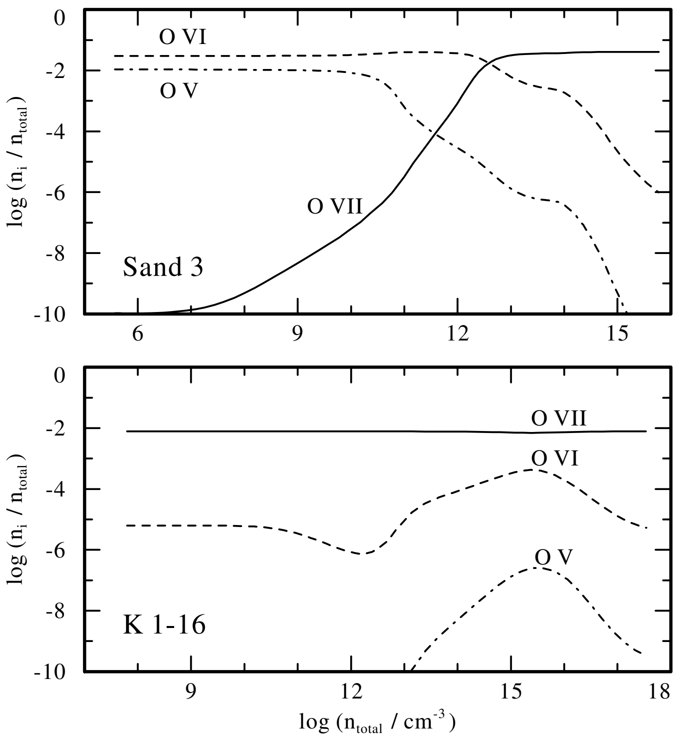

Fig. 5. Ground-level non-LTE occupation numbers versus the heavy particle density of O VII (solid), O VI (dashed), and O V (dash-dotted) for Sand 3 (top) and K 1-16 (bottom). While the whole atmosphere of K 1-16 is dominated by O VII, the degree of ionization changes in the atmosphere of Sand 3. At number densities of about $10^{12.5}$ O VII recombines and the outer region is dominated by O VI. Below number densities of 10^{10} the occupation of O V is almost of the same value than O VI.

erably high amount of hydrogen. Hamann et al. (1995, their Fig. 7.) found for massive WN stars that the higher the hydrogen abundance in the atmospheres the weaker the mass-loss.

Following the assumption that the mass-loss rate depends on the ionization stratification of the atmospheres, further conclusions can be drawn. We speculate that the small amount of nitrogen of about 1.5% by mass in CSPN with [WN]-type composition might not be sufficient to cool down the outer layers of the atmospheres and that consequently no changes of ionization occur, neither of nitrogen nor of iron. On the other hand the amount of carbon and oxygen in [WC] and PG 1159-CSPN is about 50% by mass which might be enough to cool down the outer layers.

All together, this leads to the following hypothesis. After suffering a late thermal pulse the stars leave the AGB for the second time. Their atmospheres are then hydrogen deficient. The stars evolve at constant luminosities towards higher temperatures up to about 140 kK. During all these phases the degree of ionization across their atmospheres changes and multi-scattering processes enhance the efficiency of the radiation driven wind. Consequently their spectra are dominated by strong emission lines in the UV and the optical and the stars fall into the group of [WCL] and [WCE] stars. In the following the temperature increases further to a point where no recombination occurs in the outer parts of their atmospheres. The multi-scattering mechanism breaks down and the mass-loss returns to the strength predicted by the radiation driven wind theory with $\eta \approx 1$. The star has then become a PG 1159 star showing no wind-emission lines in the optical but only weak P Cygni profiles in the UV. Some of the stars are found to be just in the transition phase where the mass-loss is slightly enhanced by a factor of two and where, in case of Lo 4, the wind is not stable (Werner et al. 1992). While the evolution discussed up to this point has taken place at constant luminosity the stars do now enter the White Dwarf cooling sequence. The temperature drops and the surface gravity increases further which leads to significantly lower luminosities. Due to the lower luminosities the stars do not show strong mass-loss although their atmospheres are expected to have ionization gradients.

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