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Spectral analysis of O(He)-type post-AGB stars*

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Abstract. We present an analysis of two recently discovered, very hot hydrogen-deficient post-AGB stars of spectral type O(He), namely HS 1522+6615 and HS 2209+8229, by means of state-of-the-art NLTE model atmospheres based on new optical, UV, and X-ray observations.

In the spectra of HS 1522+6615 we discovered a variability of the O VI $\lambda\,5290$Å line complex on a time scale of few days. We also report on the discovery of a ring structure in the planetary nebula K 1-27 which has an O(He)-type central star.

We discuss how the group of O(He) stars fits in our picture of hydrogen-deficient post-AGB stellar evolution.

Key words: stars: abundances – stars: evolution – stars: individual: HS 1522+6615 – stars: individual: HS 2209+8229 – stars: AGB and post-AGB – planetary nebulae: individual: K 1-27

1. Introduction

The spectral sub-type O(He) was introduced by Méndez et al. (1986) for central stars of planetary nebulae (CSPN) showing absorption-line spectra dominated by He. The only two presently known O(He) CSPN are the central stars of K 1-27 (PN G286.8-29.5) and of LoTr 4 (PN G291.4+19.2) which have recently been analyzed by Rauch et al.(1994 Paper I, 1996 Paper II). From their effective temperatures $T_{\rm eff}$ and surface gravities g (Table 5), they are found in the post-Asymptotic Giant Branch (post-AGB) region of the $\log T_{\rm eff} - \log g$ diagram (Fig. 1), just amongst the exotic He- and C-rich PG 1159 stars which cover a wide parameter range ($T_{\rm eff} = 180 - 75$kK, $\log g = 5.5 - 8.0$; for a recent review see Werner et al. 1997).

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* Based on observations obtained at the German-Spanish Astronomical Center, Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy; collected at the European Southern Observatory, La Silla, Chile; on observations made with ROSAT, retrieved from the archive; and on observations made with the International Ultraviolet Explorer (IUE) and retrieved from the IUE Final Archive; this research has made use of the SIMBAD database, operated at CDS, Strasbourg, France

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In contrast to the O(He) stars, the PG 1159 stars show additionally strong lines of carbon and sometimes of oxygen. Their photospheric composition (typically He:C:O = 33:50:17 by mass) is a challenge for evolutionary theory: None of the presently available standard evolutionary calculations is able to predict these so far.

Recent calculations of Blöcker et al. (1997) and Herwig et al. (1997) which consider a realistic overshoot of the He convection zone have shown that the observed post-AGB abundance patterns of PG 1159 stars are found much closer to the stellar surface already at the thermally pulsing (TP-) AGB, and a stellar wind in agreement with radiation driven wind theory is able to lay bare these layers within time scales which are in agreement with the expansion times of known PG 1159 PN. Although a final flash is still necessary in order to mix the H-rich envelope matter downwards and burn it completely (Iben & MacDonald 1995), it appears likely that the post-AGB evolution is predetermined already at the TP-AGB.

The study of an associated PN which consists of matter ejected during the very last pulses at the TP-AGB allows to derive information about the surface composition at the moment of the star's departure from the AGB.

One critical point for the detection of an associated PN is how fast the star evolves in its post-AGB phase (after the ejection of its PN at the tip of the TP-AGB) relative to the expansion (and dissipation) of its PN. A "typical" PN ($M = 0.2\,{\rm M}_\odot$, $v_{\rm exp} = 20\,{\rm km/sec}$) will disperse within ≈25 000 years below the detection limit.

The evolutionary time scales for post-AGB stars are controversial: The fact that most of the hot ($T_{\rm eff} \gtrsim 80\,{\rm kK}$) DA white dwarfs but only about every other PG 1159 star have an associated PN is a hint that the H-rich stars evolve faster.

The largest presently known PN (G080.3-10.4, angular diameter 14′45″) has been found around one of the hottest PG 1159 stars, RX J2117.1+3412 (Motch et al. 1993, Appleton et al. 1993). At a distance of 1.4 kpc (Motch et al. 1993), it has a linear diameter of about 6 pc which gives an expansion time of ≈150 000 years ($v_{\rm exp} = 20\,{\rm km/sec}$).

Recent evolutionary calculations of Blöcker & Schönberner (1990) indicate that the evolution of stars with post-AGB ages of more than about 20 000 years does not depend strongly on their stellar masses. Earlier calculations of Iben et al. (1983) predicted

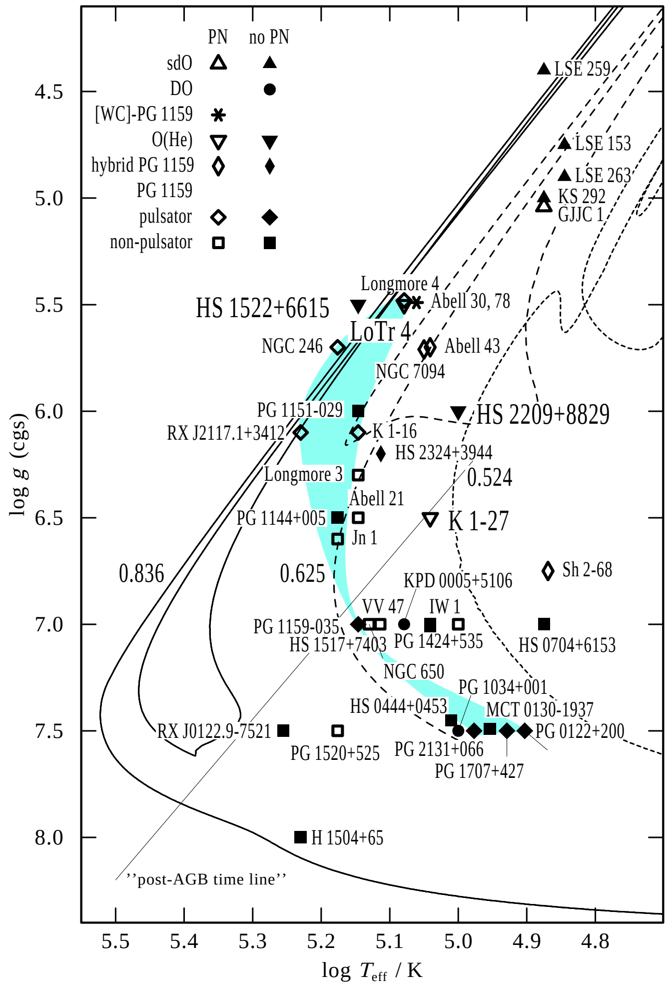

Fig. 1. Positions of the known O(He) stars and related objects in the $\log T_{\rm eff} - \log g$ diagram compared to theoretical evolutionary tracks for born-again post-ABG stars (Blöcker 1995). The tracks are labeled with the respective stellar masses (in $M_\odot$). The "post-AGB time line" indicates approximately the time scales given by Blöcker (1995): It cuts the 0.836, 0.625, and 0.524 $M_\odot$ tracks at post-AGB evolutionary times of $2 \cdot 10^3$, $2 \cdot 10^4$, and $2 \cdot 10^5$ years, respectively. The shaded area indicates the approximate position of the GW Vir instability strip

a three times longer time scale for He-burners, which could explain much better the "missing" PN around H-deficient post-AGB stars.

In Paper I and II we tried to construct consistent models CSPN↔PN of the two O(He)-type central stars of the PN K 1-27 and LoTr 4. In the case of LoTr 4 we got satisfying results while in the case of K 1-27 the central star model did not provide enough hard photons to ionize the nebula. In Sect. 2 we describe an investigation on this problem.

Two new objects which fit into the O(He) classification were recently discovered (Sect. 3). We present a first NLTE model atmosphere analysis of these objects in Sect. 3.3.

2. A close look onto K 1-27 and its exciting star

K 1-27 is a high-excitation PN with a O(He) - type central star. This PN has an unusually low mass (Table 5) and a solar metal composition (Paper I).

Our first attempt to construct a consistent CSPN↔PN model yields a discrepancy: The flux necessary to ionize the nebula was found far in excess of what the atmospheric models predicts (of the order of 10^3). Two explanations are conceivable: First, the CSPN is hotter than determined, and second, our nebula model is not appropriate. In the following we describe an investigation on these two possibilities.

First, we re-analyzed the CSPN K 1-27 with our improved model atmospheres (Sect. 3.3). As expected, the theoretical He II line profiles calculated from these models appear slightly deeper. We find the best fit to the observed spectrum at $T_{\rm eff} = 105 \rm kK$ instead of $T_{\rm eff} = 100 \rm kK$.

For the analysis of the ROSAT[1] data, we used the original IUE image (SWP 55116) and IRAF[2] (Tody 1986) to extract the stellar spectrum and to determine the neutral hydrogen column density $N_{\rm H}$ (Fig. 2). We found $N_{\rm H} = 2^{+2}_{-1} \cdot 10^{20}\,\rm cm^{-2}$ which is lower than derived in Paper I: $N_{\rm H} = 8.8 \cdot 10^{20}\,\rm cm^{-2}$ from the extinction $c = 0.28$ using the nebular H α / H β ratio. Since a relative error of 10 % in this ratio yields an absolute error of about 30 % in c, both values agree within their error ranges. However, since $N_{\rm H}$ is used in the analysis of the total ROSAT PSPC[3] count rate of the CSPN K 1-27, we extrapolated to the new value (cf. Paper I) and arrived at $T_{\rm eff} \approx$ 108 kK, which is in good agreement with our new optical determination (Sect. 2). We finally adopt $T_{\rm eff} = 105 \rm kK$. This value is well within the error range of our first analysis and thus, does not solve the flux problem (compare Paper I, Table 4). In the next step, we try to judge the sophistication of our nebula model.

Our analysis of the nebula was hampered by the fact that only little was known about the spatial structure of the nebula: On the finding chart of Acker et al.(1992) K 1-27 appears just above the background exhibiting two bright arcs on the northern and southern side. These are even better visible on our reproduction from the ESO-SRC survey (Paper I) but we felt unable to interpret this two-dimensional projection. Thus, the validity of our (one-dimensional, spherical symmetric) photoionization models (Köppen 1979) for this nebula has to be questioned.

In order to investigate the distribution of brightness and matter more closely, we took new narrow-band images of K 1-27 at ESO (La Silla, Chile) with the 2.2m ESO/MPG telescope (observing proposal ESO N° 54.C-0506, Table 1). We used EFOSC 2[4] and the CCD ESO # 19 (THX 31156, 19μ, 1024×1024 px, $0\farcs336$ / px). The data reduction was carried out

[1] Röntgensatellit
[2] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation
[3] Position Sensitive Proportional Counter
[4] ESO Faint Object Spectrograph and Camera

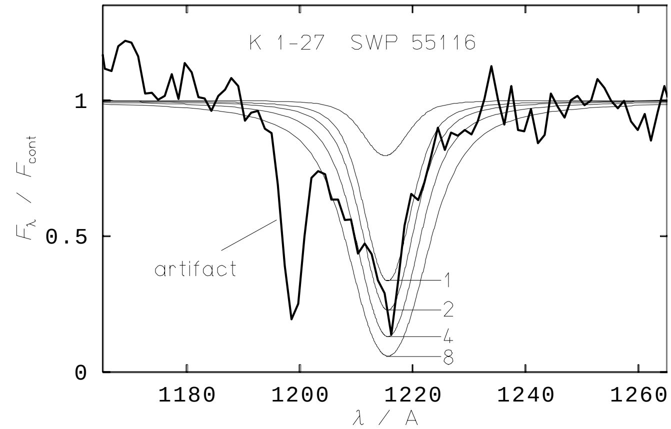

Fig. 2. Theoretical Lyman α profiles compared with the IUE UV spectrum of the CSPN K 1-27. The profile is strongly dependent on $N_{\rm H}$ $(= 1, 2, 4, 8 \cdot 10^{20}\,{\rm cm}^{-2})$

Table 1. Observation log of the direct images of the PN K 1-27. The image numbers given are referred to in the text

No.	ESO filter	time / min	date
1	# 694 Hα	10	6-Feb-95
2	# 689 [O III] λ 5007 Å	10	6-Feb-95
3	# 629 Hα + N II	3×5	6-Feb-95
4	# 702 S II	10	7-Feb-95

using IRAF. The images were flatfielded using suitable dome flats and were normalized to the local background (Fig. 3).

On our new H α and [O III] λ 5007 Å images (Fig. 3, # 1 and # 2, of Table 1) a ring structure with a radius of $\approx 17''$ in a plane located SW – NE with an inclination of $\approx 70°$ is conspicuous. Another arc which is approximately symmetric around the central star with the same radius may belong to an outer bubble whereas the bright region within 10″ from the central star (invisible in the [O III] image) belongs to an inner bubble.

Due to the strong deviation from spherical symmetry and homogeneity in K 1-27 even more photons than assumed in Paper I will escape through the optically thinner parts of the nebula which increases the number of missing ionizing photons. We cannot provide a solution for this problem.

The nebula's extension, measured from a co-added image (# 4, Fig. 3) is about 50″ in W-E and 65″ in N-S direction which is larger than the value (47″) measured by Kohoutek (1977). The nebula is not detectable on our S II image.

3. HS 1522+6615, HS 2209+8229

Two new objects which we classify as O(He) stars were recently discovered within the framework of NLTE analyses of the stellar component in the Hamburg-Schmidt quasar survey (Heber et al.1996): HS 1522+6615 and HS 2209+8229. For none of these an associated PN has been detected so far. In the following, we describe a NLTE analysis of these objects.

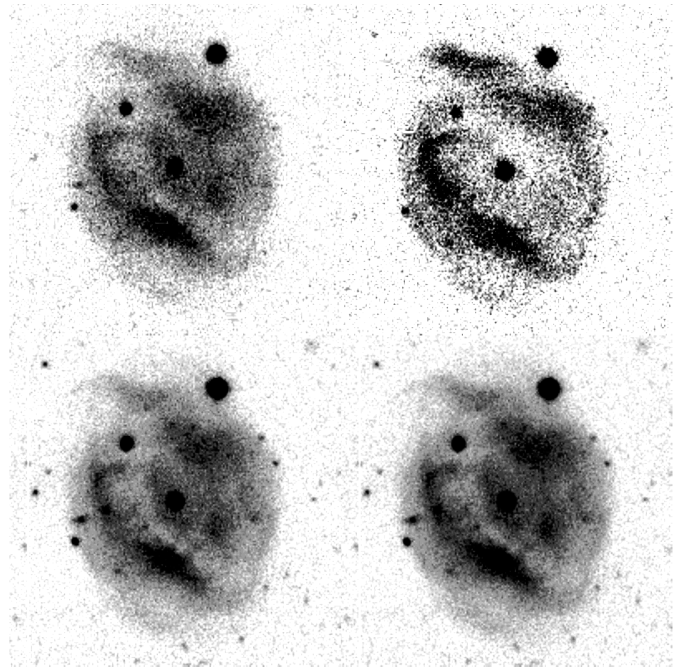

Fig. 3. The planetary nebula K 1-27. Images taken with the 2.2m telescope at ESO with different filters (Table 1): H α (image # 1 from Table 1, top, left), [O III] λ 5007 Å (# 2, top, right), H α + N II (# 3,bottom, left, three images co-added). The fourth image (bottom, right) is a co-addition of our H α image and the three H α + N II images. The single images cover 67″×67″ (orientation: north down, east right). Note that the nebula's extension is about 50″ in W-E and 65″ in N-S direction

Table 2. Observation log of the optical spectra taken at the 3.5m telescope at the Calar Alto Observatory (9-01-98: two spectra). The dispersion is given in Å/mm, in the case of the TWIN spectrograph for both (blue/red) channels

name	dispersion	date	instr.	observer
HS 1522+6615	72/72	1-09-93	TWIN	Dreizler
	36/36	21-05-94	TWIN	Rauch
	72/72	23-09-94	TWIN	Dreizler
	72/72	25-09-94	TWIN	Dreizler
	72/72	10-06-96	TWIN	Dreizler
	72/72	13-06-96	TWIN	Dreizler
	36/36	9-01-98	TWIN	Dreizler
HS 2209+8229	72/72	14-06-96	TWIN	Dreizler

3.1. Observations

3.1.1. Optical spectra

Optical spectra of HS 1522+6615 and HS 2209+8229 have been taken in the last years at the Calar Alto Observatory (Table 2).

A comparison of the optical spectra of the known O(He) stars is shown in Fig. 4. In Fig. 5 we show all spectra (blue channel) of HS 1522+6615 from Table 2. The O VI $\lambda\,5290$Å complex appears at different strength from observation to observation which suggests a variability on a time scale not longer than a few days.

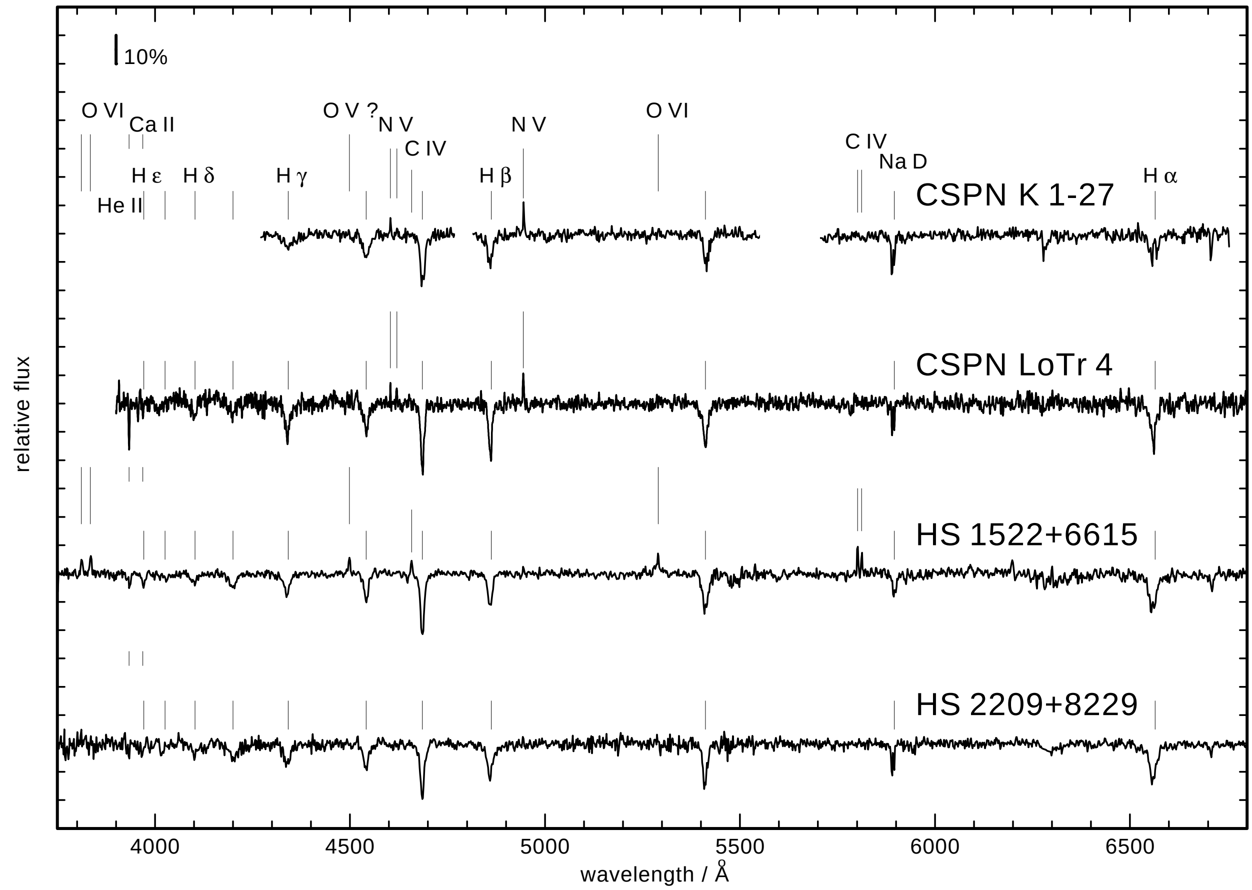

Fig. 4. Optical spectra of the presently known O(He) stars. The identified lines are marked

Table 3. $N_{\rm H}$ and $E(B-V)$ of three O(He) stars derived from their UV spectra (Fig. 6)

name	$\log N_{\rm H} \cdot cm^2$	$E(B-V)$	gal. lat. / degr
CSPN K 1-27	20.3	$0.^{\rm m}05$	-29.58
HS 1522+6615	20.7	$<0.^{\rm m}03$	+44.56
HS 2209+8229		$0.^{\rm m}15$	+21.54

In none of the spectra of the new O(He) stars N V emission lines have been identified which is in contrast to both O(He)-type CSPNe, K 1-27 and LoTr 4 (Fig. 4).

3.1.2. UV spectra

IUE UV spectra of three O(He) stars have been retrieved from the IUE Final Archive. A comparison is shown in Fig. 6. Although these are low resolution / large aperture spectra, it was possible to determine the interstellar neutral hydrogen column density $N_{\rm H}$ and the reddening in the case of two of them (Fig. 6, Table 3). The determined values are in agreement with the tables by Burstein & Heiles (1982).

3.2. Data reduction

The data reduction of the optical spectra was performed using ESO-MIDAS (up to 1996) and IRAF. The spectra were wavelength calibrated with He-Ar comparison spectra taken directly before or after the respective science exposures. All spectra of HS 1522+6615 were co-added (the 26 and 36 Å/mm spectra were convolved with a Gaussian with 3.4 and 3.2 Å FWHM, respectively, in order to match the resolution (3.7 Å) of the 72 Å/mm spectra).

3.3. NLTE analysis

In the following we describe briefly the analysis of the O(He) stars which was carried out analogously to Paper I and II. We calculated plane-parallel, hydrostatic NLTE model atmospheres using our Accelerated Lambda Iteration (ALI) code (Werner 1986). Since Paper I, these were significantly improved by the consideration of level dissolution following the Hummer-Mihalas (1988) occupation probability formalism for H I and He II (Hubeny et al. 1994, Werner 1996). The model atoms are the same as in Paper I but we consider additionally Stark line broadening for the H I and He II Lyman series (Werner 1996).

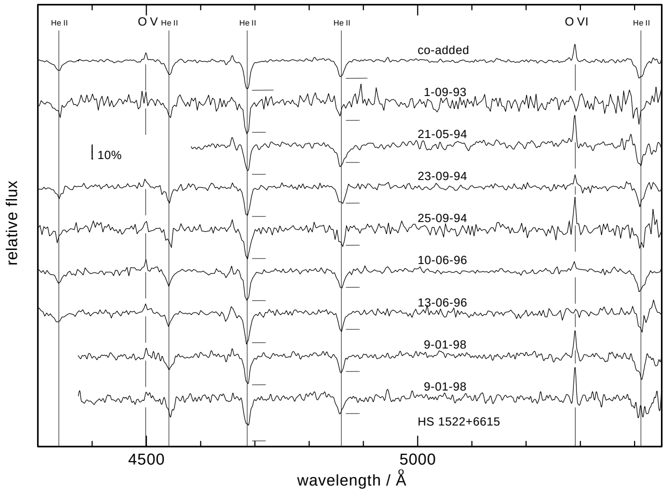

Fig. 5. Optical spectra of HS 1522+6615 taken at different times. The higher resolution (1.8 and 1.5 Å) spectra (21-05-94 and 9-01-98) were convolved with Gaussians (3.2 and 3.4 Å FWHM) to achieve the same resolution (3.7Å) as the other spectra. Note that O VI $\lambda\,5290$Å shows a variability within some days, e.g. the 25-09-96 emission profile ist much shallower than the 23-09-96 profile, at 1-09-93 it appeared even in absorption! In all spectra there appears an almost non-variable emission feature at 4499 Å which might be identified as O V but test calculations have shown that it is impossible to fit the O V and O VI lines simultaneously. The horizontal bars indicate the central depression of He II $\lambda\lambda\,4686, 4859$Å in the co-added spectrum (top) in order to compare their strength in the single spectra

Table 4. Predicted mass-loss rates of the O(He) stars interpolated from Fig. 6a of Pauldrach et al. (1988)

name	$\log \dot{M}/\mathrm{M}_{\odot}$
CSPN K 1-27	-9.1
CSPN LoTr 4	-7.7
HS 1522+6615	-7.6
HS 2209+8229	-9.5

3.3.1. HS 1522+6615

In the spectrum of HS 1522+6615, lines of He, C, and O are identified (Fig. 4). We started with a coarse determination of T_{eff} and $\log g$ analogously to (Sect. 3.3.2). While the surface gravity can be fixed within small error limits, we adopt $\log g = 5.5 \pm 0.3$, variation of T_{eff} over a relatively wide range yields fits to the observation with similar quality.

Fortuitously, HS 1522+6615 (RX J1522.9+6604) had been observed with the PSPC detector of the ROSAT satellite with a total exposure time of 5875 sec. The data were extracted using the EXSAS software package (Zimmermann et al. 1994). The pulse height distribution (PHD) presented in Fig. 7 was obtained by binning the counts until a signal-to-noise ratio of five has been achieved in each bin. The total count rate is 0.35 ± 0.01 cts/sec. The only other O(He) star which was observed by ROSAT is the CSPN K 1-27 which has a much lower count rate of 0.00734 cts/sec (Paper I).

For a comparison of the best model spectra with the observed PHD (Fig. 7) we normalized these spectra to the apparent visual magnitude of $m_{\mathrm{V}} = 16.9$ (Table 5) and calculated interstellar absorption according to the models of Morrison & McCammon (1983) and Cruddace et al. (1974). Convolution with detector response matrix and effective areas of the PSPC detector provides synthetic PHDs. Further details of the analysis procedure can be found in Jordan et al. (1994). Since the neutral interstellar hydrogen column density $N(\mathrm{HI})$ enters as an additional parameter, which can only be imprecisely determined by IUE observations, we chose N_{H} so that total observed and predicted PSPC count rates are equal: $N_{\mathrm{H}} = 1.05 \cdot 10^{20}\,\mathrm{cm}^{-2}$, $1.43 \cdot 10^{20}\,\mathrm{cm}^{-2}$, $3.70 \cdot 10^{20}\,\mathrm{cm}^{-2}$ at $T_{\mathrm{eff}} = 135, 140, 145$kK, respectively.

In Sect. 3.1.2 we estimated $N_{\mathrm{H}} \approx 5 \cdot 10^{20}\,\mathrm{cm}^{-2}$ from the Lyman α profile which is in agreement with the value of $2.54 \cdot 10^{20}\,\mathrm{cm}^{-2}$ derived by Dickey & Lockman (1990).

We finally arrived at $T_{\mathrm{eff}} = 140$kK and $\log g = 5.5$ ($N_{\mathrm{H}} = 1.43 \cdot 10^{20}\,\mathrm{cm}^{-2}$). With these values, we start with an examination of the He / H abundance ratio. In Fig. 8 we compare synthetic spectra with the observations: At first glance, the higher (1.8Å) and lower (3.7Å) resolution (co-added!) spectra are remarkably different. An analysis of the single (3.7Å) spectra shows a variability in the He II/H I blends (e.g. Fig. 5 at 4860 Å) which suggests a variable He / H ratio. This phenomenon is unexplainable. It appears likely that this is due to the poor quality of the single spectra. Thus, high S/N and high resolution spectra are highly desirable for a reliable analysis.

The single high resolution spectrum suggests He / H = 3 while the lower resolution spectrum does not show any contribution of hydrogen. Thus we can estimate a lower limit and adopt He / H = 10 for the further analysis.

In the next step, we determined the C / He ratio from the co-added optical spectrum (5 spectra with a dispersion of 72 Å / mm, Table 2) using the C IV $\lambda\lambda\,5801, 5812$Å doublet (Fig. 9). Since the quality of the single spectra at this wavelength is poor, we cannot determine a variability of this line. However, we achieved a good fit at $n_{\mathrm{C}}/n_{\mathrm{He}} = 0.003 \pm 0.002$.

The O / He ratio is uncertain because the strength of O VI $\lambda\,5290$Å is variable (Fig. 5). Line profile calculations have shown that for modeling of the strong emission features (e.g. 9-01-98) T_{eff} in excess of 140 kK is necessary. At this T_{eff} it is impossible to model O V $\lambda\,4498.8$Å consistently. It appears possible that both features are formed in a variable stellar wind. The quality of the single spectra around the O VI $\lambda\lambda\,3811, 3834$Å doublet is poor. Although it can be identified in all spectra, it is impossible to judge whether it is also variable. In the case of the CSPN NGC 246 (similar T_{eff} and $\log g$, Fig. 1), Méndez (1986) reported a similar phenomenon, he attributes variable emission features (perhaps O VII) to a variable stellar wind. In the case of HS 1522+6615, a further investigation on this phenomenon, based on better optical spectra which include O VI $\lambda\lambda\,3811, 3834$Å and C IV $\lambda\lambda\,5801, 5812$Å, and on UV spectra which include the resonance doublets O VI $\lambda\lambda\,1032, 1038$Å and C IV $\lambda\lambda\,1548, 1550$Å is highly desirable in order to clearly measure whether there is a distinct variability in the stellar wind.

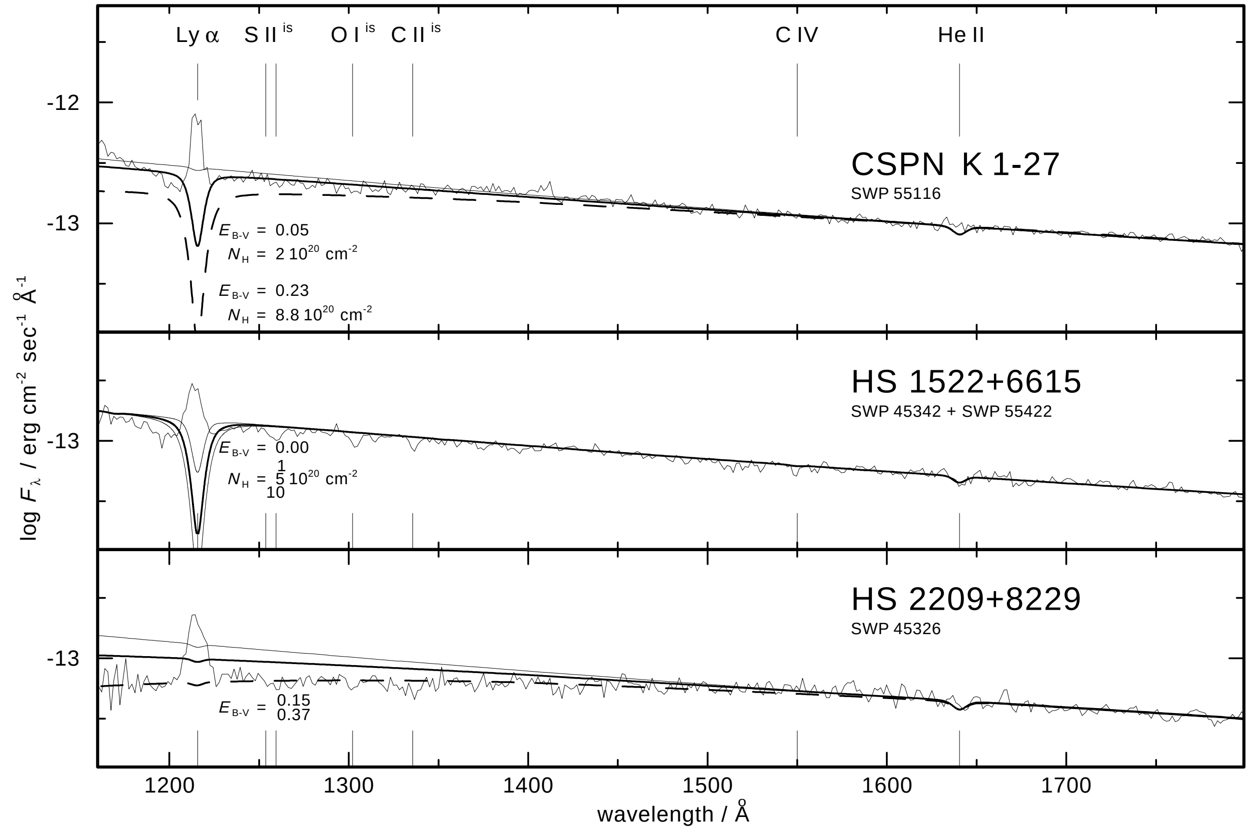

Fig. 6. Available IUE UV spectra of three of the four known O(He) stars as provided by the IUE Final Archive. Besides the prominent interstellar/geocoronal Lyman α line, some interstellar lines of e.g. S II, O I, and C II can be identified. He II $\lambda\,1640$Å is visible in all spectra, C IV $\lambda\,1550$Å is identified only in the spectrum of HS 1522+6615. Theoretical spectra (parameters see Table 5) are overplotted. They account for interstellar absorption and reddening (standard Seaton law, Seaton 1979) with the given column density $N_{\rm H}$ and $E_{\rm B-V}$, respectively. In the case of the CSPN K 1-27 (top panel), the dashed line shows the synthetic spectrum calculated with the values $N_{\rm H} = 8.8 \cdot 10^{20}{\rm cm}^2$ and $E_{\rm B-V} = 0.23$ which were determined in Paper I from the nebular Hα / Hβ ratio and are obviously too high. In the case of HS 2209+8229 $E_{\rm B-V} = 0.37$ (dashed line) seems to fit best the UV spectrum but if we take into account its optical brightness (Table 5), we arrive at $E_{\rm B-V} = 0.15$. Then, we find a flux deficiency at wavelengths smaller than about 1500 Å which might be explained by an anomalous reddening law. The thin lines show spectra with $N_{\rm H} = 0$ and $E_{\rm B-V} = 0$

From its photospheric parameters, HS 1522+6615 resembles the CSPN LoTr 4.

3.3.2. HS 2209+8829

In the case of HS 2209+8829 the He II Pickering series can be identified up to the transition $4 - 14$ (Fig. 4). We found that the reproduction of the series decrement is possible only in a narrow range of $T_{\rm eff}$ and $\log g$ (Fig. 10). We determined $T_{\rm eff} = 100 \pm 10$kK, $\log g = 6.0 \pm 0.5\,{\rm dex}$, He/H$\gtrsim$10. These parameters are similar to those of the CSPN K 1-27.

4. The CSPN GJJC 1 – not an O(He) star!

The PN GJJC 1 (PN G009.8-07.5) was discovered by Gillet et al.(1989) as the optical counterpart to IRAS 18333-2357. Its CSPN has been classified by Jeffery et al.(1996) as O(He) - type: Harrington & Paltoglou (1993) determined equivalent widths of H, He, C, and N lines in its optical spectrum (taken by the HST) by Gaussian fits and compared them to results of an NLTE model atmosphere analysis of the sdO star KS 292 (Rauch et al.1991). From the good agreement they have concluded that both stars have similar parameters: $T_{\rm eff} = 75$kK, $\log g = 5.0$, He/H = 0.5, C ($6 \times \odot$) as well as N ($14 \times \odot$) strongly enriched. However, GJJC 1 exhibits He II, C IV, N IV, and N V lines of similar strengths and hence, might better be classified as a "normal" H-deficient sdO star. The presence of the PN itself is remarkable and makes the CSPN GJJC 1 and KS 292 ("PN-free") an interesting pair in analogy to similar pairs within the PG 1159 group (Sect. 1).

It is worthwhile to note here that the PN : no PN – ratio of $\approx$ 1:1 is valid for the PG 1159 stars as well as for the O(He) stars. The discovery of the He-rich sdO-CSPN GJJC 1 shows that the PN : no PN – ratio is at least greater than 0 for this subclass.

5. Masses, luminosities and distances

The masses and luminosities of the O(He) stars are determined by comparison with evolutionary tracks for "born-again post-AGB" stars (Blöcker 1995) in the $\log T_{\rm eff}$ – $\log g$ diagram (Fig. 1). Distances are calculated analogously to Paper I, using

Table 5. Parameters of the four presently known O(He) stars. The post-AGB ages (t) are taken from Blöcker (1995, see Fig. 1). In the case of the CSPN LoTr 4 and of HS 1522+6615 the two times given refer to a first and a second departure from the AGB. The distances are calculated following the flux calibration of Heber et al.(1984, cf. Paper I). The typical error are: $T_{\rm eff}$ ± 10 %, $\log g$ ± 0.5 dex, d ± 0.5 dex

name	$T_{\rm eff}$	$\log g$	H / He	C / He	N / He	O / He	$m_{\rm v}$	d	$M_\star$	$\log L_\star$	t	PN	$M_{\rm PN}$
	kK	cgs	number ratio					kpc	$M_\odot$	$L_\odot$	a		$M_\odot$
CSPN K 1-27	105	6.5	<0.2	<0.005	0.005		$16\overset{\rm m}{.}1$ [1]	1.3	0.55	2.7	<150 000	yes	0.018 [1]
CSPN LoTr 4	120	5.5	0.5	<0.004	0.001	<0.008	$16\overset{\rm m}{.}5$ [2]	6.0	0.80	4.0	≈300/2000	yes	0.29 [2]
HS 1522+6615	140	5.5	0.1	0.003			$16\overset{\rm m}{.}9$ [3]	13.6	0.85	4.2	≈200/800	no	
HS 2209+8229	100	6.0	<0.2				$16\overset{\rm m}{.}9$ [3]	2.7	0.55	2.6	≈160 000	no	

[1]: Paper I
[2]: Paper II
[3]: $m_{\rm B}$ given by Heber et al.1996, using $m_{\rm B} - m_{\rm V} = -0.46 + E(B-V)$ for $T = \infty$ (Allen 1973)

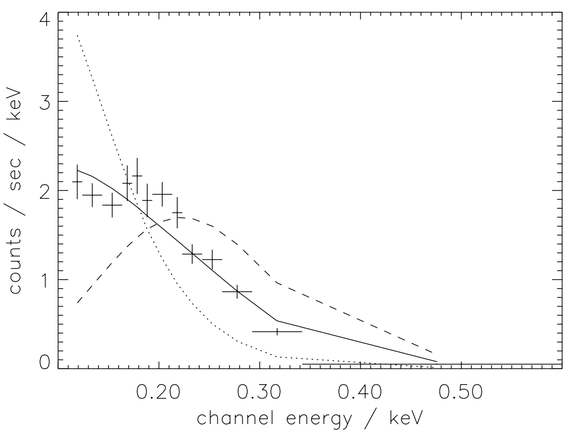

Fig. 7. ROSAT PSPC spectrum of HS 1522+6615. The theoretical count rates were calculated from H+He+C+O NLTE model atmospheres with $T_{\rm eff}$ / kK = 135 (dotted), 140 (fully drawn), 145 (dashed), $\log g = 5.5$, He/H = 10, C/He = 0.003, O/He = 0.005

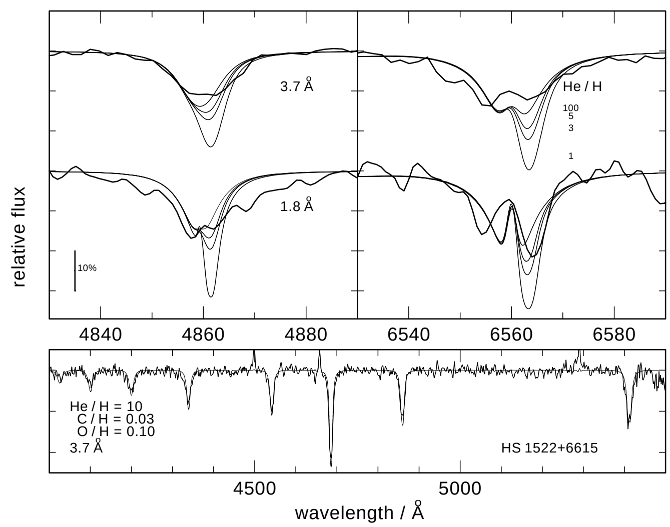

Fig. 8. He / H abundance ratio in HS 1522+6615. Theoretical spectra were calculated with $T_{\rm eff} = 140$kK, $\log g = 5.5$, He / H = 1, 3, 5, and 100 (by number) and are compared with the co-added spectrum (resolution ≈ 3.7 Å) and the single spectrum with higher ≈ 1.5 Å) resolution. In the lower panel a fit of a synthetic spectrum with He / H = 10, C / H = 0.03, and O / H = 0.1 to the observation is shown. Note that the C IV λ 4658Å emission is matched sufficiently well while the oxygen features cannot be modeled

the flux calibration of Heber et al.(1984). The derived parameters are summarized in Table 5.

6. Discussion

"Standard" evolutionary calculations for post-AGB stars (e.g. Schönberner 1979, 1983) are not able to explain the evolution neither of the H-deficient and C-rich PG 1159 stars nor of the He-rich O(He) stars. At the time of its departure from the AGB, a "standard" ($0.6\,M_\odot$ core mass) post-AGB star model predicts still a H-rich envelope of $\approx 5 \cdot 10^{-4}\,M_\odot$ and below this, a He-rich envelope of $\approx 2 \cdot 10^{-2}\,M_\odot$ (Schönberner & Blöcker 1996). Typical PG 1159 abundance patterns are found only close to the C-O core. If we assume that H is burned to He with a rate of $\log \dot{M}/(M_\odot/{\rm yr}) = -7$ (Schönberner & Blöcker 1996) and a mass loss due to a stellar wind is approximately of the same order (Koesterke et al. 1998), then more than 10^3 years are necessary to take off the H-rich envelope, more than 10^5 years to reach the relevant abundances. However, these rates decrease with time and thus, the required times are much too long to obtain the observed abundances.

The photospheric composition of the PG 1159 stars (Table 5) can be explained by the "born-again post-AGB" scenario (Iben et al. 1983, Werner et al. 1991). It predicts a possible final He-flash after the departure from the AGB which brings back the star to the AGB, followed by a second (He burning) departure from the AGB where a superwind and a CSPN wind may take off the entire H-rich and most of the He-rich envelope and lay bare deep intershell layers. However, mass-loss rates much higher (about 2 to 3 orders of magnitude!) than predicted by radiation driven wind theory (Pauldrach et al. 1988) would be necessary because the PG 1159 abundance pattern is found only close to the C-O core.

A well established evolutionary sequence for H-deficient post-AGB stars leads from the Wolf-Rayet [WC] – type CSPN through the PG 1159 phase into the DO white dwarfs (Fig. 11).

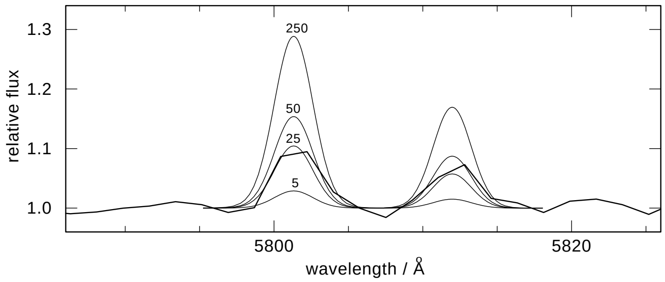

Fig. 9. Carbon abundance in HS 1522+6615. Theoretical spectra were calculated with $T_{\rm eff} = 140$kK, $\log g = 5.5$, He/H = 10, and C/He = 5, 25, 50, 250 $\cdot 10^{-4}$ and are compared with the co-added spectrum (resolution ≈ 3.7 Å). One can interpolate that C IV $\lambda\lambda\, 5801, 5812$Å is best reproduced at C/He = 0.003

The CSPN K 1-27 can be a successor of those He-rich sdO stars (Paper I) which are in a post-AGB evolutionary stage (Fig. 1). In particular, LSE 263 (Husfeld et al.1989) appears to be a good candidate due to similar photospheric abundances. This would define a distinct "sdO(He) $\rightarrow$ O(He) $\rightarrow$ DO white dwarf" channel (Fig. 11) which runs parallel to the PG 1159 evolution.

It seems likely that the post-AGB evolution of both, of O(He) as well as of PG 1159 stars, is already predetermined on the TP-AGB (Sect. 1) where their presently visible abundance pattern is formed under their surface.

Their individual evolution may depend on the phase (between two thermal pulses) at which they leave the TP-AGB: In the case that the departure from the AGB occurs during a helium shell flash, Iben (1995, his case 3) predicts that the fast stellar wind may blow off enough hydrogen from the envelope to prevent a re-ignition of the hydrogen burning. Chemical diffusion may increase the hydrogen (from outside) and carbon (from inside) abundances in the helium buffer layer and a hydrogen shell flash is ignited, creating a "self-induced" nova. The remaining object will exhibit this buffer layer of then almost pure helium with some admixture of nitrogen at an abundance equal to the total number abundance of CNO of the main sequence precursor (that's what the CSPNe K 1-27 and LoTr 4 presently do).

Another possibility is that the O(He) stars just simply experienced a less drastic mass loss than the PG 1159 stars in their TP-AGB and post-AGB phases and the envelope is not that highly eroded. However, then the mass-loss rate would be large enough to expel their entire H-rich envelope at the first departure from the AGB within times which are in accordance with the post-AGB ages of the stars (Table 5).

Concerning their progeny, since nothing is known about the present mass of their remaining He-rich envelopes, a variety of further evolution appears possible:

1. O(He) stars with $\log g \gtrsim 6.0$ will directly evolve into WD because they are close to the WD cooling sequence and their mass-loss rates are probably low. This might be the case for the CSPN K 1-27 and HS 2209+8229.
2. In case of an already very thin He-rich envelope at the time of their departure from the AGB, ongoing mass loss due the

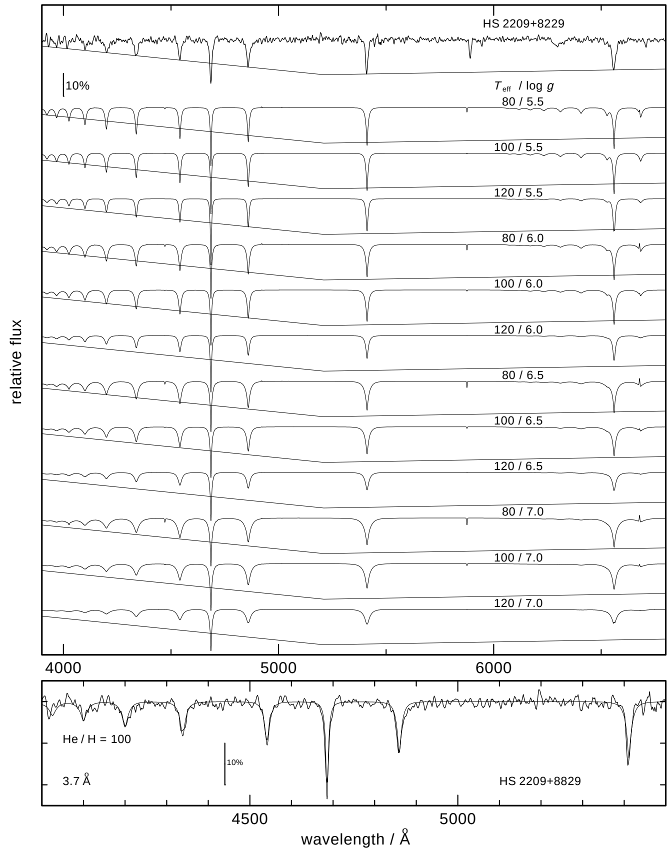

Fig. 10. Theoretical spectra of HS 2209+8829 (convolved with a 3.7Å Gaussian in order to match the spectral resolution) compared with its optical spectrum. The thin lines follow the central depressions of the He II Pickering $(4 - n)$ lines. Note that at $T_{\rm eff} = 80$kK the He I $\lambda\lambda\, 4471, 5876$Å lines are visible but not observed (Fig. 4). At $\log g = 5.5, 6.0$ the He II $5 - n$ series (around 6000Å) is prominent — too strong at $\log g = 5.5$ and $T_{\rm eff} \lesssim 100$ kK! At $\log g = 7.0$ it is impossible to achieve a fit to the observation. The Pickering lines are reproduced well at $T_{\rm eff} = 100$kK and $\log g = 6.0$. The lower panel shows a fit of a synthetic spectrum, calculated with these parameters, with the observation

a stellar wind may lay bare C- and O-rich matter making them "real" PG 1159 stars.
3. In case of a "normal" He-rich envelope ($\approx\, 2 \cdot 10^{-2}\, {\rm M}_\odot$, see above) they may appear as O(He) stars during their first departure from the AGB, experience a late He-shell flash, and then start their second departure from the AGB and follow case 2.

The two objects with lower g and higher mass (Table 5), the CSPN LoTr 4 and HS 1522+6615, are good candidates to be progenitors of the PG 1159 stars: In the case of HS 1522+6615 it is possible that this object is on its first departure from the AGB (post-AGB age of about 200 a) and will experience a late helium flash within about the next 200 a. Its high helium abundance He/H$\gtrsim$10 may then be the result of the high mass-loss rate (Table 4) of this high-mass object (Table 5) at the TP-AGB. A nebula which could be expelled on the AGB is still too close to the star to be spatially resolved. In the case of the CSPN

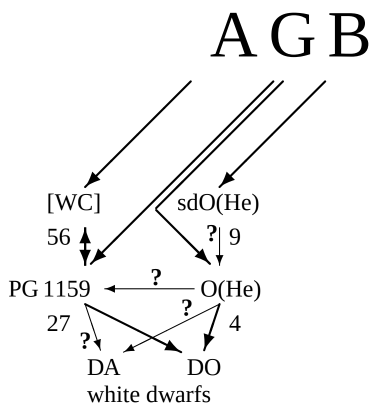

Fig. 11. Scheme of our current picture of He-rich pre - white dwarf evolution. While the [WC] $\rightarrow$ PG 1159 $\rightarrow$ DO white dwarfs sequence appears well established, the evolution of the O(He) strongly depends on both, present mass-loss rate and present mass of the remaining He-rich envelope – the first has not been investigated so far, the latter cannot be determined. The numbers indicate the numbers of presently known objects ([WC] taken from Jeffery et al. 1996; post-AGB sdO(He) from Lemke et al. 1997, Thejll et al. 1994, Harrington & Paltoglou 1993, Rauch et al. 1991, Husfeld et al. 1989). Interestingly, the [WC] : sdO(He) ratio is almost the same like the PG 1159 : O(He) ratio

LoTr 4, a post-AGB age of 29 000 a was estimated (Paper II) and hence, the central star may have already passed a final He flash. However, the additionally identified C IV and O VI lines may suggest that HS 1522+6615 is in a later stage of evolution than the CSPN LoTr 4 but this may also be a result of a higher mass loss due to HS 1522+6615's higher mass (Table 5) already on the AGB.

Within both spectroscopic sub-types, O(He) stars as well as PG 1159 stars, there appear spectroscopic twins (same $T_{\rm eff}$ and g – within the error limits), one of them with an associated PN and one without: The PN / no PN O(He) twins are the CSPN K 1-27 and HS 2209+8229, and the CSPN LoTr 4 and HS 1522+6615 (Table 5), between the PG 1159 stars such pairs are e.g. CSPN NGC 650 / PG 1159-035 and CSPN Abell 21 / PG 1144+005 (Fig. 1). The existence of PN / no PN twins is an unsolved problem:

1. If all O(He) stars and PG 1159 stars are post-AGB stars and have ejected a PN on the AGB, then "PN / no PN" requires that the no PN – object has to evolve much more slowly for the PN to disappear which seems impossible because the twins have similar masses (Fig. 1).
2. If the no PN – object avoided to eject a PN on the AGB, how could this happen?
3. If the no PN – object is not a post-AGB object, how could it evolve into the CSPN region in the $\log T_{\rm eff} - \log g$ diagram (Fig. 1)?

We speculate that the lower degree of erosion of the O(He) envelopes is mainly due to a different evolution on the TP-AGB where e.g. the mass-loss rate is a sensitive function of initial mass and the phase (between the thermal pulses) of their departure determines their further evolution.

However, the final evolution of both, O(He) stars as well as PG 1159 stars, into WD is inevitable – if there is any remaining hydrogen in their envelopes they will appear as hydrogen-rich (DA) WD when the heavier elements sink down due to gravitational settling. Otherwise they will start on the WD cooling sequence as a helium-rich DO WD.

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References

Acker A., Ochsenbein F., Tylenda R., Marcont J., Schohn C. 1992, Strasbourg-ESO Catalogue of galactic planetary nebulae
Allen C.W. 1973, Astrophysical Quantities, The Athlone Press, London
Appleton P.N., Kawaler S.D., Eitter J.J. 1993, AJ 106, 1973
Blöcker T. 1995, A&A 299, 755
Blöcker T., Schönberner D. 1990, A&A 240, L11
Blöcker T., Herwig F., Schönberner D., El Eid M. 1997, in: B. Wing (ed.), The Carbon Star Phenomenon, IAU Symp. 177, Kluwer, Dordrecht, in press
Burstein D., Heiles C. 1982, AJ 87, 1187
Cruddace R., Paresce F., Bowyer S., Lampton M. 1974, ApJ 187, 497
Dickey J.M., Lockman F.J. 1990, ARA&A 28, 215
Gillet F.C., Jacoby G.H., Joyce R.R., et al. 1989, ApJ 338, 862
Harrington J.P., Paltoglou G. 1993, ApJ 411, L103
Heber U., Dreizler S., Hagen H.-J. 1996, A&A 311, L17
Heber U., Hunger K., Jonas G., Kudritzki R.P. 1984, A&A 130, 119
Herwig F., Blöcker T., Schönberner D., El Eid M. 1997, A&A 324, L81
Hubeny I., Hummer D.G., Lanz T. 1994, A&A 282, 157
Hummer D.G., Mihalas D. 1988, ApJ 331, 794
Husfeld D., Butler K., Heber U., Drilling J.S. 1989, A&A 222, 150
Iben I.Jr. 1995, Phys. Rep. 250, 1
Iben I.Jr., MacDonald J. 1995, in: D. Koester, K. Werner (eds.) White Dwarfs, Lecture Notes in Physics 443, Springer, Berlin, p. 48
Iben I.Jr., Kaler J.B., Truran J.W., Renzini A. 1983, ApJ 264, 605
Jeffery, C.S., Heber, U., Hill, P.W., et al. 1996, in: Hydrogen-Deficient Stars, eds. C.S. Jeffery, U. Heber, ASP Conference Series, Vol. 96, p. 471
Jordan S., Wolff B., Koester D., Napiwotzki R. 1994, A&A 290, 843
Köppen J. 1979, A&AS 35, 111
Koesterke L., Dreizler S., Rauch T. 1998, A&A 330, 1041
Kohoutek L. 1977, A&A 59, 137
Lemke M., Heber U., Napiwotzki R., Dreizler S., Engels D. 1998, in: A.G.D. Philip, J. Liebert, R.A. Saffer (eds.) The Third Conference on Faint Blue Stars, L. Davis Press, Schenectady, NY, in press
Méndez R.H., Miguel C.H., Heber U., Kudritzki R.P. 1986, in: Hunger K., Schönberner D., Rao N.K. (eds.), Hydrogen deficient stars and related objects, Reidel, Dordrecht, p. 323
Morrison R., McCammon D. 1983, ApJ 270, 119
Motch C., Werner K., Pakull M.W. 1993, A&A 268, 561
Pauldrach A., Puls J., Kudritzki R.P., Méndez R.H., Heap S.R. 1988, A&A 207, 123

Rauch T., Heber U., Hunger K., Werner K., Neckel T. 1991, A&A 241, 457
Rauch T., Köppen J., Werner K. 1994, A&A 286, 543 (Paper I)
Rauch T., Köppen J., Werner K. 1996, A&A 310, 613 (Paper II)
Schönberner D. 1979, A&A 79, 108
Schönberner D. 1983, ApJ 272, 708
Schönberner D., Blöcker T. 1996, Ap&SS 245, p. 201
Seaton M.J. 1979, MNRAS 187, 73P
Thejll P., Bauer F., Saffer R., Liebert J., Kunze D., Shipman H.L. 1994, ApJ 433, 819
Tody D. 1986, in: Crawford D.L. (ed.) Proc. SPIE 627, 733
Werner K. 1986, A&A 161, 177
Werner K. 1996, ApJ 457, L39
Werner K., Heber U., Hunger K. 1991, A&A 244, 437
Werner K., Dreizler S., Heber U., et al.1997, in: Schielicke R.E. (ed.), Reviews in Modern Astronomy 10, Astronomische Gesellschaft, Hamburg, p. 219
Zimmermann H.U., Becker W., Belloni T., et al. 1994, EXSAS User's Guide, MPE Report 257