[WN] central stars of planetary nebulae [1][2]

H. Todt*, M. Peña†, W.-R. Hamann* and G. Gräfener**,*

*University of Potsdam, Institute for Physics and Astronomy, 14476 Potsdam, Germany
†Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70264, México D.F. 04510, México
**Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland

Abstract. Hydrogen-deficient central stars are commonly considered as the progenitors of H-deficient white dwarfs. Spectroscopically, many H-deficient central stars resemble massive Wolf-Rayet stars of the carbon sequence and are therefore classified as [WC] stars. The massive WR stars of the nitrogen sequence (WN), however, have no spectroscopic counterpart among the central stars. With PB 8 we found for the first time a central star with a WR-type emission line spectrum that resembles the nitrogen sequence with only a slight enhancement of carbon lines, and therefore we classified this star as [WN/C]. Our analysis reveals that its atmosphere consists mainly of helium, with some hydrogen and only traces of carbon, nitrogen, and oxygen. This is very different from any other Wolf-Rayet type central stars. The results of our analyses, especially the chemical composition, strongly constrains possible scenarios for the formation of PB 8. For the time being, we don't know any path of single-star evolution that could explain this enigmatic central star. In this context, we will also discuss the status of the central star of PMR 5, which is another candidate for a [WN] spectral type.

Keywords: Stars: abundances – Stars: AGB and post-AGB – Stars: atmospheres – Stars: mass-loss – Stars: PN PB 8 – Stars: PMR 5 – Stars: Wolf-Rayet
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INTRODUCTION

Wolf-Rayet central stars are hydrogen deficient central stars of planetary nebulæ which exhibit in their spectra strong emission lines of carbon, helium, and oxygen. Because their spectra resemble those of massive WC stars, they are called [WC] stars, with brackets to distinguish them from their massive counterparts. In spite of spectral similarities and comparable chemical composition, the formation of the low-mass [WC] stars is completely different from the formation of the massive WC stars. Stellar evolutionary models accounting for simultaneous burning and mixing explain the formation of a [WC] star by the occurrence of a thermal pulse (TP) at the very end or after the asymptotic giant branch (AGB) phase of a H-normal low-mass star. These models predict a hydrogen-deficient surface composition with carbon enriched up to X_C = 40%

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[1] This paper includes data gathered with the 6.5-m Magellan Telescopes located at Las Campanas Observatory, Chile.
[2] Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the AURA, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided mainly by the NASA Office of Space Science via grant NAG5-7584. Based on INES data from the IUE satellite.

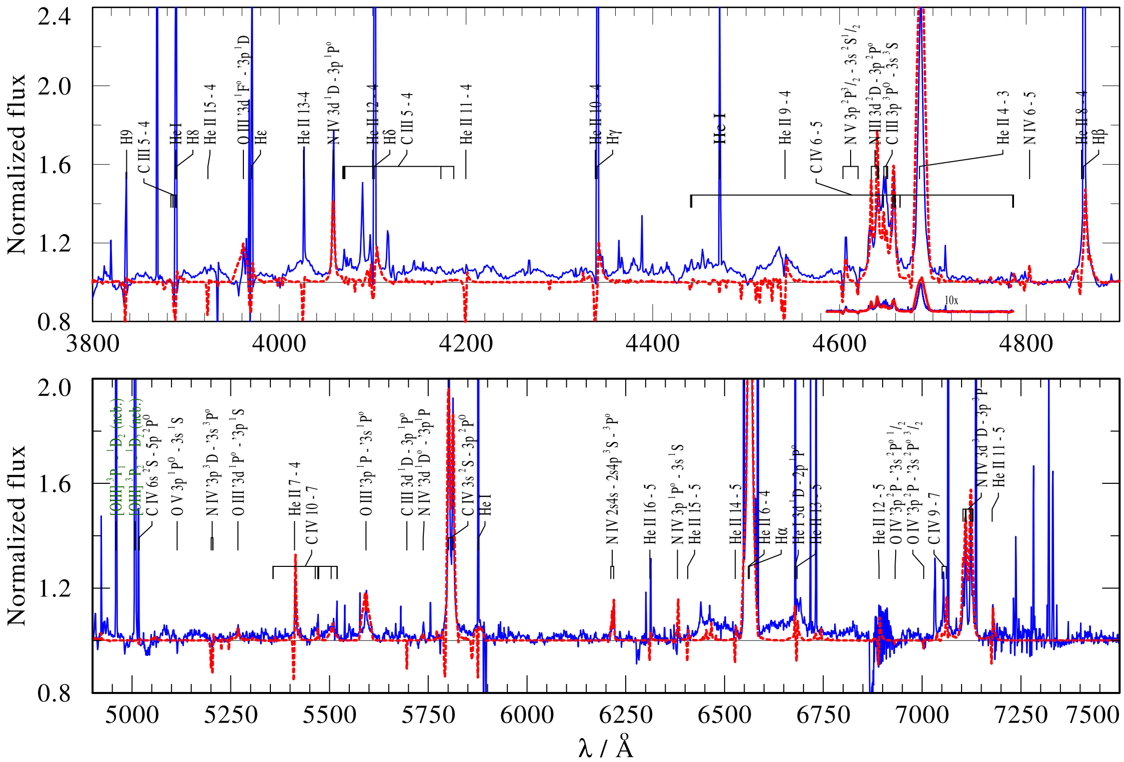

FIGURE 1. Optical spectrum of PB 8: observation (blue, thin line) and best-fitting PoWR model (red, thick dotted line), both normalized to the model continuum. The observation is rebinned to 1 Å.

after a late or very late TP [1, 2]. Only in the case of a very late TP (VLTP) a supersolar nitrogen abundance of about $X_{\rm N} = 1\%$ is expected, but without any remaining hydrogen. Thus low-mass central stars with WN-like surface abundances are theoretically not expected.

PB 8

The central star of the planetary nebula (PN) PB 8 (PN G292.4+04.1) was first classified by Méndez [3] as a hydrogen-rich Of-WR(H) star. In contrast, Acker and Neiner [4] classified this star as a [WC5-6] type star. Therefore we included PB 8 in our analyses of [WC] stars.

High-resolution optical spectroscopy of PB 8 was performed on 2006 May 9 at Las Campanas Observatory (Carnegie Institution) with the Clay 6.5m-telescope and the double échelle spectrograph MIKE (Magellan Inamori Kyocera Echelle) with a wavelength coverage of 3350 – 5050 Å and 4950 – 9400 Å (cf. Fig. 1). A low-resolution UV spectrum (1200 to 2000 Å), taken with the International Ultraviolet Explorer (IUE), and a high-resolution FUV spectrum (960 to 1190 Å), taken with the Far Ultraviolet Spectroscopic Explorer (FUSE), were retrieved from the MAST archive. Photometric data from optical to IR range were used in addition.

For the spectral analysis we employed the Potsdam Wolf-Rayet (PoWR) models of

TABLE 1. Parameters of PB 8

T_*	52 ± 2	kK
υ_∞	1000 ± 100	$\mathrm{km\,s^{-1}}$
$\log \dot{M}$	$-7.07^{+0.17}_{-0.13}$	$M_\odot\,\mathrm{a}^{-1}$
$\log R_\mathrm{t}$	$1.43^{+0.12}_{-0.08}$	$R_\odot$
D	10	(density contrast)
$E_\mathrm{B-V}$	0.41 ± 0.01	mag
$d(L_* = 6000\,\mathrm{L}_\odot)$	4.2 ± 0.2	kpc
υ_rad	12	$\mathrm{km\,s^{-1}}$
H	40^{+20}_{-10}	% mass fraction
He	55^{+11}_{-22}	% mass fraction
C	$1.3^{+0.7}_{-0.3}$	% mass fraction
N	$2.0^{+1.0}_{-0.5}$	% mass fraction
O	$1.3^{+0.7}_{-0.3}$	% mass fraction
Fe	1.6×10^{-3}	% mass fraction
P	5.2×10^{-6}	% mass fraction
Si	3.2×10^{-4}	% mass fraction

expanding atmospheres. The PoWR code solves the radiative transfer in the comoving frame and calculates consistently the non-LTE population numbers. Iron-line blanketing is treated by the superlevel approach. Optically thin inhomogeneities (micro-clumping) are taken into account.

For a given stellar temperature T_* and chemical composition, the equivalent width of the emission lines depend mainly on the *transformed radius*

$$R_\mathrm{t} = R_* \left[\frac{\upsilon_\infty}{2500\,\mathrm{km\,s^{-1}}} \Big/ \frac{\dot{M}\sqrt{D}}{10^{-4}\,\mathrm{M}_\odot\,\mathrm{a}^{-1}} \right]^{2/3} . \tag{1}$$

For the lack of a reliable distance estimate, the stellar luminosity was set to a typical value for CSPNe, $L = 6000\,L_\odot$ [see e.g. 5, 6]. With the help of Eq. (1) the results can be easily scaled to different luminosities. The results of our analysis are summarized in Table 1, details are described in Todt et al. [7]. We found that the chemical composition is very different from other [WC] stars and resembles more that of the massive WNC stars.

Therefore we considered the possibility of PB 8 being a massive WR star with a *ring nebula*. However, the nebular analysis by García-Rojas et al. [8] found evidence that the nebula of PB 8 is indeed a PN. Furthermore, if the central star of PB 8 were a massive star, this would imply a luminosity of at least $\log(L/L_\odot) = 5.3$, which shifts the distance to ≈ 24.2 kpc. With a Galactic latitude of $4°$ this corresponds to a height of 1.7 kpc above the fundamental plane of the Galaxy. This is much more than the scale height of the thin disk and therefore an unlikely location for a massive star.

We also discussed the possibility that PB 8 is a binary. Méndez [3] did not find any variability of radial velocities. Moreover, the nebula appears spherically symmetric [9],

TABLE 2. Parameters of PMR 5.

T_*	56	kK
v_∞	1500 ± 400	$\mathrm{km\,s^{-1}}$
$\log \dot{M}$	-5.5	$M_\odot\, a^{-1}$
$\log R_\mathrm{t}$	0.56	$R_\odot$
D	4	(density contrast)
$E_\mathrm{B-V}$	3	mag
$d(L_* = 6000\, L_\odot)$	0.5	kpc
H	20	% mass fraction
He	69	% mass fraction
C	< 1	% mass fraction
N	10	% mass fraction
O	-	% mass fraction

also in velocity space. Hence binarity of PB 8 is rather unlikely. The surface composition of PB 8 appears unique among all CSPNe. Only two other CSPNe (PMR 5 and the enigmatic variable LMC-N 66) are known to show a WN-type composition. Two more CSPNe are known to be helium-rich, but without strong winds [LoTr 4 and K 1-27, 10]. Note that there is a He-sdO star without PN, KS 292 (alias Hbg 292), that shows a similar composition as PB 8, including the enhanced carbon abundance [11]. This poses the question of how to explain the evolutionary origin of PB 8. As mentioned above, only in the case of a VLTP a supersolar nitrogen abundance is expected. On the other hand, the observed hydrogen and carbon abundance would rather favor a TP at the end of the AGB phase. However, one can imagine scenarios of a weak or anomalous thermal pulse, occurring on the AGB or later, which may explain the unique chemical composition of this star.

PMR 5

PMR 5 was discovered by Morgan et al. [12], who classified it as a [WN] star, due to its helium an nitrogen emission lines. Because of the high reddening of $E_\mathrm{B-V} = 3.0\,\mathrm{mag}$ towards PMR 5 they could only obtain a low quality optical spectrum without the blue part (cf. Fig. 2). We tried to reproduce this spectrum with our PoWR models. The results of our tentative fit are given in Table 2. In spite of the extremely high nitrogen abundance, the chemical composition is very similar to that of a massive WN star. With the help of photometric data for B, I, R, and JHK we derive a relatively low distance of only 500 pc when adopting a CSPN luminosity. On the other hand, if PMR 5 were a massive WN star, the luminosity distance would be 2.9 kpc and the height above the Galactic plane would be 35 pc. This location is not implausible for a massive WN star and more consistent with the high reddening. Furthermore, the nebular analysis by Morgan et al. [12] yields a nebular expansion velocity of $165\,\mathrm{km\,s^{-1}}$. This is about ten times the typical expansion velocities of PNe and rather typical for ring nebulæ around massive stars.

Therefore we doubt that PMR 5 is a central star of a PN.

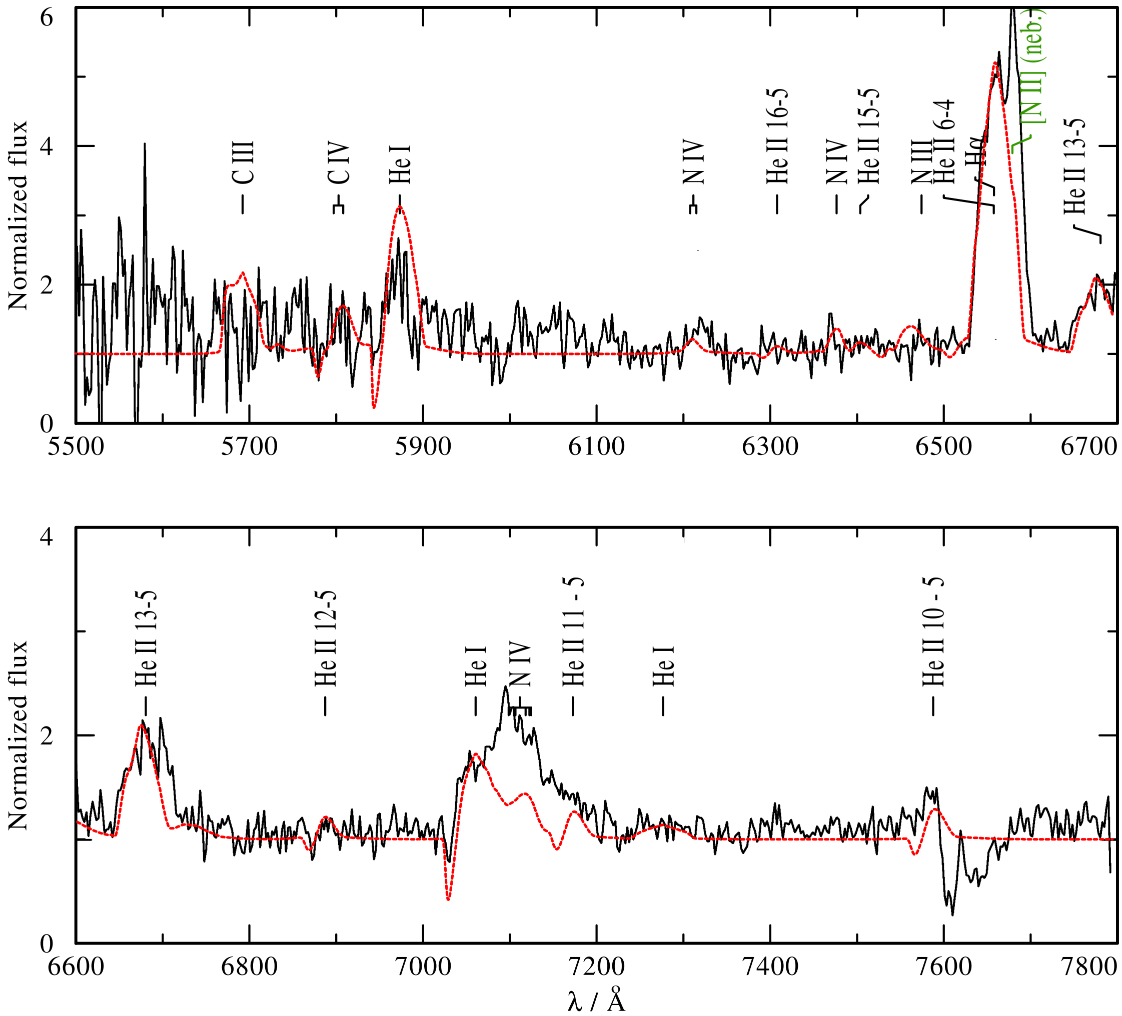

FIGURE 2. Optical spectrum of PMR 5: observation (black thin line) adopted from Morgan et al. [12] vs. a PoWR-model with 10 % nitrogen (red, thick dotted line). To match the observation, the model spectrum and the identifiers for the spectral lines are shifted to shorter wavelengths by $v_{\rm rad} = 200\,{\rm km\,s^{-1}}$.

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