Hydrogen-deficient central stars of planetary nebulae

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Abstract. A significant number of the central stars of planetary nebulae (CSPNe) are hydrogen-deficient and are considered as the progenitors of H-deficient white dwarfs. Almost all of these H-deficient CSPNe show a chemical composition of helium, carbon, and oxygen. Most of them exhibit Wolf-Rayet-like emission line spectra and are therefore classified as of spectral type [WC]. In the last years, CSPNe of other Wolf-Rayet spectral subtypes have been identified, namely PB 8 (spectral type [WN/WC]), IC 4663 and Abell 48 (spectral type [WN]). We performed spectral analyses for a number of Wolf-Rayet type central stars of different evolutionary stages with the help of our *Potsdam Wolf-Rayet (PoWR)* model code for expanding atmospheres to determine relevant stellar parameters. The results of our recent analyses will be presented in the context of stellar evolution and white dwarf formation. Especially the problems of a uniform evolutionary channel for [WC] stars as well as constraints to the formation of [WN] or [WN/WC] subtype stars will be addressed.

1. Introduction

Low mass stars in a certain mass range become central stars of planetary nebulae (CSPNe) during their evolution. Central stars (CSs) are post-AGB stars on the way to the white-dwarf (WD) cooling track with effective temperatures above 25 kK, thus hot enough to ionize circum-stellar material, that was ejected during the AGB phase. The ionized circum-stellar gas becomes visible as a planetary nebula (PN) around the CS. While most of the low mass stars stay hydrogen-rich at the surface throughout their life, a fraction of about 20 per cent of CSs show a hydrogen-deficient surface composition. Almost all of these H-deficient CSs exhibit spectra with strong carbon and helium lines, indicating that their surface is composed predominantly by these elements (e.g. Górny & Tylenda 2000; Werner & Heber 1991). As these objects show spectra very similar to the massive WC stars, they are classified as [WC], where the brackets distinguish them from their massive counterparts.

A refined classification of [WC] stars is based on spectral lines from different ions. The so-called "early" subtypes [WCE] show lines of highly ionized species like C IV, He II, O V, and O VI, while the spectra of the "late" subtypes [WCL] are dominated by lines from C II - IV and He I. Hence, the sequence of decreasing subtype number corresponds to increasing ionization, and therefore increasing effective temperature. If central stars evolve directly from the AGB to the WD stage, they should first become [WCL] and then [WCE] subtypes, according to the suggested sequence AGB → [WCL] → [WCE] → [WC]-PG 1159 → WD (e.g. Werner & Heber 1991).

Stellar evolutionary models accounting for simultaneous burning and mixing explain the formation of [WC] stars by the occurrence of a thermal pulse (TP) either at the very end or after the AGB phase of a H-normal low-mass star. These models predict a hydrogen-deficient atmospheric composition with carbon enriched up to $X_{\rm C} = 40\,\%$ by mass after a late or very late TP without drastic changes during the following [WC] phase. In the case of a very late TP (VLTP Herwig 2001; Althaus et al. 2005) a supersolar nitrogen abundance of about $X_{\rm N} = 1\,\%$ is expected, while hydrogen is completely burnt.

However, previous analyses of [WC] stars based on optical and UV spectra resulted in systematically different abundance patterns for [WCE] and [WCL] subtypes. For the [WCL] stars, atmospheric abundances of about He:C:O=0.4:0.5:0.1 by mass were found (Leuenhagen & Hamann 1994; Leuenhagen et al. 1996; Leuenhagen & Hamann 1998; Marcolino et al. 2007), while Koesterke & Hamann (1997) and Koesterke (2001) found He:C:O=0.6:0.3:0.1 for a sample of 12 [WCE] stars. In contrast, Crowther et al. (2003) and Marcolino et al. (2007) determined He:C:O=0.45:0.45:0.1 for three [WCE] stars. Moreover, for some of the [WCL] objects (Leuenhagen & Hamann 1998) reported supersolar nitrogen and neon abundances.

To clarify the situation we re-analyzed a sample of 11 [WCE] stars with improved line-blanketed stellar atmosphere models.

2. Analysis

For the determination of the atmospheric abundances and other stellar parameters we performed spectral analyses with help of the *Potsdam Wolf-Rayet (PoWR)* models of 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 (microclumping) are taken into account. For a given stellar temperature T_* and chemical composition, the equivalent widths of the emission lines depend in first approximation only on the *transformed radius*

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

As we lack of reliable distance estimates for our objects, we set the stellar luminosity and mass to typical values for CSPNe, i.e. $L = 6000\,L_\odot$ and $M = 0.6\,M_\odot$ (see e.g. Schönberner et al. 2005; Miller Bertolami & Althaus 2007). With help of Eq. (1) the results can be scaled to different luminosities.

The preliminary results of our analyses are summarized in Table 1. While the C:He abundances are similar for these objects, we found different nitrogen abundances, ranging from subsolar (NGC 6905) up to 1.5% by mass (e.g. PB 6). Interestingly, those stars with supersolar nitrogen abundances also show an overabundance of neon.

Table 1. Preliminary results of our analyses of [WCE] stars

Object	X_C	X_He	X_O	X_N	X_Ne	T_*	R_t	υ_∞
			% mass fraction			[kK]	[$R_\odot$]	[km s^{-1}]
NGC 2867	30	60	10	< 0.5	2	160	5.0	2000
PB 6	30	60	10	1.5	>2	160	5.0	2200
NGC 5189	30	60	10	1.5	>2	160	5.0	2000
NGC 6905	30	60	10	$< 1 \times 10^{-4}$	2	150	4.0	2000
NGC 7026	30	60	10	< 0.06	–	140	6.3	2000
Hen 2-55	30	60	10	≤ 0.1	0.001	126	10	2000
[S71d]3	30	60	10	1	1.5	180	2.5	2400
IC 1747	30	60	10	< 0.5	–	112	10	2000
NGC 1501	40	50	10	7×10^{-4}	–	126	5.0	2000
NGC 6369	30	56	14	–	–	126	5.0	2000
NGC 5315	30	60	10	< 0.1	–	79	6.3	2000

3. The [WN] and [WN/WC] central stars

Recently, quantitative spectral analyses of three CSs with broad emission lines revealed that they do not belong to the [WC] class. The first one was PB 8 (Todt et al. 2010), which should be classified as [WN/WC] type. The other ones, IC 4663 (Miszalski et al. 2012) and Abell 48 (Todt et al. 2013; Frew et al. 2014) show [WN] type spectra (see Fig. 1). The atmospheres of these stars are mainly composed of helium (cf. Tab. 2), with supersolar mass fractions of nitrogen and only traces of carbon.

The surface compositions of the [WN] and [WN/WC] stars are completely different from those of the [WC] stars. This poses the question how to explain the evolutionary origin of these objects. As mentioned above, only in the case of a VLTP a

Table 2. Stellar and wind parameters of the known [WN] and [WN/WC] stars from (Todt et al. 2010, 2013) and (Miszalski et al. 2012)

Object	X_H	X_{He}	X_C	X_N	X_O	T_*	R_t	$\log \dot{M}$	v_∞
		% mass fraction				[kK]	$[R_\odot]$	$[M_\odot\,\mathrm{yr}^{-1}]$	$[\mathrm{km\,s}^{-1}]$
PB 8	40	55	1.3	2.0	1.3	52	27	−7.1	1000
IC 4886	< 2	95	< 0.1	0.8	0.05	140	12	−7.7	1900
Abell 48	10	85	0.3	5	≤ 0.6	70	0.85	−6.4	1000

supersolar nitrogen abundance is expected. On the other hand, for PB 8 and Abell 48 the observed hydrogen abundances would rather favor a TP at the end of the AGB phase. Alternatively, Miller Bertolami et al. (2011) proposed that PB 8 was formed by a diffusion-induced CNO flash during the early cooling-stage of a DA white dwarf of low metallicity.

4. Summary

Our newly derived chemical abundances of [WCE] stars and of the [WC]-PG 1159 born-again stars Abell 30 and Abell 78 (cf. Todt et al., these proceedings) corroborate the suggested sequence [WCE] → [WC]-PG 1159. The supersolar nitrogen abundance which we found for the [WC]-PG 1159 stars and for some of the [WCE] stars favor a VLTP scenario for these objects. However, for those [WCE] stars that show subsolar nitrogen abundances it remains uncertain whether they are really formed by a VLTP.

The [WN/WC] and [WN] stars PB 8, IC 4663, Abell 48 seem to come from a different evolutionary channel, as they do not show high carbon and oxygen abundances. PB 8 may have been created by a diffusion-induced nova.

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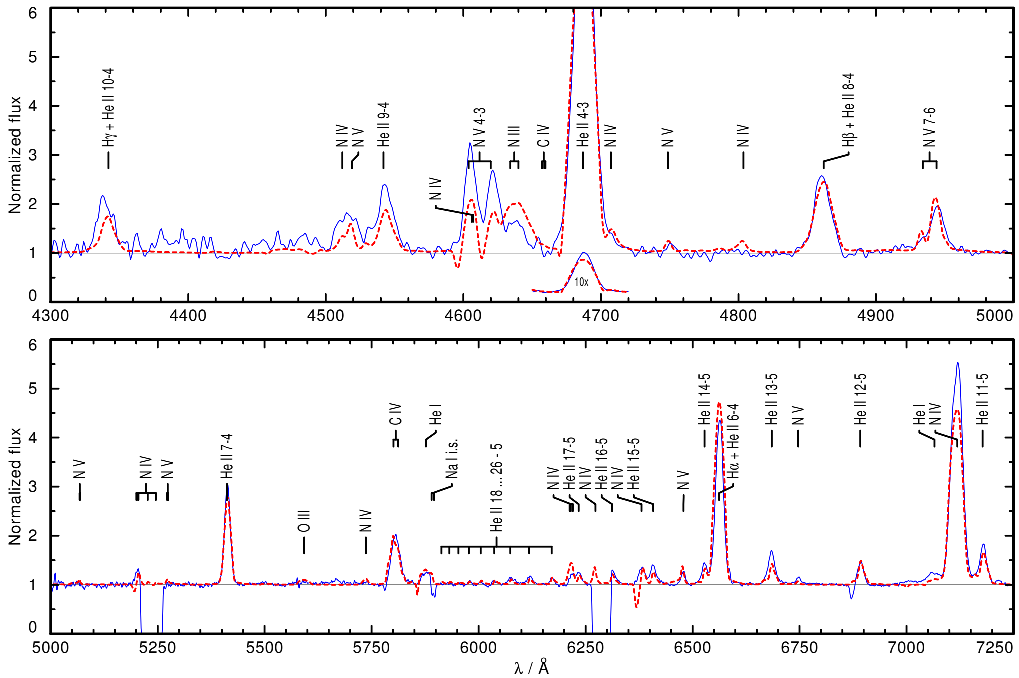

Figure 1. Abell 48 optical spectrum: observation (blue solid lines), obtained with the *South African Large Telescope (SALT)* vs. best fitting *PoWR* model (red dashed)

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