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# Determining element abundances of [WC]-type Central Stars for probing stellar evolution and nucleosynthesis

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**Abstract.** [WC]-type CSPNs are hydrogen-deficient Central Stars of Planetary Nebulae showing strong stellar winds and a carbon-rich chemistry. We have analyzed new high-resolution spectra of [WC]-type CSPNs with the Potsdam Wolf-Rayet (PoWR) non-LTE expanding atmosphere models, using upgraded model atoms and atomic data. Previous analyses are repeated on the basis of the current models which account for iron-line blanketing. We especially focus on determining the chemical composition, including some trace elements like nitrogen which are of key importance for understanding the evolutionary origin of the hydrogen-deficient Central Stars.

## 1. Introduction

Roughly 10% of the galactic Central Stars of Planetary Nebulae are hydrogen-deficient (Gorny 2001, Tylenda et al. 1991). Their spectra are dominated by helium, carbon, and oxygen emission lines and hence very similar to those of massive PopI WC stars. Their spectral type is termed [WC], where the brackets distinguish them from their massive counterparts.

Similar to the PopI WC classification scheme there is a sequence from the "early" subtypes [WC2-5] showing lines of C IV, He II and O V-VII to the "late" subtypes [WC6-11] with spectra dominated by lower ions. This scheme was later refined by Acker & Neiner (2003) such that the earliest types of [WC] stars which show very strong emission of O VI are designated as [WO1-4] stars.

It was suggested that this classification scheme corresponds to an evolutionary sequence from the cooler [WC]-late types to the hotter [WC]-early types. The determination of element abundances by spectral analyses provides the empirical base for understanding the origin and evolution of H-deficient [WC] stars.

## 2. Formation of [WC] Central Stars

According to stellar evolution modeling from Herwig (2001), [WC] stars have lost their hydrogen envelope after the AGB evolution during a last thermal pulse. Depending on the evolutionary stage at which this pulse overtakes the star there are three possible scenarios resulting in different element abundances:

The AGB Final Thermal Pulse (AFTP) at the tip of the AGB only mixes the hydrogen down, so that e.g. a model for simultaneous burning and mixing yields mass fractions of $X_{\rm H} = 0.17$, $X_{\rm He} = 0.33$, $X_{\rm C} = 0.32$, $X_{\rm O} = 0.15$. The Late Thermal Pulse (LTP) occurs just before entering the White Dwarf cooling track, bringing the star back to the beginning of the post-AGB evolution and results in $X_{\rm H} = 0.02$, $X_{\rm He} = 0.37$, $X_{\rm C} = 0.40$, $X_{\rm O} = 0.18$. The last pulse can also happen very late (VLTP), after entering the White Dwarf cooling track. Then the hydrogen is completely burnt, and enhanced abundances of nitrogen and neon are predicted. The star is thrown back to the post-AGB phase like in the LTP scenario and has finally $X_{\rm He} = 0.31$, $X_{\rm C} = 0.42$, $X_{\rm O} = 0.23$ and $X_{\rm N} = 0.012$, $X_{\rm Ne} = 0.021$, as derived by Althaus et al. (2005).

## 3. Stellar wind models with PoWR

[WC] stars have extended atmospheres with complex ionization structure. For a determination of stellar temperature, mass-loss rate and element abundances by spectral analyses, an appropriate modeling of the wind is necessary. Such models are provided by codes like CMFGEN and the Potsdam Wolf-Rayet model atmospheres (PoWR), which treat the radiative transfer in the comoving frame in full non-LTE. We used our code, PoWR, which includes iron-line blanketing and clumping. Additionally we implemented higher ions, which were not considered in previous analyses.

## 4. Analysis

*Carbon and helium.* Spectral analyses revealed that the main constitutes of the expanding atmospheres are helium and carbon, in agreement with the above-mentioned last thermal pulse scenarios. However, a difference was found between the C:He ratios for the late-subtypes ([WCL]) and the early-subtypes ([WCE]). Previous analyses of [WCL] stars by Leuenhagen et al. (1996, 1998) yielded typical ratios $X_{\rm C}$:$X_{\rm He}$ = 50:40. This was also found by Crowther & Abbott (2003) and Marcolino et al. (2007), see also Crowther (these proceedings). Similar ratios for [WCE] stars were found by De Marco et al. (2001) and Marcolino et al. (2007). In contradiction, Koesterke & Hamann (1997a, 1997b) found for [WCE] stars typically $X_{\rm C}$:$X_{\rm He}$ = 30:50, as we confirm by our new analyses. We employed new high-resolution observations of [WCE] stars in order to clarify the carbon abundances. By fitting all carbon and helium lines with special focus on the diagnostic line pair He II (5412Å) / C IV (5470Å), as for NGC 2867 ([WC2]) in Fig. 1, our preference for lower carbon abundance seems to be confirmed.

*Nitrogen.* Following Werner & Herwig (2006), only a VLTP can efficiently produce nitrogen overabundance. We focused on two lines of N V being sensitive to the nitrogen abundance, namely around 4600 and 4940 Å, which are used for PopI WR analyses, too. We found $X_{\rm N} = 1 \ldots 2\%$ for most of our [WCE] stars, e.g. PB6 (Fig. 2), NGC 2867, and NGC 5189.

*Hydrogen.* Hydrogen could discriminate between the different scenarios, but H lines are always blended with He II lines and nebular emission. Leuenhagen & Hamann (1998) estimated upper limits for few [WCL] stars and estimated $X_{\rm H} = 0.01$ for PM 1-188 and $X_{\rm H} = 0.10$ for IRAS 21282+5050. A more definite detection of $X_{\rm H} = 0.037$ for V 348 Sgr was reported by Leuenhagen & Hamann (1994). For the hotter of the [WCE] stars even a mass fraction of 10% would escape detection.

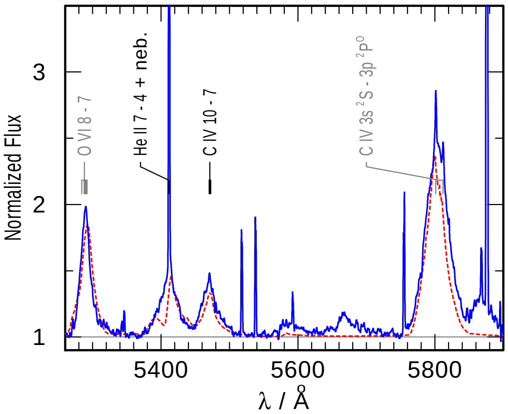


Figure 1. Spectrum of NGC 2867 ([WC2]), observation (solid line) and model with $X_{\rm C}$:$X_{\rm He}$ = 26:65 (dashed).

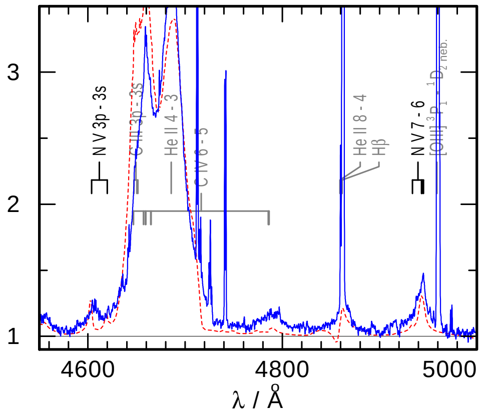


Figure 2. Spectrum of PB 6 ([WC2]), observation (solid) and model with $X_{\rm N} = 1.5\%$ (dashed).

*Neon.* Stars that suffered a VLTP should show an overabundance of neon. Herald, Bianchi, & Hillier (2005) found a strong Ne VII resonance line (973.33 Å) in the FUSE spectrum of NGC 2371. Unfortunately this line is almost saturated already at solar neon abundance, and other lines like the Ne VI multiplet around 2225 Å or the Ne VII absorption line at 3644.3 Å are needed for the determination of neon abundances (Fig. 3). However, spectra in these ranges are only available for some of the [WC] stars. Furthermore, the modeled line in the IUE range is neither qualitatively nor quantitatively fitting the observation with any reasonable neon abundance and is therefore raising doubts whether the observed P Cygni profile is really due to neon. The line at 3644.3 Å shows no evidence for higher neon abundance.

*Iron.* Iron depletion via s-process nucleosynthesis was predicted by Herwig, Lugaro, & Werner (2003) and observed by Stasinska et al. (2004) and Marcolino et al. (2007) for [WC] stars. In contrast, for the [WCE] stars of our analysis we

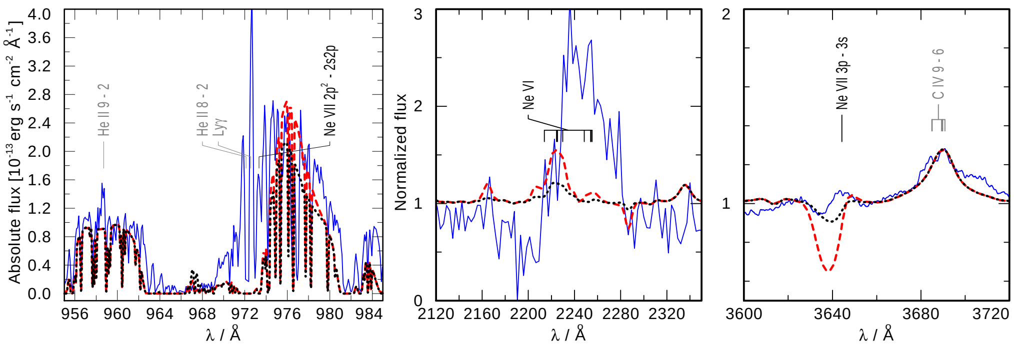


Figure 3. NGC 5189 ([WC2]): observations (solid line) from FUSE, IUE, Magellan Telescope and models with $X_{\rm Ne} = 3\%$ (dashed) and 0.3% (dotted) respectively. Models for FUSE range were corrected for ISM absorption.

observed only for NGC 6751 an iron forest but without any unambiguous hint for a subsolar iron abundance. This is in agreement with models of very hot [WCE] stars, which do not show an iron forest.

## 5. Conclusions

The [WCL] analyses by Leuenhagen et al. (1996, 1998) resulted in abundances of neon of 2 . . . 4%, nitrogen about 1%, and carbon around 50%, as confirmed by De Marco et al. (2001), Crowther & Abbott (2003) and Marcolino et al. (2007). These abundances would be consistent with the VLTP scenario. But the detection of hydrogen up to 10% rather points to an AFTP or LTP origin.

We re-analyzed [WCE] stars with improved models and new high-resolution spectra in the optical and FUSE range. The neon lines could not be fitted consistently, thus leaving the Ne abundance unclear. More definite is the over-abundance of nitrogen of 1 . . . 2% for many of the [WCE] stars. This points to a VLTP origin. Contradictory are the systematically lower carbon abundances of [WC2] stars compared with [WCL] type stars. This challenges the scenario of an evolutionary sequence from [WCE] to [WCL]. Moreover, the low carbon abundances are indicative for the AFTP scenario. But despite problems with analyses one should keep in mind that even theoretical predictions for carbon abundances scatter.

As the situation is still unclear, we will proceed with our spectral analyses, employing new observations and refining our models with improved atomic data.

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