***Volume Title***
*ASP Conference Series, Vol. **Volume Number***
***Author***


# Spectral analyses of Wolf-Rayet type central stars

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**Abstract.** A considerable fraction of the central stars of planetary nebulae (CSPNe) are hydrogen-deficient. These stars are commonly considered as the progenitors of H-deficient white dwarfs. As a rule, these CSPNe exhibit a chemical composition of helium, carbon, and oxygen, most of them showing Wolf-Rayet-like emission line spectra and are therefore classified as of spectral type [WC]. Moreover, a few CSPNe of other Wolf-Rayet spectral subtypes have been identified in the last years, e.g. PB 8, which is of spectral type [WN/C]. We performed spectral analyses for a number of Wolf-Rayet type central stars with the help of our Potsdam Wolf-Rayet (PoWR) model code for expanding atmospheres to determine meaningful stellar parameters. The results of our analyses are presented here in the context of stellar evolution and white dwarf formation. We discuss the problems of a uniform evolutionary channel for [WC] stars as well as constraints of the formation of [WN/WC] subtype stars.

## 1. Introduction

From the fraction of non-DA white dwarfs it is estimated that about 20 per cent of the post-AGB stars are H-deficient. These H-deficient post-AGB stars belong to a diverse group of spectral types, e.g. O(He), RCrB, EHe, sdO, PG 1159, and [WR]. The latter contribute about 10 per cent to the Galactic Central Stars of Planetary Nebulae (e.g. Górny 2001). Allmost all [WR] stars show emission line spectra that are dominated by carbon, helium, and oxygen lines, similar to those of massive WC stars. They are therefore 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 white dwarf 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) at either 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 $X_{\mathrm{C}} = 40\,\%$ by mass after a late or very late TP without drastic changes during the follwing [WC] phase. In the case of a very late TP (VLTP Herwig 2001; Althaus et al. 2005) a super-solar nitrogen abundance of about $X_{\mathrm{N}} = 1\,\%$ is expected.

However, previous analyses of [WC] stars 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.

To clarify the situation we re-analyzed a sample of 11 [WCE] stars with improved models and updated atomic data. Moreover, high-resolution optical spectroscopy was performed for some of the [WCE] stars of our sample 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.

## 2. Analysis

For the determination of the atmospheric abundances and other stellar parameters we perfomed 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 popuplation numbers. Iron-line blanketing ist 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*

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

As we lack of reliable distance estimates for our objects, we set the stellar luminosity to a typical value for CSPNe, $L = 5000\,L_\odot$, as used in previous analyses by Koesterke (2001). With help of Eq. (1) the results can be easily scaled to different luminosities. The results of our analyses are summarized in Table 1.

An example of a model fit is shown in Fig. 1.

We found that for most of our objects the observed spectra are best fitted by models with abundances C:He:O=0.3:0.6:0.1 by mass. Remarkably, although most of our [WCE] stars have the same C:He:O abundances, there are significant differences concerning the nitrogen abundances.

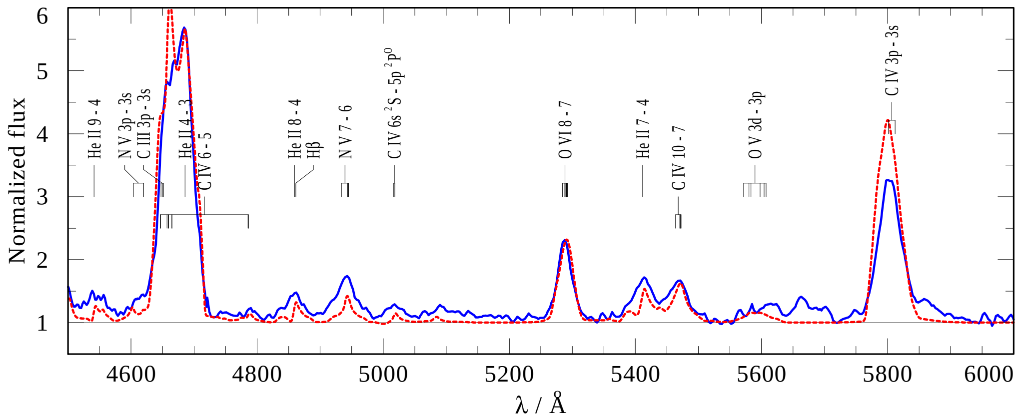


Figure 1. The [WC] star [Sd71]3 (aka Sand 3): Observed optical spectrum (blue solid line) vs. PoWR model (red dotted).

Table 1. Results of our analyses of [WCE] stars

| Object | $X_C$ | $X_{He}$ | $X_O$ | $X_N$ | $T_*$ | $R_t$ | $\log \dot{M}$ | $v_\infty$ |
|---|---|---|---|---|---|---|---|---|
| | % mass fraction | | | | [kK] | [$R_\odot$] | [$M_\odot\,yr^{-1}$] | [$km\,s^{-1}$] |
| NGC 2867 | 30 | 60 | 10 | < 0.5 | 158 | 5.0 | −7.2 | 2000 |
| PB 6 | 30 | 60 | 10 | 1.5 | 158 | 5.0 | −7.2 | 2000 |
| NGC 5189 | 30 | 60 | 10 | 1.5 | 158 | 5.0 | −7.2 | 2000 |
| NGC 6905 | 30 | 60 | 10 | – | 150 | 4.5 | −7.0 | 2000 |
| NGC 7026 | 30 | 60 | 10 | < 0.06 | 130 | 6.3 | −7.1 | 2000 |
| Hen 2-55 | 30 | 60 | 10 | ≤ 0.1 | 126 | 10 | −7.4 | 2000 |
| [S71d]3 | 30 | 60 | 10 | 1.5 | 158 | 3.2 | −6.9 | 1800 |
| IC 1747 | 30 | 60 | 10 | < 0.5 | 112 | 10 | −7.2 | 2000 |
| NGC 1501 | 35 | 54 | 10 | 0.5 | 128 | 4.8 | −6.9 | 1700 |
| NGC 6369 | 30 | 56 | 14 | – | 158 | 1.8 | −6.7 | 1200 |
| NGC 5315 | 30 | 60 | 10 | – | 71 | 5.0 | −6.1 | 2000 |

## 3. PB 8 - A [WN/WC] star

The central star of the planetary nebula PB 8 was classified as [WC5-6] star by Acker & Neiner (2003) and therefore included in our sample. The results of our analysis are given in Tabel 2, details are described in Todt et al. (2010). Note that the mass-loss rates are based on the assumption of a stellar luminosity of $L = 6000\,L_\odot$.

We found that the atmospheric composition ist 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. (2009) 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 $\approx 24.2$ kpc. With a Galactic latitude of 4° this corresponds to a height of 1.7 kpc above the fundamental

Table 2. Stellar parameters of PB 8 and Abell 30

| Object | $X_H$ | $X_{He}$ | $X_C$ | $X_N$ | $X_O$ | $T_*$ | $R_t$ | $\log \dot{M}$ | $v_\infty$ |
|---|---|---|---|---|---|---|---|---|---|
| | | % mass fraction | | | | [kK] | $[R_\odot]$ | $[M_\odot\,yr^{-1}]$ | $[km\,s^{-1}]$ |
| PB 8 | 40 | 55 | 1.3 | 2.0 | 1.3 | 52 | 27 | −7.1 | 1000 |
| Abell 30 | – | 63 | 20 | 1.5 | 15 | 115 | 35 | −7.7 | 4000 |

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.

In analogy to the massive WNC stars, we suggested the new class [WN/WC] for PB 8. Its surface composition is unique among all CSPNe and poses the question 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. Alternatively, Miller Bertolami et al. (2011) proposed that PB 8 was formed by a diffusion-induced CNO flash during the early cooling-stage of DA white dwarf of low metallicity.

## 4. The PG 1159-[WC] stars

As already mentioned, it was suggested that there exists an evolutionary sequence [WC] → [WC]-PG 1159. Previous analyses of the [WC]-PG 1159 star Abell 30 (aka PN A66 30) by Leuenhagen et al. (1993) found a He:C abundance ratio of 0.41:0.40 by mass, similar to that found for the [WCL] stars. In the framework of an X-ray analysis of Abell 30 we also performed new a analysis of the central star (Guerrero et al. 2012) and arrived at a different He:C ratio of 0.63:0.20, see also Table 2. Thus, the carbon abundance in Abell 30 is actually lower than for the [WCL] stars, but fits better to the sequence [WCE] → [WC]-PG 1159, as the [WCE] have a similar He:C abundance ratio.

## 5. Summary

Our newly derived chemical abundances of [WCE] stars and the [WC]-PG 1159 star Abel 30 corroborates the suggested sequence [WCE] → [WC]-PG 1159. The supersolar nitrogen abundance which we found in Abell 30 and in some of the [WCE] stars favour a VLTP scenario for these objects. The unique [WN/WC] star PB 8 seems to come from a different evolutionary channel. Perhaps it was created by a diffusion-induced nova.

In the next step we will re-analyze a sample of [WCL] stars. If [WCL] stars are the precursors of the [WCE] stars, we expect to find carbon abundances of about 30 per cent by mass for at least some of the [WCL] stars.

**Acknowledgments.** M. Peña acknowledges financial support from FONDAP-Chile and DGAPA-UNAM (grants IN118405 and IN112708).

### References

Acker, A., & Neiner, C. 2003, A&A, 403, 659

Althaus, L. G., Serenelli, A. M., Panei, J. A., Córsico, A. H., García-Berro, E., & Scóccola, C. G. 2005, A&A, 435, 631. arXiv:astro-ph/0502005
Crowther, P. A., Abbott, J. B., Hillier, D. J., & De Marco, O. 2003, in Planetary Nebulae: Their Evolution and Role in the Universe, edited by S. Kwok, M. Dopita, & R. Sutherland, vol. 209 of IAU Symposium, 243
García-Rojas, J., Peña, M., & Peimbert, A. 2009, A&A, 000, xxx
Górny, S. K. 2001, Ap&SS, 275, 67
Guerrero, M. A., Ruiz, N., Hamann, W.-R., Chu, Y.-H., Todt, H., Schönberner, D., Oskinova, L., Gruendl, R. A., Steffen, M., Blair, W. P., & Toalá, J. A. 2012, ApJ, 755, 129. 1202.4463
Herwig, F. 2001, Ap&SS, 275, 15. arXiv:astro-ph/9912353
Koesterke, L. 2001, Ap&SS, 275, 41
Koesterke, L., & Hamann, W.-R. 1997, A&A, 320, 91
Leuenhagen, U., & Hamann, W.-R. 1994, A&A, 283, 567
— 1998, A&A, 330, 265
Leuenhagen, U., Hamann, W.-R., & Jeffery, C. S. 1996, A&A, 312, 167
Leuenhagen, U., Koesterke, L., & Hamann, W.-R. 1993, Acta Astron., 43, 329
Marcolino, W. L. F., Hillier, D. J., de Araujo, F. X., & Pereira, C. B. 2007, ApJ, 654, 1068
Miller Bertolami, M. M., Althaus, L. G., Olano, C., & Jiménez, N. 2011, MNRAS, 415, 1396. 1103.5455
Todt, H., Peña, M., Hamann, W.-R., & Gräfener, G. 2010, A&A, 515, A83. 1003.3419
Werner, K., & Heber, U. 1991, A&A, 247, 476