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[WN] central stars of planetary nebulae

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Abstract. While most of the low-mass stars stay hydrogen-rich on their surface throughout their evolution, a considerable fraction of white dwarfs as well as central stars of planetary nebulae have a hydrogen-deficient surface composition. The majority of these H-deficient central stars exhibit spectra very similar to massive Wolf-Rayet stars of the carbon sequence, i.e. with broad emission lines of carbon, helium, and oxygen. In analogy to the massive Wolf-Rayet stars, they are classified as [WC] stars. Their formation, which is relatively well understood, is thought to be the result of a (very) late thermal pulse of the helium burning shell.

It is therefore surprising that some H-deficient central stars which have been found recently, e.g. IC 4663 and Abell 48, exhibit spectra that resemble those of the massive Wolf-Rayet stars of the nitrogen sequence, i.e. with strong emission lines of nitrogen instead of carbon. This new type of central stars is therefore labelled [WN]. We present spectral analyses of these objects and discuss the status of further candidates as well as the evolutionary status and origin of the [WN] stars.

Keywords. Stars: abundances – Stars: AGB and post-AGB – Stars: atmospheres – Stars: mass-loss – Stars: PN PB 8 – Stars: IC 4663 – Stars: Abell 48 – Stars: PMR 5 – Stars: Wolf-Rayet

1. Introduction

Wolf-Rayet central stars are hydrogen deficient central stars of planetary nebulae which exhibit in their spectra strong emission lines of helium, carbon 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 $X_{\rm C} = 40\%$ after a late or very late TP (Althaus *et al.* 2005, Herwig 2001). 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.

2. The [WN] stars

2.1. *PB 8*

The CS PB 8 was classified as [WC 5-6] by Acker & Neiner (2003) based on a low-resolution spectrum. A spectral analysis based on a high resolution spectrum, Todt *et al.* (2010) revealed that this object has a stellar temperature of about 50 kK and an unusual composition with He:H:C:N:O=55:40:1:1:1 by mass and resembles spectroscopically a massive WN/C star.

Due to its unknown distance, also L is unknown, so whether this star is a true [WN/C] CS can only be inferred indirectly.

The nebula analysis by García-Rojas (2009) yield values for $T_{\rm e}$ and $n_{\rm e}$ which are typical for young PNe, as well as the small $v_{\rm exp} \approx 30\,{\rm km/s}$. Regarding the luminosity distance, one finds that for a CSPN with $L/L_{\odot} = 6000$, PB 8 would be at a distance of 4.2 kpc and at a height of 300 pc above the Galactic plane, whereas a massive WR star would have at least $L/L_{\odot} = 2 \times 10^5$, and so at least a distance of 24 kpc and a height of 1.7 kpc above the Galactic plane. This is a rather untypical location for a massive WR star. So, PB 8 is indeed a CSPN.

We also considered the possibility that PB 8 may be a binary. Although this can not be excluded completely, it is rather unlikely as there were no shifts of radial velocities of spectral lines detected (Méndez 1989) and the nebula appears spherically symmetric, also in velocity space.

2.2. *IC 4663*

The first "pure" [WN] was discovered by Miszalski *et al.* (2012). Their spectral analysis based on an optical spectrum revealed that IC 4663 is an almost hydrogen-free ($< 2\,\%$ by mass) [WN] star, whose wind is 95% helium with only 0.8% nitrogen. Interestingly it is of early spectral subtype ([WN3]) with a temperature of about 140 kK and a relatively low mass-loss rate of about $2 \times 10^{-8}\,M_{\odot}\,{\rm yr}^{-1}$. Miszalski *et al.* (2012) showed that if IC 4663 were a massive WN star it would be at an implausible distance of 58 kpc and more than 8 kpc below the Galactic plane. Moreover, they discovered an AGB halo around IC 4663, proving it is a CSPN.

2.3. *Abell 48*

DePew *et al.* (2011) mentioned the CS of Abell 48, but it was unclear whether this is really a CSPN and not a massive WN star (Wachter *et al.* 2010 classified it as WN6). The CS Abell 48 was found to have a helium-rich (85%) wind with about 10% hydrogen, and a nitrogen abundance of about 5% (Todt *et al.* 2013, see Fig, 1; Frew *et al.* 2014). From the nebula analysis (line ratios of S II and Hα, as in Riesgo-Torado & López 2002) it was concluded that Abell 48 is indeed a CSPN. This is also consistent with the measured extinction and its significant proper motion - Abell 48 is a runaway. The CS has a mass-loss rate of $4 \times 10^{-7}\,M_{\odot}\,{\rm yr}^{-1}$ and a temperature of about 70 kK. Its spectral subtype is [WN5].

3. [WN] candidates

The earliest claim for the discovery of a [WN] central star was by Morgan *et al.* (2003), who observed the highly reddened ($E_{\rm B-V} = 3\,{\rm mag}$) object PMR 5, which shows a WN spectrum (subtype WN6) and a round nebula. However, it is not clear whether this is a PN or ring nebula around a massive WR star. While the electron density is consistent with a PN, the expansion velocity of $v_{\rm exp} = 165\,{\rm km/s}$ is rather unusual for a PN, but

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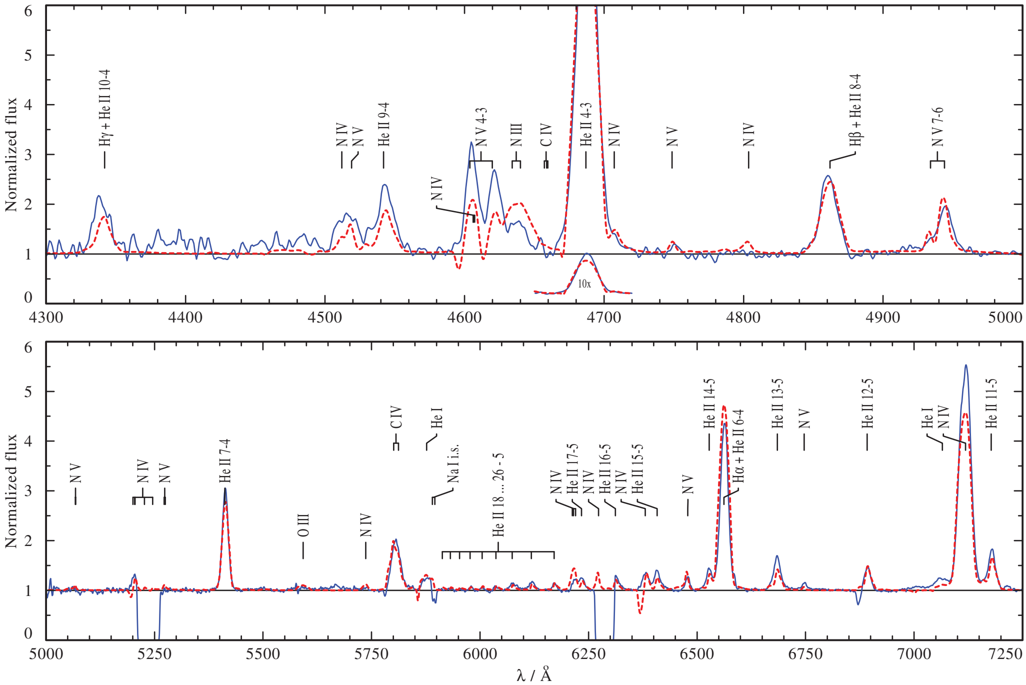

Figure 1. Optical spectrum of Abell 48: observation (blue, thin line) and best-fitting PoWR model (red, thick dotted line; see Todt *et al.* 2013), both normalized to the model continuum

typical for a ring nebula. Moreover, the luminosity distance is consistent with a massive WR star. For a typical CSPN luminosity of $L/L_{\odot} = 6000$ PMR 5 would be located at a distance of 0.5 kpc and at a height of 6 pc above the Galactic plane, while for a typical luminosity of a massive WN star PMR 5 would be at 2.9 kpc away and 35 pc above the Galactic plane. Hence, both locations are consistent with the corresponding type of star. However, a reddening of $E_{\mathrm{B-V}} = 3$ mag is rather untypical for a distance of only 500 pc. A spectral analysis based on the published spectrum revealed a chemical composition of a typical WNh star, but with a large mass fraction of N ($\approx 10\%$). Overall, chemistry and v_{exp} point to a massive WN star with a ring nebula.

So far, all of the confirmed [WN] stars are of earlier spectral subtypes. It may be that late [WN] stars have escaped detection because of their narrower stellar lines which can be confused with nebular emission lines, especially at low spectral resolution. Moreover, also some H-rich CSs show emission lines, e.g., NGC 6543, and are therefore classified as of WR/Of spectral type (Smith & Aller 1969). The stellar Hβ line, which is used for spectral classification of WN/Of stars (Crowther & Walborn 2011), is often blended with the nebular emission. Thus high spectral resolution is also needed to tell WN type central stars from Of type central stars.

4. Evolutionary status

The evolutionary channel by which [WN] stars are formed is unclear. None of the recent late TP scenarios predicts the observed surface compositions of PB 8, IC 4663, and Abell 48. It was speculated whether these objects belong to an alternative evolutionary sequence [WN] → O(He) (Miszalski *et al.* 2012, Werner 2012) or that [WN] stars are O(He) stars with higher masses (Reindl *et al.* 2014), evolving from RCB or sdO(He)

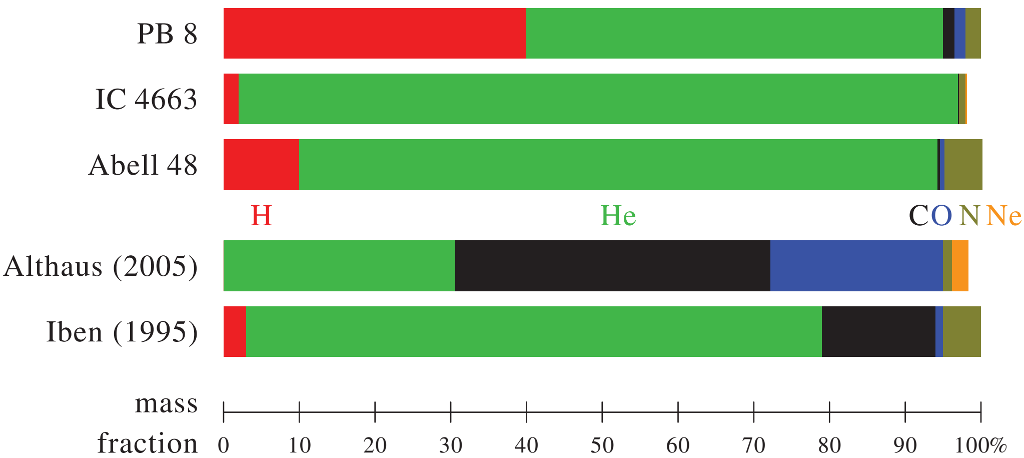

Figure 2. Observed abundance patterns of the [WN] stars vs. predicted abundances for H-deficient central stars in the VLTP / born-again scenario (Althaus *et al.* 2005, Iben & MacDonald 1995)

stars, which might be merger products of non-DA WDs. However, the merger scenario seems to be rather unlikely due to the long timescales involved, which are incompatible with the observed low ages of the PNe of the [WN] stars. Moreover, PB 8 and Abell 48 also contain hydrogen while the assumed progenitors are H-free.

Note that the "classical" born-again scenario by Iben & MacDonald 1995 yields abundances that are somehow similar to the observed ones, including residual hydrogen and and a supersolar nitrogen abundance (see Fig. 2).

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Discussion

Schoenberner: Driving late thermal pulses one has to consider time-dependent convection and incomplete non-equilibrium nuclear burning. I imagine that the result concerning the nucleosynthesis is highly uncertain.

Mendez: PB 8 has 4541 He II in absorption (Fig. 2e in Mendez *et al.* 1988, A&A, 190, 113) that would not correspond to a classical WN spectral type, which show He II 4541 as a broad emission. (see Mendez *et al.* 1990, A&A, 229, 152, last paragraph of Section 3).

Todt: I think that He II 4541 rather shows a weak P Cygni-like line profile than a pure photospheric absorption profile. Even for massive WN stars exist examples where He II 4541 appears as weak P-Cygni line (e.g. WR 24, spectral sub-type WN6ha) or in absorption (SMC AB2 of spectral subtype WN5ha) due to a weaker wind. However, Crowther & Walborn (2011) define WN stars with help of the Hb profile. If it is in emission, as it is for PB 8 and WR 24, then it's a WN spectrum. If it shows a P-Cygni profile then they call it an Of/WN star.

De Marco: Have you ever analyzed the [WR] that is a member of a binary? Is it different in any way?

Todt: You may refer to NGC 5189. The optical and UV spectrum looks very similar to the spectra of other hot [WC] stars, e.g., PB 6, NGC 2867, NGC 6905, [S71d]3. Analyses by Keller *et al.* (2014) as well as my preliminary analysis didn't show any remarkable differences compared to other [WCE] stars.

Muthumariappan: The evolutionary sequences [WCL] $->$ [WCE] $->$ WC/PG1159 is likely, however, how do we account for the observed gap in the [WC5] - [WC8] subclasses of [WR] PN distribution?

Todt: The spectral subtypes of the [WC] stars correspond to different ionization stages of C, He, O and therefore reflect different stellar temperatures. It may be that these subtypes are not equally spaced with respect to the evolution timescale of the [WC] stars. So, perhaps, the subtypes [WC5] -[WC8] correspond to shorter phase in the evolution of [WC] stars making it more unlikely to observe them during this phase. Alternatively, one may think of [WCE] and [WCL] stars belonging to different populations. E.g. V605 Aql seemed to have evolved directly VLTP $->$ [WCE]. This seems to be corroborated by the different abundance patterns found for [WCL] and [WCE]. However, in this scenario it is not clear to what type of star the [WCL] stars eventually evolve if not to [WCE] stars.

Sterling: Can you expand on the models without convective overshoot, which maybe the best (so far) evolutionary channel for [WN] CSPN?

Todt: For the [WN] stars with significant amount of hydrogen (e.g. PB 8) we expect to get DA WDs. Even for those with very small amounts (e.g. IC 4663)this will be the case (Miller Bertolami *et al.* 2016). So far the parameter space for the VLTP/LTP/AFTP scenarios hasn't been explored enough to give distinct predictions, but the presence of hydrogen and nitrogen in the [WN] stars may point to an AFTP, where 14N could be the consequence of dredging up material only from the He-buffer zone or from hot-bottom burning in stars of M_i $\sim$ 4 M_Sun (Miller Bertolami *et al.*, priv. comm.)