Wolf-Rayet Stars
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Wolf-Rayet central stars of planetary nebulae

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A significant number of the central stars of planetary nebulae (CSPNe) are hydrogen-deficient, showing a chemical composition of helium, carbon, and oxygen. Most of them exhibit Wolf-Rayet-like emission line spectra, similar to those of the massive WC Pop I stars, 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, which is of spectral type [WN/C], and IC 4663 and Abell 48, which are of spectral type [WN].

We review spectral analyses of Wolf-Rayet type central stars of different evolutionary stages and discuss the results in the context of stellar evolution. Especially we consider the question of a common evolutionary channel for [WC] stars. The constraints on the formation of [WN] or [WC/N] subtype stars will also be addressed.

1 Introduction

Central stars of planetary nebulae (CSPNe) are evolved low-mass stars in the phase after the asymptotic giant branch (AGB) and before the white dwarf (WD) stage. The outer envelope of the former AGB star was shed off by a slow but strong AGB wind and is then swept up by a fast stellar wind of the CSPN. As the star evolves towards higher surface temperatures the surrounding material gets ionized as soon as the star reaches $T \approx 25\,000\,\mathrm{K}$ and a PN gets visible.

While most of the low mass stars stay hydrogen-rich on their surface throughout their life, there exist a considerable fraction of post-AGB stars with H-deficient surface composition. Almost all H-deficient CSPNe exhibit spectra with strong carbon and helium lines (see Fig. 1), 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, as suggest by van der Hucht.

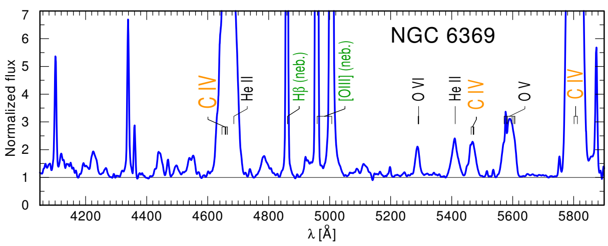

Fig. 1: NGC 6369: optical spectrum of a [WC4] type CS

Closely related to the [WC] stars are the PG 1159 stars, whose spectra are characterized by an absorption trough at about 4680 Å formed by C IV and He II lines. The corresponding gravity is of the order of $\log g = 7$. They are named after their prototype PG 1159-035 and show a strong excess in the UV (e.g. GALEX) due to their high temperatures. As their surface composition is rich in carbon and oxygen, they are considered as the descendants of the [WC] stars. This idea of an evolutionary link was corroborated by the discovery of the [WC]-PG 1159 stars Abell 30 and Abell 78, which exhibit weak emission *and* absorption lines of carbon, oxygen, and helium.

The first calculations of the post-AGB phase were performed by Paczyński (1970, 1971). In his models the surface composition remains H-rich throughout the evolution of the post-AGB object. An interesting feature of the late AGB evolution phase is the occurrence of a thermo-nuclear instability of the helium-burning shell – below the hydrogen-burning shell –, the so-called thermal pulse (TP).

The discovery of H-deficient, C-rich knots in the PNe of A 30 and A 78 (Hazard et al. 1980; Greenstein 1981; Jacoby & Ford 1983) motivated the idea of the born-again scenario (Iben et al. 1983; Iben 1984), where a TP occurs when the post-AGB star is already on the WD cooling track (Very Late TP), and the star is thrown back to the AGB regime. One should note that already Schoenberner (1979) encountered TPs *after* the AGB phase in his numerical simulations.

In this "classical" born-again scenario by Iben & MacDonald (1995) the H-rich envelope is removed *during the 2nd* post-AGB phase, resulting in a He-rich surface composition with $X_{\mathrm{H}} \approx 0.03$, $X_{\mathrm{He}} \approx 0.76$, $X_{\mathrm{C}} \approx 0.15$, $X_{\mathrm{O}} \approx 0.01$, and $X_{\mathrm{N}} \approx 0.05$.

However, first quantitative spectral analyses of PG 1159 stars (Werner et al. 1991), Abell 78 (Werner & Koesterke 1992) and [WCL] stars (Leuenhagen et al. 1996) raised the following problems (cf. Werner 2001) with this born-again scenario: [WCL] stars are relatively cool, i.e. young post-AGB stars, so the hydrogen must have been removed already *on* the AGB. The low expansion velocities of the H-free knots in Abell 30 and Abell 78 imply that the ejection happened during a low surface gravity phase, i.e. during the AGB phase. Moreover, the atmospheres of PG 1159 and [WC] stars are found to be rich in oxygen (≈ 15%), whereas the models predict high amounts of oxygen only at the bottom of the

He-rich intershell region, but max. 3% at the surface.

These problems can be solved when additionally to the simultaneous mixing and burning in the models also diffusive overshoot (Freytag et al. 1996) is taken into account. Such models develop an efficient dredge-up (Herwig et al. 1997, 1999) and result in a carbon and oxygen enriched surface composition.

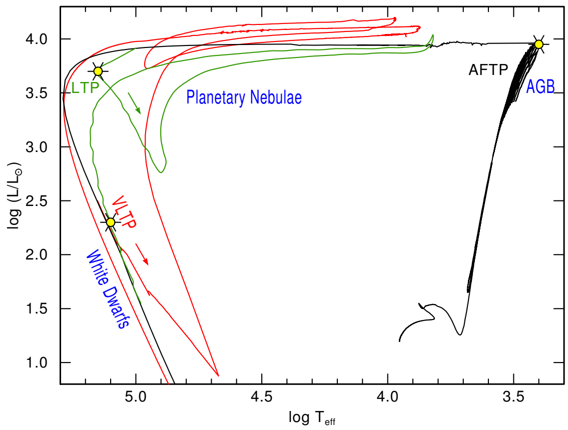

Fig. 2: Stellar evolutionary tracks for AGB final thermal pulse (black line, beginning from the ZAMS for $M_{\rm ini} = 2\,M_\odot$ Herwig 2001), late thermal pulse (green line, for $M_{\rm ini} = 3\,M_\odot$ Blöcker 1995), and very late thermal pulse (red line, for $M_{\rm ini} = 2\,M_\odot$ Herwig 2001)

Depending on the time at which these TPs occur (cf. Fig. 2), they can lead to an efficient subsequent dredge-ups of processed intershell material which is than displayed at the surface. An AGB final thermal pulse (AFTP) occurs at the tip of the AGB and a late thermal pulse (LTP) occurs just before the stars enters the White Dwarf cooling track.

While hydrogen is only diluted by intershell material in the case of the AFTP and LTP, it is completely burned in the VLTP scenario. Moreover, nitrogen and neon are also produced in the VLTP up to a mass fraction of a few percent (cf. Fig. 3).

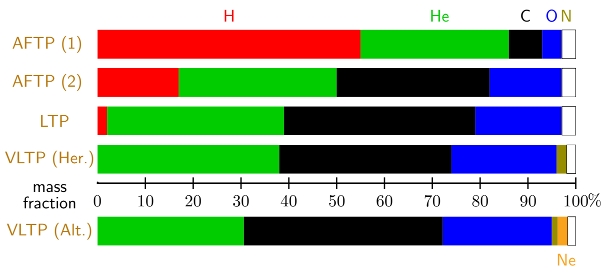

Fig. 3: Expected abundance patterns for [WC] stars from stellar evolutionary models. Upper panel: Herwig (2001); lower panel: Althaus et al. (2005)

2 Spectral analyses of [WC] stars

Analogously to the spectral subtypes of the massive WC stars, the [WC] subtypes form a sequence where the hottest objects, i.e. those showing He II and C IV lines, belong to the early-type [WC] stars ([WCE]) and the cooler ones with He I and C II, C III lines belong to the late-type [WC] stars ([WCL]).

Previous analyses of [WCL] and [WCE] stars, based on optical and UV spectra, resulted in systematically different abundances of He and C for these subtypes.

For the majority of the [WCL] stars, analyzed e.g. by Leuenhagen & Hamann (1994); Leuenhagen et al. (1996); Leuenhagen & Hamann (1998), 13 objects, Marcolino et al. (2007), two objects, and De Marco & Crowther (1998, 1999), three objects, a C:He:O abundance ratio of about 50:40:10 (by mass) was found. Only for three [WCL] stars De Marco et al. (2001) and Crowther et al. (2003) found $X_{\rm C} < X_{\rm He}$. Their models accounted also for density inhomogeneities and line blanketing due to the iron group elements. Leuenhagen & Hamann (1998) also inferred enhanced $(1 - 4\,\%)$ neon and nitrogen abundances in six of their objects.

Koesterke & Hamann (1997a,b) analyzed 12 [WCE] stars, and derived a typical abundance ratio C:He:O of 30:60:10. Crowther et al. (2003) and Marcolino et al. (2007) studied two [WCE] stars each and found almost equal mass fractions of carbon and helium, similar to the result of an analysis of the extragalactic [WCE] star LMC-SMP 61 by Stasińska et al. (2004) and to the findings for two objects in the sample of Keller et al. (2014), whose analyses are based on UV spectra only. The other two [WCE] stars in the sample of Keller et al. (2014) have an abundance ratio similar to that found by Koesterke & Hamann (1997a,b).

Hydrogen. Hydrogen could in principal help to distinguish between the VLTP and AFTP/LTP scenario, but it is hard to detect, as in [WC] stars hydrogen emission lines are always blended with He II lines, often outshone by nebular emission lines, and generally weak in [WCE] stars. However, in the [WCL] stars IRAS 21282+5050, Hen 2-113 (Leuenhagen & Hamann 1998), and M 4-18 (De Marco & Crowther 1999) evidences for stellar hydrogen were found, based on the analysis of the broad wings of the Hα emission line.

Iron. Iron depletion would be an evidence to the s-process nucleosynthesis (neutron capture) in the former AGB star. Such deficiency was derived for LMC-SMP 61, where $X_{\rm Fe} = \frac{1}{6} X_{\rm Fe,\,LMC}$ and was also claimed by Marcolino et al. (2007) and Keller et al. (2014). However, only 10 % iron depletion due to neutron capture is predicted. For PG 1159 stars the originally claimed iron depletion was later revoked by the detection of Fe VIII / X lines (Werner et al. 2010, 2011).

Nitrogen, Neon. The detection of super-solar neon abundances was already claimed for [WCL] stars. For the hotter [WCE] stars only few lines lie in the optical range, Werner et al. (2007) identified some Ne VIII lines, but as the oscillator strengths of the corresponding transitions are only estimated, they are not useful for abundance determinations. Herald et al. (2005) discovered a strong Ne VII line in the FUSE range at 973.3 Å, which is not too sensitive to the mass-loss rate and can therefore be used for abundance determinations. A surface abundance of neon of the order of a few percent can be obtained not only via a VLTP, but also via an LTP (Miller Bertolami, priv. comm.).

A more unambiguous imprint of the VLTP is the presence of a considerable amount of nitrogen ($> 0.1\%$ by mass). For the [WCE] stars the nitrogen abundance can be reliably inferred from the optical emission lines of N V at 4604/4620 Å and 4934/4945 Å. Keller et al. (2014) found enhanced, i.e. $1-4\%$, Ne and N abundances for all of their objects, whereas Marcolino et al. (2007) found $X_{\rm N} < 0.1\%$.

Clumping in WR-CSPN. As shown by Hillier (1991), the clumpiness of WR star atmospheres can be estimated from the strength of electron scattering (e.s.) line wings. However, the degree of density inhomogeneities (microclumping) in [WC] star winds is generally hard to determine, because in the normalized spectrum the e.s. line wings are much weaker than for massive WC stars. This may help to distinguish between massive and low-mass WR stars, as mentioned in Todt et al. (2008) and Todt et al. (2013). Unfortunately, the stellar spectra are contaminated with nebular emission lines which often outshine the e.s. wings.

3 [WC]-PG 1159 stars

As the spectra of [WC]-PG 1159 stars show both, photospheric absorption lines and wind emission lines, previous analyses by either plan-parallel or pure wind models were limited. The analyses by Leuenhagen et al. (1993) of Abell 30 and Abell 78 were based on pure wind models and resulted in abundance patterns similar to those for [WCL] stars, i.e. with C : He : O : N=50 : 33 : 15 : 2 (Abell 78) and C:He:O:N=40 : 41 : 15 : 4 (Abell 30).

Results of improved analyses (Guerrero et al. 2012; Toalá et al. 2015), which account for pressure broadened absorption lines as well as Doppler broadened wind lines ($v_\infty \approx 4000\,$km/s) revised the carbon abundances downwards to a more [WCE]-like chemical composition, i.e. C : He : O : N = 20 : 63 : 15 : 1.5 for Abell 30 and C : He : O : N : Ne : F = $30:55:10:1.5:4:1.3\times10^{-5}$ for Abell 78. The abundances of N and Ne are consistent with predictions for the VLTP, which is the suggested evolutionary channel for both objects.

4 [WN] central stars

While the low-mass spectral twins of the massive WC stars have been known since the discovery of the first WC stars, it was until recently not clear whether there also exist [WN] central stars, i.e., CSPNe whose spectra resemble those of the massive WN stars. At least this was not expected from the stellar evolutionary models of Herwig (2001) and Althaus et al. (2005).

4.1 PMR 5 - a [WN] suspect

The earliest claim for the discovery of a [WN] central star was by Morgan et al. (2003), who observed the highly reddened ($E_{\rm B-V} = 3\,$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 $v_{\rm exp} = 165\,$km/s is rather unusual for a PN, but 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 Galatic 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 $E_{\rm B\text{-}V} = 3\,$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 $v_{\rm exp}$ point to a massive WN star with a ring nebula.

4.2 PB 8 - a [WN/C] star

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 et al. (2009) yield values for $T_{\rm e}$ and $n_{\rm e}$ which are typical for young PNe, as well as the small $v_{\rm exp} \approx 30\,$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 Galatic 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.

4.3 IC 4663 - [WNE] type CS

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 consists to 95 % of 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 $2 \times 10^{-8}\,M_{\odot}\,\mathrm{a}^{-1}$. 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.

4.4 Abell 48

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; Frew et al. 2014). From the nebula analysis (line ratios of S II and Hα, as in Riesgo-Tirado & 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.

5 Discussion

The evolutionary channel by which [WC] stars are formed is still unclear. Neither the VLTP nor the AFTP or LTP scenario yield a consistent picture. While the observed super-solar nitrogen abundances can be explained by the VLTP scenario, the corresponding PNe are much younger than predicted by this scenario. Moreover, within the [WCE] sample the nitrogen abundances vary from solar to a few percent. The AFTP scenario would better fit to the derived ages of the PNe, but the observed abundances, especially of hydrogen and nitrogen, are not matched by stellar evolutionary models.

Regarding the systematic differences of the C:He ratio between [WCE] and [WCL] stars in previous analyses it is even unclear whether the suggested evolutionary sequence AGB → [WCL] → [WCE] → [WC]-PG1159 → PG1159 → non-DA WD (e.g. Werner & Heber 1991) is appropriate. Further analyses with updated models on larger wavelength ranges with more spectral lines may resolve the discrepancy. Note, for example, that the born-again object V605 Aql (Clayton et al. 2006) has apparently evolved directly from the VLTP to the [WCE] stage.

The situation is even more puzzling for the [WN] stars. 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) (Werner 2012) or that [WN] stars are O(He) stars with higher masses (Reindl et al. 2014), evolving from RCB or sdO(He) 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.

Another remaining questions is how H-deficient central stars become [WR] stars, or: Why do they have so strong winds?

For massive WNL stars Gräfener & Hamann (2008) demonstrated that it is the proximity to the Eddington limit, i.e. high L/M ratios of $\approx 15\,000 - 30\,000$ (in solar units), which determines the strength of the stellar wind.

For CSPNe in general, $L/M \approx 3\,000 - 30\,000$ in average (e.g. 15 000 for LMC-SMP61, with assumed $M = 0.6\,M_{\odot}$), although for most CSPNe the individual distances are unknown, and so are L and M.

For stellar models with $M_{\mathrm{ini}} > 2M_{\odot}$ the ratio L/M for H-rich CSPNe is about the same as for H-deficient CSPNe (Miller Bertolami & Althaus 2006) and model calculations show that the most massive H-rich CSPNe are already close to the Eddington limit (Miller Bertolami 2015). Moreover, some of the H-rich CSPNe, like NGC 6543, show WR features in their spectra and are therefore classified as of type WR-O(f).

In our wind models with fixed $L = 6000\,L_{\odot}$ and $M = 0.6\,M_{\odot}$, the wind efficiency $\eta = \dot{M}v_{\infty}/(L/c)$ is always smaller than 1 (for a β-law with $\beta = 1$ and $\dot{M} \approx 10^{-7}\,M_{\odot}/\mathrm{a}$) and the only hydrodynamically consistent model of a [WCE] star, NGC 6905, by Gräfener et al. (2008) needed strong clumping with $D = 100$. It may be that additional opacity is provided by enriched s-process elements (produced on the AGB), which are not included in our models, as the atomic data are hardly available.

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Martin Guerrero: Do planetary nebulae with [WR] CSPNe have more complex morphologies? Could this be related to the stellar wind of [WR] stars?

Helge Todt: I am not an expert on PNe in general, but it seems that PNe with [WR] central stars have similar morphologies to other PNe.

Marcelo Miguel Miller Bertolami: One should be careful when comparing the ^{16}O abundances of [WC] and PG1159 stars with the "predictions" of the models. In fact, there are *no true predictions* for ^{16}O from stellar evolution models of LTP and VLTP scenarios. This is because the oxygen abundance is completely dependent on the intensity of diffusive extra mixing during the whole TP-AGB which is indeed calibrated to reproduce the O abundance of PG 1159 stars.