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IC 4663: The First Unambiguous [WN] Wolf-Rayet Central Star of a Planetary Nebula

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Abstract. Several [WC]-type central stars of planetary nebulae (PNe) are known to mimic the spectroscopic appearance of massive carbon-rich or WC-type Wolf-Rayet stars. In stark contrast, no [WN]-type central stars have yet been identified as clear-cut analogues of the common nitrogen-rich or WN-type Wolf-Rayet stars. We have identified the [WN3] central star of IC 4663 to be the first unambiguous example in PNe. The low luminosity nucleus and an asymptotic giant branch (AGB) halo surrounding the main nebula prove the bona-fide PN nature of IC 4663. Model atmosphere analysis reveals the [WN3] star to have an exotic chemical composition of helium (95%), hydrogen (<2%), nitrogen (0.8%), neon (0.2%) and oxygen (0.05%) by mass. Such an extreme helium-dominated composition cannot be predicted by current evolutionary scenarios for hydrogen deficient [WC]-type central stars. Only with the discovery of IC 4663 and its unusual composition can we now connect [WN] central stars to the O(He) central stars in a second H-deficient and He-rich evolutionary sequence, [WN]→O(He), that exists in parallel to the carbon-rich [WC]→PG1159 sequence. This suggests a simpler mechanism, perhaps a binary merger, can better explain H-deficiency in PNe and potentially other H-deficient/He-rich stars. In this respect IC 4663 is the best supported case for a possible merged binary central star of a PN.

1. Introduction

The immediate progenitors of some non-DA white dwarfs (WDs) may be found in the H-deficient post-Asymptotic Giant Branch (AGB) nuclei of PNe. Most common amongst H-deficient nuclei are those with fast and dense stellar winds that mimic the carbon sequence of massive Wolf-Rayet (WR) stars (Crowther 2008). These stars, denoted as [WC] stars to separate them from their massive WC counterparts, have atmospheres rich in carbon, oxygen and helium as readily seen in their remarkable emission line spectra (Crowther et al. 1998; Acker & Neiner 2003). Stellar atmosphere analyses have demonstrated a strong similarity between compositions of [WC] stars and PG1159 stars (Werner & Herwig 2006; Crowther 2008), implying an evolutionary sequence [WC]→PG1159→WD. Werner & Herwig (2006) give several examples of He-rich/H-deficient stars that do not seem to fit this sequence. Perhaps the least understood are the O(He) stars, hot post-AGB stars ($T_{\rm eff} \geq 100$ kK) with atmospheres dominated by helium (Rauch et al. 1998, Reindl et al., these proc.). The final destiny of O(He) stars will be either a helium-rich DO WD or a DA WD (if it contains some residual hydrogen), but essentially nothing is known about their origin.

As two O(He) stars are surrounded by PNe, it would not be unexpected to find a progenitor amongst other central stars of PNe. No other central stars were known to have comparable He-dominated compositions, i.e. a helium mass fraction $\gtrsim$90%, until we studied the unique central star of IC 4663 (Miszalski et al. 2012). Unlike all other WR central stars, it is the first proven case of a central star mimicking the nitrogen sequence of massive WR stars, a true [WN] star! Here we summarise its properties from which we were compelled to propose a new, second He-rich/H-deficient post-AGB evolutionary sequence [WN]→O(He)→WD.

1.1. First of a kind: IC 4663

While there are $\gtrsim$100 [WC] central stars known (Depew et al. 2011), only a handful of [WN] candidates have been identified. These candidates have often turned out to be massive WN stars with ejecta nebulae (Stock & Barlow 2010), due to the very large uncertainty in estimating distances to PNe, or could not be proven one way or the other. The most promising candidates were LMC-N66, which has an uncomfortably high luminosity (Hamann et al. 2003), and PMR5 (Morgan et al. 2003), for which several indicators now suggest it is a reddened massive WN star (Todt et al. 2010b). Todt et al. (2010a) studied the WR-like central star of PB8 (a bona-fide PN) and found an unusual atmospheric composition unlike [WC] stars. The spectral classification of PB8 is not entirely clear and may be a hybrid [WN/WC] type rather than a pure [WN] type. Another [WN] candidate is the nucleus of Abell 48 (Bojicic et al. these proc.), however a definitive study has yet to be published for this object.

We obtained imaging and spectroscopy of IC 4663 (PN G346.2−08.2) in June and July 2011 with GMOS on Gemini South (Hook et al. 2004). Figure 1 shows our spectrum of the previously unstudied central star which has a [WN3] spectral type following Smith et al. (1996). The luminosity of the $V = 16.9$ mag central star is always consistent with a PN, i.e. 4–6 mag fainter than massive WN stars of the same spectral type for all reasonable distances (Hamann et al. 2006). At an assumed distance of 3.5 kpc (Stanghellini et al. 2008) this corresponds to $L = 4000$ $L_\odot$ and $M_V = +3.1$ mag. Furthermore, the nebula is clearly a PN with an elliptical morphology, a low expansion velocity of 30 km s^{-1} (Hajian et al. 2007) and a newly discovered AGB halo (Fig. 2).

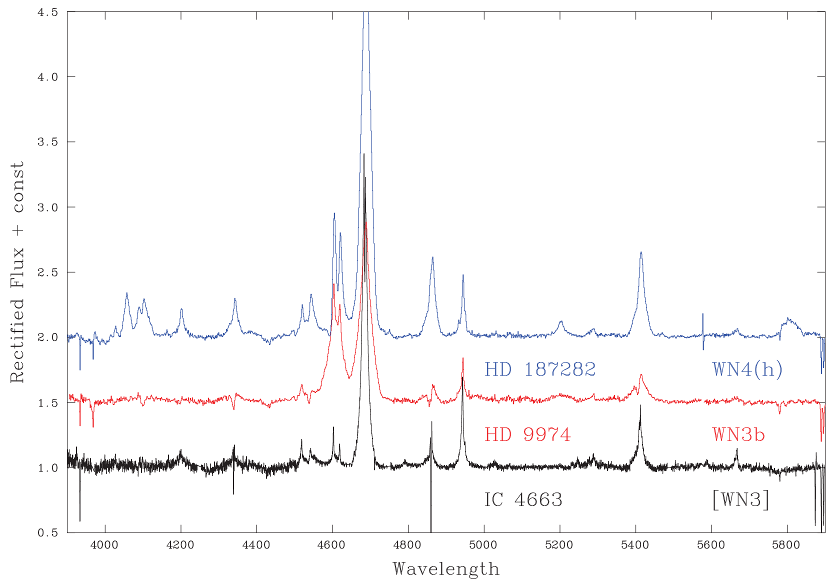

Figure 1. Gemini GMOS spectrum of the [WN3] central star of IC 4663 in comparison to massive WN stars of similar spectral type.

A chemical abundance analysis of the nebular emission lines reveals an approximately solar abundance pattern with slight enhancements in helium, nitrogen and neon, and carbon may be underabundant.

2. Evolutionary status of IC 4663

We analysed the GMOS spectrum with the CMFGEN NLTE model atmosphere code (Hillier & Miller 1998), the full details of which may be found in Miszalski et al. (2012). The physical properties are not dissimilar from hot [WO] central stars, namely $T_* = 140 \pm 20$ kK, $v_\infty = 1900$ km s^{-1}, log $g = 6.1$ (assuming $M = 0.6$ M$_\odot$), and for $d = 3.5$ kpc we find $R_* = 0.11$ R$_\odot$, $\dot{M} = 1.8 \times 10^{-8}$ M$_\odot$ yr^{-1}, and $L = 4000$ L$_\odot$. The most surprising results from this analysis is the atmospheric composition which contains by mass helium (95%), hydrogen (< 2%), carbon (< 0.1%), nitrogen (0.8%), oxygen (0.02%) and neon (0.2%). Clearly the He-dominated composition of IC 4663 does not fit the [WC]→PG1159 sequence (Werner & Herwig 2006), but rather matches closely the composition of O(He) stars (Rauch et al. 1998). This strongly suggests there is a second, parallel H-deficient and He-rich post-AGB evolutionary sequence [WN]→O(He). There has been some suggestion that this sequence exists (Werner 2012), however only with our study of IC 4663 has this now become tangible. The O(He) stars are therefore the He-rich analogues of PG1159 stars. The nebular evolutionary status of IC 4663 and other PNe with H-deficient central stars are also consistent with this evolutionary sequence (Miszalski et al. 2012).

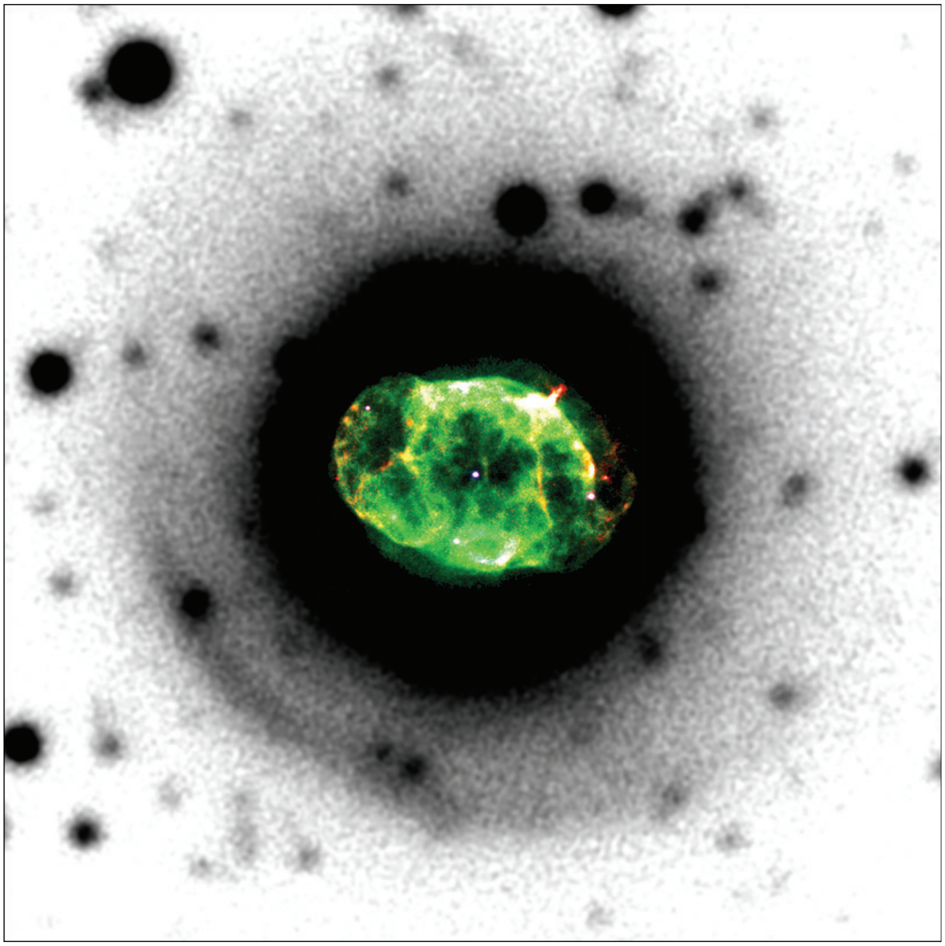

Figure 2. A newly discovered faint AGB halo (GMOS [OIII] image, background) surrounds an *HST* colour-composite image of IC 4663 where $F658N$ is red, $F502N$ is green and $F555W$ is blue (Miszalski et al. 2012). AGB haloes are a telltale feature of PNe (Corradi et al. 2003). The image dimensions are 60×60 arcsec^2 with North up and East to the left.

None of the scenarios proposed to explain the composition of [WC] or PG1159 stars can produce the composition of IC 4663 (Werner & Herwig 2006), suggesting there is another simpler mechanism that may be responsible for creating H-deficient central stars of PNe. The most promising of which may be a double-degenerate merger (Saio & Jeffery 2002). Reindl et al. (these proc.) showed that the composition of IC 4663 agreed well with predictions of the slow merger of two He-WDs described by Zhang & Jeffery (2012). This picture is consistent with the lack of radial velocity variability seen in our three GMOS spectra and makes IC 4663 the best supported case for a possible merged binary central star of a PN.

3. Implications for central star classification

How does IC 4663 affect existing classification schemes for PNe central stars? Firstly, the discovery of its [WN3] central star means that there should exist other [WN] stars that mimic WN stars of later sub-types. We have identified several late-[WN] stars that we are analysing in the context of establishing the basic characteristics of the [WN] sequence in PNe.

Secondly, there is a close relationship between massive Of and WN stars (Crowther & Walborn 2011). Intermediate Of/WN types exist and in PNe these have sometimes been classified as Of-WR central stars (Méndez 1991). The best example of which is NGC 6543 which exhibits a WN-like spectrum and an H-rich atmosphere (Méndez et al. 1990; Georgiev et al. 2008). A useful diagnostic plot for distinguishing bona-fide [WN] stars from Of or Of/[WN] types may be that found in Fig. 3. The equivalent width W of HeII λ4686 for IC 4663 is comparable to WN stars of similar type, whereas the full width at half-maximum (FWHM) is lower. Both values are lower in the isolated NGC 6543 of Of/WN type. Figure 3 also shows that BD+30 3639 ([WC9]) follows a similar pattern c.f. WC9 stars in the CIII λ5696 emission line and that SwSt 1 is a carbon-rich analogue of NGC 6543. Note that BD+30 3639 has always been considered a [WC9] star. Miszalski et al. (2012) also demonstrated that the transformed radius (Hamann et al. 2006) for IC 4663 is comparable to WN stars of similar spectral types, ruling out any Of or Of/WN classification of the [WN3] star. Other examples of Of or Of/WN types may have mistakenly been classified as so-called 'weak emission line' central stars, but this usage should be discontinued in favour of a new scheme that is cognisant of Of/WN types and close binary central stars (e.g. Miszalski et al. 2011).

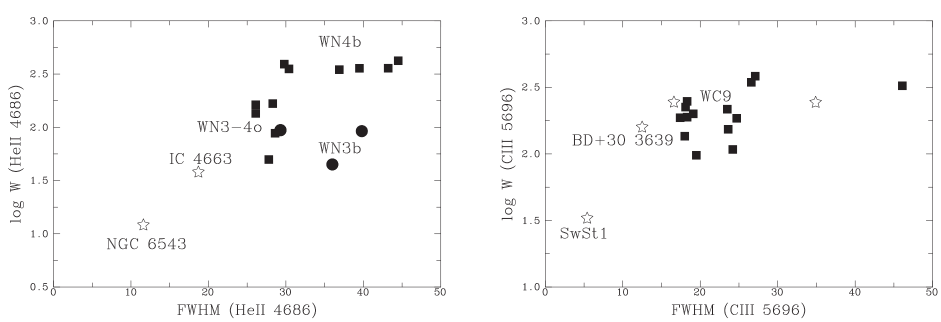

Figure 3. *(left)* The position of IC 4663 ([WN3]) in log W/FWHM space of He II λ4686 with NGC 6543 (Of/WN) and massive WN3/WN4 stars (filled symbols). *(right)* A similar plot for BD+30 3639 ([WC9]), SwSt 1 (Of/WC) and massive WC9 stars using C III λ5696.

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