by Brent Miszalski, Paul Crowther, and Anthony Moffat

A Second Flavor of Wolf-Rayet Central Stars of Planetary Nebulae

Gemini South optical observations of the planetary nebula IC 4663 reveal the first proven case of a central star with a nitrogen-sequence Wolf-Rayet spectrum. Its existence challenges the conventional view of how certain solar-mass stars become hydrogen-deficient white dwarfs.

Population I classical Wolf-Rayet stars represent the short-lived, hydrogen-deficient, pre-supernova phase of very massive stars. These hot, high-luminosity bodies possess powerful, fast, dense winds (for recent review see Crowther, 2007). They exhibit unique, broad emission lines generated via Doppler expansion that are readily seen spectroscopically.

Wolf-Rayet stars come in two main flavors: nitrogen-rich WN-type stars and carbon-rich WC-type stars. These two classes reflect the products of hydrogen and helium-burning, respectively; whereas helium and nitrogen emission lines dominate in WN-types, the WC-types show emission lines mostly of carbon, oxygen, and helium. Very high-mass stars are thought to end their lives as WN or WC stars, although they are exceptionally rare, with only a few hundred cases known in the Milky Way.

The Wolf-Rayet Star Phenomenon

A subset of low-mass, post-Asymptotic Giant Branch (AGB) stars are also hydrogen-deficient (Werner Herwig, 2006). High temperature examples include He-rich subdwarf OB stars, O(He) stars, and DO white dwarfs. In addition, around 100 hydrogen-deficient central stars of planetary nebulae also exhibit a Wolf-Rayet spectroscopic signature. To date, all Wolf-Rayet central stars have been carbon-rich variants, with square brackets added to distinguish [WC]-type central stars from WC stars.

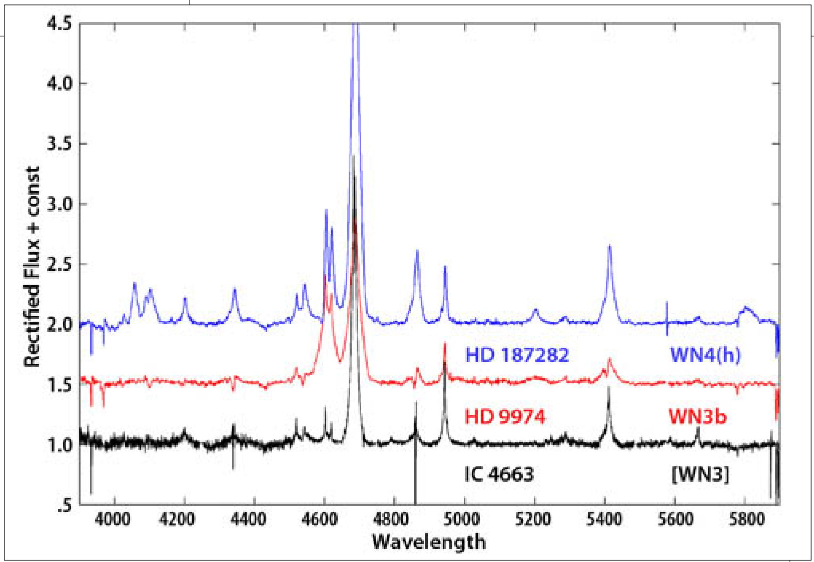

Figure 1. *Gemini South GMOS spectroscopy of the planetary nebula IC 4663's central star (black) and two massive WN stars of a similar spectral type. The numerous helium and nitrogen emission lines seen, combined with the absence of neutral helium and carbon emission lines, give a [WN3] classification for IC 4663.*

The spectroscopic properties of these low-mass remnants of solar-type stars are remarkably similar to their higher mass cousins. See, for example, the detailed comparison by Crowther, Morris, and Smith (2006) between HD 164270, a WC9 star, and BD +30 3639, a [WC9] star. This study quantitatively builds on the earlier qualitative study of Smith and Aller (1971) that 35 years earlier compared the same stars. Hence the Wolf-Rayet star phenomenon is dictated by similar plasma conditions, regardless of the context.

Among massive Wolf-Rayet stars, the observed statistics of WN- and WC-types in the Milky Way are roughly equal. Surprisingly, no one has identified any bona-fide examples of [WN] stars to date in the Wolf-Rayet central stars of planetary nebulae. Several [WN] candidates have been proposed, but most have turned out to be massive WN stars, since around 1 in 10 of them are also surrounded by nebulae. The most infamous example is WR 124 and its ejecta nebula M 1-67.

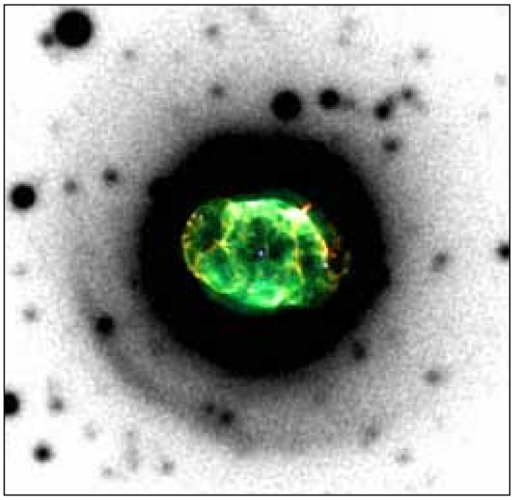

Figure 2. *The planetary nebula IC 4663 viewed by the Hubble Space Telescope (inset; red, green and blue channels made from ionized hydrogen and nitrogen, doubly ionized oxygen, and visual light, respectively) and GMOS at Gemini South (background; doubly ionized oxygen). The newly-discovered faint halo is a telltale signature of a planetary nebula, and the central star is at the center of the image, which measures 1 arcminute on each side (~ 3.26 light-years).*

A Serendipitous Discovery

With the advent of efficient spectrographs on 8- to 10-meter telescopes, very faint central stars of planetary nebulae can be accessed spectroscopically. As part of our ongoing survey work to look for binary central stars, we finally stumbled across a magnificent [WN] specimen in the poorly studied planetary nebula IC 4663. Figure 1 shows our Gemini Multi-Object Spectrograph (GMOS) spectrum of the [WN3] central star, which bears an uncanny resemblance to other massive WN stars of similar spectral type.

Could this be yet another case of mistaken identity? Unlike many previous [WN] candidates, the nebula and central star properties of IC 4663 were ideal for an unambiguous answer. Figure 2 shows the planetary nebula exquisitely imaged by the HST along with a much fainter surrounding halo discovered by our GMOS imaging. The inner nebula expands at 30 kilometers per second (km/s) as an elliptical, filamentary bubble with a highly ionized emission-line spectrum.

All of these properties are typical of planetary nebulae. The halo provides an even stronger clue that IC 4663 is a planetary nebula, since it must have formed during its progenitor's evolution near the end of the AGB phase, a path that massive Wolf-Rayet stars do not follow. As an additional sanity check, we verified that the brightness of the central star did not rival the massive WN stars of similar spectral type. With the HST imaging we measured a visual brightness of 16.9 magnitude, which is four

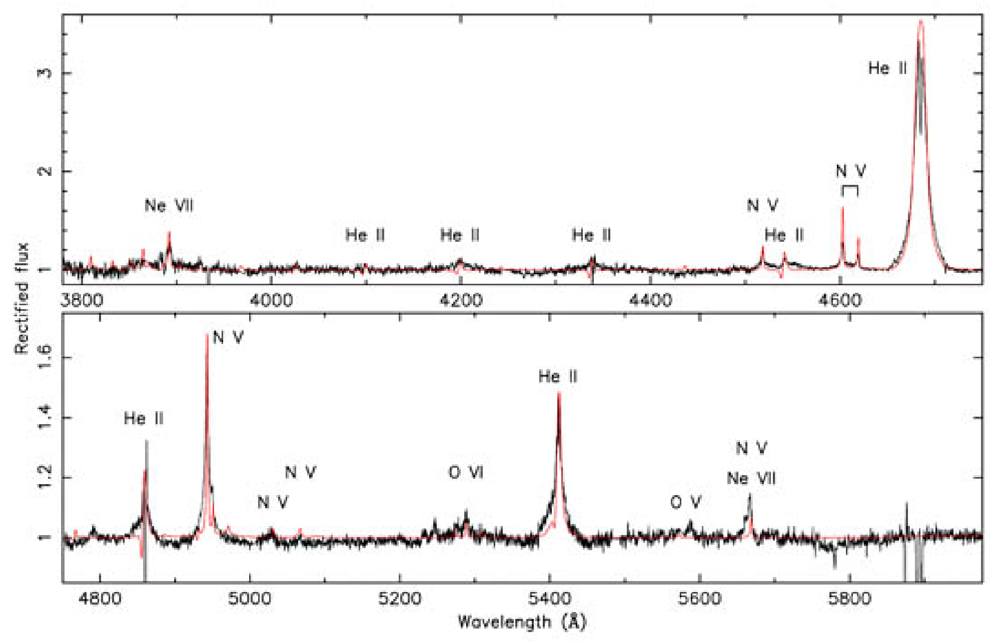

Figure 3. *Gemini South GMOS spectrum of the [WN3] central star of IC 4663 (black), with our model atmosphere (red). The main emission lines are labeled.*

to six magnitudes fainter than a massive WN3 star assuming reasonable distances to IC 4663.

All of the above leaves no doubt that IC 4663 is a planetary nebula, rather than an ejecta nebula around a massive WN star.

Stellar Properties

Wolf-Rayet stars have dense, expanding atmospheres that require specialized models to reproduce their observed spectra. We used the CMFGEN code to build a model atmosphere of the [WN3] star that takes into account metal-line blanketing and wind clumping (see Miszalski *et al.*, 2012).

Figure 3 shows our best model that provides a satisfactory fit to the GMOS spectrum. The model parameters at our adopted distance of 11,400 light-years include an extremely hot effective temperature of 140,000 K, a relatively fast wind expanding at a terminal speed of 1900 km/s, a radius 0.11 times the solar radius, a luminosity 4000 times greater than the Sun, and a mass loss rate of 1.8 x 10^{-8} solar masses per year. These parameters are comparable to the hottest [WC]-type Wolf-Rayet central stars.

In stark contrast to [WC]-type central stars, whose atmospheres are made up of a uniform pattern of 30-50 percent helium, 30-60 percent carbon, and 2-20 percent oxygen, the atmosphere of IC 4663 is made up almost entirely of helium (≥ 95 percent) along with 0.8 percent nitrogen; it is also depleted in carbon (< 0.1 percent) and oxygen (0.05 percent). This most unusual abundance pattern suggests that as the [WN3] star's wind starts to dissipate, it will evolve into an O(He) star whose known compositions closely match the abundance pattern of IC 4663, in the same way that [WC] central stars are thought to evolve into PG 1159 stars (see Figure 4).

These stages are the penultimate phase before the formation of a hydrogen-deficient DO white dwarf. The discovery of the [WN] nature of IC 4663 has clarified the uncertain evolutionary position of the O(He) stars, of which only four are known, and two of these have planetary nebulae (Rauch *et al.*, 1998), as the helium-rich equivalents of carbon-rich PG 1159 stars. This discovery in IC 4663 provides the best evidence so far for a second pathway for a subset of Sun-like stars to lose their hydrogen, one that is helium-rich in addition to the more common carbon-rich pathway (see Werner and Herwig, 2006).

Unexplained Origins

Most classical Wolf-Rayet stars (especially WC types) are very hydrogen-deficient, with hydrogen usually making up no more than a few percent of their atmospheres. In massive Wolf-Rayet stars, this can be explained by their strong wind peeling off the outer layers of hydrogen. In contrast, it is thought that an AGB precursor to a Wolf-Rayet central star experiences either a late or very late thermal pulse, reigniting helium-shell burning to burn up or mix away the remaining hydrogen. Although this scenario can reproduce the chemical sig-

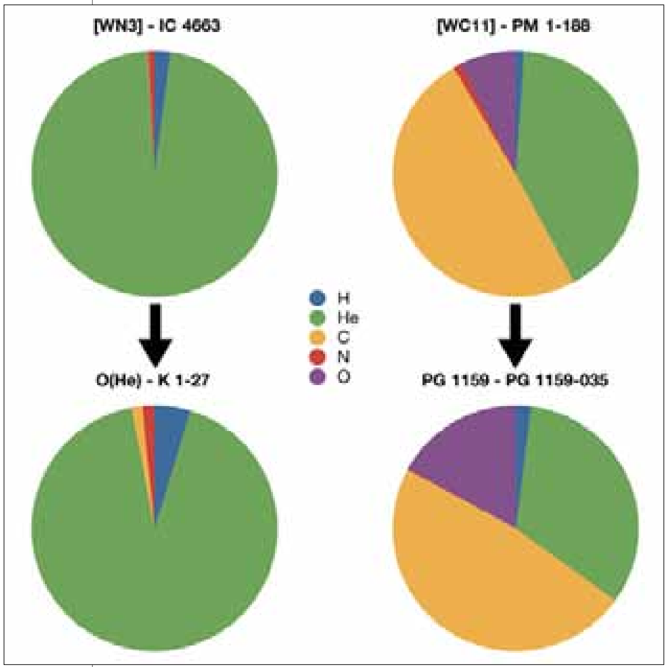

Figure 4.
Atmospheric compositions (by mass) of a [WN3] star (IC 4663), an O(He) star (K 1-27), a [WC11] star (PM 1-188), and a PG 1159 star (PG 1159-035, the prototype of the class), from our study and Werner and Herwig (2006). Note the similarity between the [WN3] and O(He), and the [WC11] and PG 1159, compositions. The carbon-rich [WC]→PG 1159 evolutionary sequence is well established, but only with IC 4663 are we able to newly propose the helium-rich equivalent [WN]→O(He). Only the main subset of elements are used to illustrate the similarity between the two separate groups.

nature found in most [WC] atmospheres, it has never reproduced the extreme helium-rich nature of O(He) stars or IC 4663. This suggests another explanation is required to produce [WN] central stars and their O(He) progeny.

At present it is unclear what this mechanism may be. Binary interactions may be the most promising avenue for investigation, especially considering the rapidly growing evidence for binarity in the central stars of planetary nebulae (Miszalski, *IAU Symposium 283*, in press, 2012; and references therein). Lack of radial velocity variability in IC 4663 suggests it is not a binary system, but it may have been in the past. One possible explanation for the formation of R Coronae Borealis stars, which share a similar hydrogen-deficient and helium-rich composition to IC 4663, involves a merger of two white dwarfs. There may also be some follow-on evolutionary ties to helium-rich novae and cataclysmic variables.

Whatever the reason behind the unusual composition of IC 4663, solving this puzzle will certainly require new ideas enriched by the prospect of future [WN] discoveries. We look forward to further developments in this exciting field of study.

For more information:

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