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Wolf-Rayet Central Stars of Planetary Nebulae: Their Evolution and Properties

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Abstract. Over the past decade, the number of planetary nebula central stars (CSPN) known to exhibit the Wolf-Rayet (WR) phenomenon has grown substantially. Many of these discoveries have resulted from the Macquarie/AAO/Strasbourg Hα (MASH) PN Survey. While WR CSPN constitute a relatively rare stellar type ($\lesssim$10% of CS), there are indications that the proportion of PN harbouring them may increase as spectroscopy of more central stars is carried out. In addition, with new and better distances from the Hα surface brightness-radius relationship of Frew (2008), we can attempt a dynamical age sequence which may provide insight into the evolution of these stars.

1. Introduction

Among central stars of planetary nebulae (CSPN), there exists a class of H-deficient objects that exhibit high mass-loss rates ($\gtrsim 10^{-6}$ M$_\odot$ yr^{-1}) due to strong, fast stellar winds. Their spectra resemble those of massive Wolf-Rayet stars, but these CSPN evolve from low- and intermediate-mass main sequence stars instead of massive O stars. They are designated as [WR] stars to differentiate them (van der Hucht et al. 1981).

The [WR] class is subdivided into an oxygen sequence (designated [WO]), a carbon sequence ([WC]) and two controversial subclasses, the [WN] and [WN/WC] types. Nitrogen lines are enhanced in the latter two, accompanied in the [WN/WC]s by higher carbon abundances (Todt et al. 2010). Massive WOs and WCs possess surface abundances that differ from those of WNs. These stars are believed to represent an evolutionary sequence in which progressively deeper layers of the star are exposed through strong wind-driven mass loss (e.g. Crowther 2007, and references therein). Thus, WCs and WOs possess different surface abundances than WNs. C/He ratios were at one time thought to be less in late-type [WC]s than in early types (e.g. De Marco & Barlow 2001), but as noted by Crowther (2007), the lack of common diagnostics between late and early types could be a source of error. More recent studies find that chemical abundances appear to be similar across [WC]s and [WO]s (He:C:O ~ 50:40:10 by mass for both; Crowther 2008), and their subclasses are primarily distinguished by temperature and degree of ionization. PB 8, the lone published [WN/WC] type, has a much higher mass fraction of H (40%) than [WC]s and [WO]s (Todt et al. 2010).

The first scenario proposed to explain the formation of [WR] CSPN was the so-called "Born-Again Scenario" (e.g. Schönberner 1979; Iben et al. 1983), in which a CSPN undergoes a thermal pulse that throws it back into the AGB. Possible [WR]

evolutionary paths are differentiated according to the stage at which the thermal pulse occurs: the Asymptotic Giant Branch Final Thermal Pulse (AFTP), which occurs at the end of the AGB phase; a Late Thermal Pulse (LTP), which occurs when the star has left the AGB but has not yet ceased H-burning; or a Very Late Thermal Pulse (VLTP), which occurs when the star is already on the WD cooling track. See Herwig (2001) for a more detailed discussion. Formation through a binary interaction has also been proposed (e.g. De Marco & Soker 2002; De Marco 2008). Hajduk et al. (2010) conclude that emission-line stars are less likely than "normal" H-rich PN to be found in binary systems, or else have larger orbital separations. This may suggest that [WR]s result from a binary merger.

A by-product of many searches for [WR]s among the CSPN are weak emission-line stars or WELS, some of which are also H-deficient (Marcolino & de Araújo 2003). These objects exhibit weaker emission lines at many of the same high-ionization wavelengths as [WR]s, but are likely less massive, evolutionarily unrelated objects, as evidenced by differences in Galactic scale height z (DePew et al. 2010a). Overall, a near-complete volume-limited 1 kpc sample suggests that 7±3% of CSPN belong to the [WR] class, and ~20% of CSPN are H-deficient (Frew & Parker 2010).

2.   New [WR]/WELS Discoveries

Recently 33 new [WR]/WELS and emission-line star candidates have been discovered in the course of the Macquarie/AAO/Strasbourg Hα (MASH; Parker et al. 2006; Miszalski et al. 2008) survey (DePew et al. 2010c). Of these, 19 are objects first found by us within the MASH sample, and 14 are previously known objects whose [WR] or WELS nature was discovered serendipitously by us in the course of spectroscopic follow-up of MASH objects. See DePew et al. (2010c) for observational details and preliminary analysis. The 17 MASH [WR]s detailed in that paper, added to the 7 previously found in the MASH survey (Morgan et al. 2001; Parker & Morgan 2003; Morgan et al. 2003), make a contribution of 24 new objects to the list of [WR]s by our group. With the 6 serendipitous discoveries, this represents an increase of ~40% in known [WR]s. Within the MASH sample, there is also one [WN] subclass object (PM5; Morgan et al. 2003) and one probable [WN/WC] object (Abell 48; DePew et al. 2010b).

3.   The [WN] Stars

Massive WN stars possess significant amounts of hydrogen that will be lost with the surface nitrogen as they proceed toward the WC and WO phases. The existence of an actual [WN] sequence is open to debate, however. While hot bottom burning (HBB) should strongly enhance nitrogen in the more massive CSPN progenitors ($\gtrsim 4$ M$_\odot$; Lau et al. 2009), there is confusion over whether the two currently designated [WN]s, PM5 for example (Morgan et al. 2003) and LMC-N66 (Peña 1995) are truly CSPN. The high expansion velocity of the main shell of PM5 (~165 km s^{-1}) is far higher than the v_{exp} of other known PN, and is more consistent with a massive WR ring nebula. LMC-N66 could be a peculiar binary system (Hamann et al. 2003).

There exists only one published member of the [WN/WC] class, PB 8 (Todt et al. 2010). The [WN/WC] class exhibits compositions and spectra similar to a massive WR
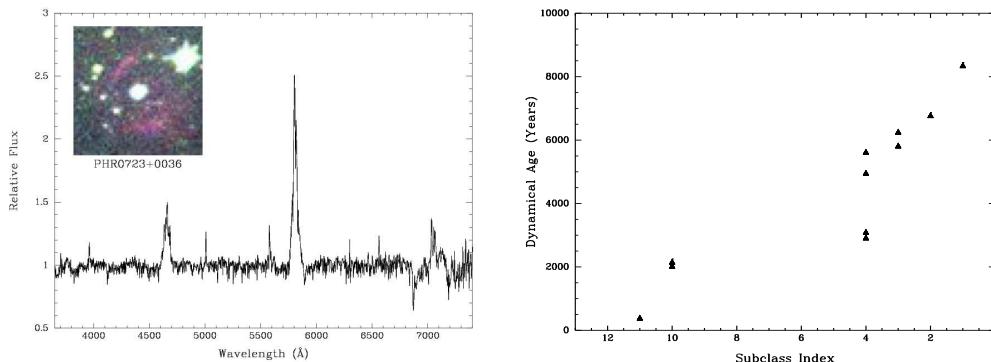
Figure 1.   At left, the spectrum and image of PHR0723+0036, a new MASH PN classifiable as a [WC4]. At right, the preliminary [WR] subclass-dynamical age relationship. Subclass index corresponds to: [WO1]=1, ..., [WO4]=4, [WC4]=5, ..., [WC11]=12.

transition type denoted as WN/WC. These objects have strong nitrogen lines, but also possess significant carbon abundances (1.3% by mass, as compared to 2% of nitrogen). Strangely, PB 8 is not a Type I nebula (Todt et al. 2010), as would normally be expected around a high-mass central star which has undergone HBB. This may not be a completely anomalous result however, as Abell 48 (also not a Type I PN; DePew et al. 2010b) appears to possess a [WN/WC] CS as well (DePew et al. 2010b).

4. Towards An Evolutionary Subclass Sequence

Distance is one of the most crucial and elusive parameters required for a determination of luminosity, mass and other important properties of a star. The new surface brightness-radius relationship found in Frew & Parker (2006) and Frew (2008) provides a new, robust method for determining distance to PN. This relation is very easy to use, requiring only the Hα flux, the extinction, and the angular dimensions of the PN.

Between 19-23 April 2010, we observed a selection of PN on the Wide Field Spectrograph (WiFeS; Dopita et al. 2010) for chemical abundance determinations at Siding Spring Observatory. From these observations we obtained the global R$_{[NII]}$ ratio ($\frac{I(\lambda\lambda 6548,84)}{I(\lambda 6563)}$). We used this value to deconvolve the [N II] contribution and extract the Hα flux using data from the SuperCOSMOS Hα Survey (SHS; Parker et al. 2005) and the Southern Hα Sky Survey Atlas (SHASSA; Gaustad et al. 2001). For those PN with nebular v_{exp} in the literature, Hα surface brightness and distance were calculated and a dynamical age derived. A preliminary plot of [WR] subclass versus dynamical age is shown in Figure 1, where a clear trend is evident. More in-depth results will follow (DePew et al. 2010a). While the analysis is not yet complete, it appears as though the late types are significantly younger than the early types, as previously suspected (e.g. Górny & Tylenda 2000). However, more data points are needed to firm up this result.

5. Conclusions

The provenance of [WR] CSPN is still uncertain. However, a larger sample size, arising largely from our new discoveries over the past decade, will enable us to fill in some of the gaps in our understanding. The [WN] and [WN/WC] classes in particular will benefit from new survey data.

In addition, using the SB-r relation of Frew (2008), we can determine more accurate distances to PN in our sample, allowing us to establish dynamical ages. The resulting evolutionary sequence, though somewhat crude, may in the future serve to inform stellar models for this rare class of objects.

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