Wolf-Rayet Stars
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General overview of Wolf-Rayet stars

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Although we all use the name Wolf-Rayet to refer to specific groups of stars, “Wolf-Rayet” *per se* is really an astrophysical phenomenon of fast-moving, hot plasma, normally expanding around a hot star. However, expediency demands that we follow established traditions by referring to three specific kinds of WR stars: (1) cWR, “classical” He-burning descendants of massive, O-type stars, presumably all of which pass through a WR stage; (2) WNh, the most massive and luminous hydrogen-rich main-sequence stars with strong winds; and (3) [WR], the central stars of some 15 % of Planetary Nebulae. Wolf-Rayet stars are the epitome of relatively stable stars with the highest mass-loss rates for their kind. It behooves us to understand the what, how and why of this circumstance, along with its manyfold and fascinating consequences.

1 Dedication

This talk is devoted to my first real WR contact and inspiration: Lindsey F. Smith. I first encountered Lindsey in 1968 when I was a doctoral student in Bonn, Germany, where she gave a colloquium on her freshly-minted Australian PhD thesis work with Bengt Westerlund on WR stars. We also met at various places thereafter, including the Elba IAU Symposium 163 on hot luminous stars in 1994, where on the banquet dance-floor I was able to convince her that “See, Lindsey, they *do* rotate after all!” I also salute “Wolf-Rayet” Hamann, our PoWRful Prussian-based hot-star king, who took the lead in organizing this extraordinary workshop. And finally, I cannot forget that 1867 was a great year, marked by the discovery at l’Observatoire de Paris of the first three WR stars (WR134, 135 & 137 in Cygnus) and by the creation of my home country.

2 WR stars in context

The upper CMD for massive stars is a rather peculiar place, with boundaries in which “allowed” stars can lie, defining a relatively small area (de Jager 1980), from the nearly vertical line at $\log(T_{\rm eff}) \approx 3.5$, i.e. the Hayashi limit to the red with $R \approx 1000R_\odot$; the also nearly vertical line at $\log(T_{\rm eff}) \approx 5.0$, i.e. the He-burning main-sequence (MS) to the blue; and the Humphreys-Davidson (H-D) limit at a maximum ($\sim$ Eddington) luminosity corresponding to $\log(L/L_\odot) \approx 6.3$. The lower boundary for massive stars ($> 8M_\odot$) is at $\log(L/L_\odot) \approx 3.5$. Only the degenerate bluer cooling sequences of very hot, but much lower-mass, white dwarfs (WDs) and neutron stars (NSs) lie outside this region. The He-burning massive WR stars are expected to occupy the extreme blue of this zone with $R \approx 1R_\odot$, but as we’ll see only few of them appear to have actually reached that far coming from the right.

While mass loss is crucial in determining the evolution for all massive stars at all stages above $M_{\rm i} \sim 20M_\odot$, it is especially important as such stars leave the MS and their outer layers puff up towards the H-D limit (while the core shrinks) or later, when its wind-bared core becomes a more compact and hotter WR star, believed to be the ultimate fate of all such stars. B-type stars in the range $8 - 20M_\odot$ lose less mass, but when they do, it is mainly as supergiants, especially in the RSG stage, where they also explode as type II (H-rich) supernovae. WR stars are believed to explode as type Ib (from H-poor WN) or Ic (from H- and relatively He-poor WC/WO) supernovae. For a typical massive star, the most important stages (especially regarding wind interactions) are:

1. first as a MS O-star (long time, fast wind), culminating in the post-MS SG stage as
2. an LBV stage (short time, slow wind), with RSG instead of LBV in the lowest part of this mass range, then
3. a WR stage (moderate time, fast wind), then
4. SN (ultra-short time and fast wind), ending in most cases as
5. a BH (essentially for infinite time, virtually no wind), or perhaps magnetars (= highly magnetic, slowly rotating NSs) in some cases.

For massive stars, thermonuclear fusion occurs in successively hotter and more compact regions from sequential “burning” of H, He, C, Ne, O and Si, finally to produce Fe, which immediately leads to a core-collapse implosion. After He-burning, a CMD is not useful, since the core evolves ever faster than the surface. Hence, the last visible stage before the SN is as a WR star, probably WC or WO in most cases, if they reach that far before their cores collapse.

While their progenitor O stars have spectra with relatively narrow photospheric absorption lines, the strongest of which reach an equivalent width (EW) up to several Å, WR stars reveal giant emission lines even in the optical domain, with EW up to ≈ 1000Å, arising in projected radial velocities from various layers of the rapidly expanding wind. Sample *optical* spectra, often considered key in distinguishing WR vs O stars, are shown in Crowther (2007) for both the WN (ranging from hot to cold: WN2-9, with CNO-cycle products of H-fusion reaching the surface and wind) and the WC (ranging over WC4-9, with triple-alpha products of He-fusion) sequences. Interestingly, WC stars form a more homogeneous sequence with regards to their fundamental properties as a function of wind temperature or spectral subtype, than do WN stars. WC stars are followed by WO stars (WO1-4), with either enhanced oxygen and/or hotter temperature (see below).

In this context I do recall once having an amusing moment during an evaluation site visit to our observatory (Observatoire du Mont-Mégantic, in Québec province) in 1988, where I was observing spectra of WR stars with a student. The external examiner, Robert Wagoner, a well-known SN expert, now emeritus at Stanford, happened to glance at one of our freshly obtained spectra and exclaim “Wow, what SN is that?” Our explanation that it was “only” a WR star created no lack of enthusiasm on his behalf, but I still wonder if our observatory grant only remained proportional to the width of the spectral lines!

So far, I’ve treated WR as only massive stars. In reality, as has been pointed out previously on various occasions, “WR” is really a phenomenon of strong, broad emission lines from a hot, expanding plasma, involving three recognized situations:

1. Classical He-rich cWR stars = evolved He-burning, pre-SN Ib,c stars of $M_\mathrm{i} \sim 25 - 100+?\ M_\odot$ (types WN, WC, WO).
2. Central stars of planetary nebulae (CSPN) - [WR], relatively massive post AGB stars (∼15 %).
3. Main Sequence H-rich WNh stars of $M_\mathrm{i} \sim 80 - 300\ M_\odot$.

We normally only see a stellar photosphere for stars in the third line above, while all massive stars above $M_\mathrm{i} \sim 25 M_\odot$ pass through a cWR phase, apparently regardless of initial metallicity (at least down to observed limits around 0.01 solar), which however, does have an effect on the wind and thus emission-line strengths.

How can such vastly different stars have similar normalized emission measures (NEM)? This was first realized by Schmutz et al. (1989), who showed that NEM can be expressed as a volume integral of density-squared per unit stellar surface, i.e.

NEM $\sim V\rho^2/R_\star^2$, so with $V \sim R_\star^3$ and $\dot{M}\sqrt{D} \sim R_\star^2 v_\infty \rho$: NEM $\sim \dot{M}^2 D/(R_\star^3 v_\infty^2)$.

Thus, for $D =$ const. (~ 10) and $v_\infty =$ const. (~ 2500km/s), $\sqrt{\mathrm{NEM}} \sim \dot{M}/R_\star^{3/2}$, which is listed in Table 1 for typical parameters of the three kinds of WR stars.

Tab. 1: Typical parameters for the three families of WR stars ([WR] for Abell 48: (Todt et al. 2013))

Type	$R_\star/R_\odot$	$\dot{M}/10^5 M_\odot$/yr	$\sqrt{\mathrm{NEM}}$
WNLh	15	10	0.017
cWR	3	1.0	0.019
[WR]	0.5	0.05	0.014

Remarkably, these 3 types do show very similar NEM and thus spectra, although line-width could be a distinguishing factor in some cases (Smith & Aller 1971).

Another puzzle with a less obvious solution is how cWR stars can have mass-loss rates that are typically 10 times higher than their progenitor O stars, despite their similar (or even slightly reduced) luminosities, which are normally believed to provide the radiation pressure needed to drive their winds, whether WR or O. One simple answer is that the theoretical (from internal models; external spectral fitting requires a rather uncertain extrapolation) radii of cWR stars are typically a factor 10 smaller than those of O stars. Thus, for flux conservation $L = 4\pi\sigma R^2 T_\star^4$, $T_\star(\mathrm{cWR}) \sim \sqrt{10}\ T_\mathrm{eff}(\mathrm{O}) \sim 100$kK, taking a typical $T_\mathrm{eff}(\mathrm{O}) \sim 30$kK. Therefore, at higher surface temperatures, there is relatively much more UV flux and thus more driving from ambient-ISM-provided Fe, with its complex atomic structure and forests of mainly UV-lines from Fe II through IV. [Note that the metallicity dependence $\dot{M} \sim Z^{0.7}$ is similar, although not identical, for both O- and WR-stars (Vink & de Koter 2005).] Thus, it is the high, stable $\dot{M}$ that distinguishes WR from their progenitor O stars.

As we’ll see later in this meeting, another factor in explaining why WR stars have such high $\dot{M}$, despite their similar Ls to those of O stars is their tendency to approach their Eddington limits with inflated envelopes. However, this might ultimately be related to the above fundamental circumstance of WR stars having hot, compact radii with enhanced wind driving.

As for their evolution, most astronomers probably agree with the general scenario, which began with that of Conti (1975):
O → LBV (RSG) → WN → WC → SN Ib,c → BH (NS)

But there are now many different detailed scenarios, of which that of Crowther (2007) is my preferred, because it is simultaneously simple and plausible, for the following approximate mass ranges:

1. $M_\mathrm{i} > \sim 75\, M_\odot$:
   [O →] WN(H-rich) → LBV → WN(H-poor) → WC → SN Ic
2. $M_\mathrm{i} \sim 40 - 75\, M_\odot$:
   O → LBV → WN(H-poor) → WC → SN Ic

3. $M_\mathrm{i} \sim 25 - 40\,M_\odot$:
   O → LBV/[RSG] → WN(H-poor) → SN Ib

(Note: In square brackets I have added possible modifications that may apply.)

In contrast, for stars with the next lower mass bracket, $M_\mathrm{i} \sim 10 - 25\,M_\odot$:
late-O/early-B → RSG → SN IIb, or bare He core if in a close binary, and some LBV may → SN IIn (Smith et al. 2007).

3 Some nagging questions

3.1 Are all WNE stars H-poor?

Answer: No, especially for lower ambient metallicity. A beautiful example is the single WN3ha (using the commonly accepted 3D classification system of Smith et al. 1996) star WR3 (in the outer Galaxy with Z like that found in the Magellanic Clouds, which contain many similar stars). Such stars often display weak lines with triangular profiles, believed to arise from lower mass-loss rates at low Z combined with rotationally induced meridional circulation. The principle parameters for WR3 from Marchenko et al. (2004) are: $\dot{M} = 2 \times 10^{-6} M_\odot/\mathrm{yr}, R_\star = 3.6\,R_\odot, R_{2/3} = 3.8\,R_\odot, \log(L/L_\odot) = 5.4, v_\infty = 2750\,\mathrm{km/s}, X_\mathrm{H} = 0.20, X_\mathrm{He} = 0.79, X_\mathrm{N} = 0.008$.

3.2 Are all WNL stars H-rich?

Answer: Again, no, contrary to common belief. A good example is the single Galactic star WR123 of type WN8o, i.e. lacking hydrogen. Along with four other Galactic runaways (WR64, 71, 93a and 148), WR123 is located over 500 pc from the Galactic plane (Rosslowe & Crowther 2015). On the other hand, the two runaway WN8h stars WR124 (surrounded by the "fireball" nebula M1-67, with $RV_\mathrm{pec} \sim 200\,\mathrm{km/s}$, although not too far from the Galactic plane) and WR148 (a close 4.2d single-line binary) do have hydrogen, like most stars of this kind. Note that WN8 stars are often found to be runaways for reasons that remain obscure at best.

On the other hand, all WN stars with high luminosity do appear to contain hydrogen (and designated WNh), since they are likely MS stars, in contrast with the He-burning cWR stars (see above).

3.3 Does intra-sequence evolution occur via the peeling-off scenario?

I.e. does one have WN9 → WN8 → WN7 → WN6 → WN5 → WN4 → WN3 → WN2, or WC9 → WC8 → WC7 → WC6 → WC5 → WC4, then → WO4→ WO3 → WO2 → WO1? In reality, a star does not need to follow the entire sequence and may transition from WN to WC or be interrupted by a SN explosion at any time in the sequence.

Answer: Yes, according to Smith & Hummer (1988) and Smith & Maeder (1991) for WC stars and Moffat (1995) for both WN and WC in limited sequences depending on the ambient metallicity, although with caveats. In addition, Moffat (1995) found that line widths have to match up at the transition from WN to WC, where the relatively rare transition WN/WC types are known to occur. More recently, however, Crowther (2007) showed that little intratype evolution occurs. This appears to be supported by the observed $f(Z)$ distribution of Galactic WR stars (van der Hucht 2001), where different subclasses tend to occupy different zones in Galactocentric distance (a proxy for metallicity Z), going from super-solar near the Galactic centre to LMC/SMC values in the outer Galaxy (1/2 – 1/4 solar). A good example here is that WC9 stars are only found in the inner Galaxy among all Local Group galaxies, where WR stars are formed at the highest Z. The main reason must be the enhanced opacity at higher ambient Z, since it is mainly Fe that drives the winds, more than the locally produced heavy elements He, N, C, O. However, there is a caveat to this, namely that poorly-determined distances may have smeared the Galactic distributions out, such that the true relation may be clearer than appears at first sight. Alternatively, if the smearing is not important, then there could indeed be some intra-sequence evolution. The astrometric satellite GAIA will hopefully straighten this out, with its vast improvement of distance determinations especially for WR stars. A recent study of abundances in WO stars may indeed suggest that peeling-off does occur, at least among these stars, after passing through a hotter WC stage (Tramper et al. 2015).

3.4 Do WR/O, WC/WN, WNL/WNE, WCL/WCE number ratios increase with Z?

Answer: No doubt, with lots of studies to back this up, both observational and theoretical. It's mainly a question of enhanced opacity (especially initial Fe), which allows more stars of lower mass to become WR. But what happens at extremely low Z ($\ll 0.01$ solar) remains to be seen.

3.5 Do all WRs start as O → Of → WNL?

Answer: This was first proposed by the wrap-up speaker at this meeting and is referred to as the Conti (1975) scenario. In reality, things have become a bit more complicated, as we have seen above and we'll see in the rest of this meeting.

3.6 What distinguishes [WR] from "normal" CSPN?

Answer: This remains a puzzle, but one idea I'd like to throw into the mix is: Stronger winds among post-AGB CSPN may possibly be due to smaller radii and higher $T_{\rm eff}$, as might be the case if [WR] stars are more massive and degenerate than most non-[WR] CSPN, something like comparing pop I cWR with their progenitor O stars (although not with respect to degeneracy). Note that [WN] stars have recently been found to exist (Miszalski et al. 2012), putting to rest the long-believed notion that all [WR] CSPN are [WC], albeit [WN] seems to be much rarer than [WC].

3.7 Does binarity affect cWR evolution?

Answer: Yes, but probably for close binaries only. From Kepler's 3rd law $M_1 + M_2 = a^3/P^2$ (for $M_\odot$, AU & yr), then with $a \sim 2R$ for two stars of similar radii, R, corresponding $\sim$ to the RLOF limit, and for a typical LBV, $R \sim 75\,R_\odot \sim 0.35\,$AU, with $M_1 + M_2 \sim 70\,M_\odot$ for a modest system: $P_{\rm i} \lesssim 25\,$d (unless there are huge outbursts). For a typical RSG, $R \sim 1000\,R_\odot \sim 5\,{\rm AU}, M_1 + M_2 \sim 50\,M_\odot$, one finds $P_{\rm i} \lesssim 4\,$yr.

Note that the shortest-period cWR binaries, which must almost certainly have gone through RLOF are:

1. Cyg X-3, WN4-6 + cc, $P = 4.8\,{\rm h} = 0.20\,{\rm d}$ (the only recognized WR + cc binary) (van Kerkwijk et al. 1996),
2. CQ Cep, WN6o + O, $P = 1.64\,$d (Marchenko et al. 1995),
3. BAT99-32, WN6(h) + O, $P = 1.91\,$d (Schnurr et al. 2008),
4. BAT99-39 = Br32, WC4 + O, $P = 1.92\,$d (Bartzakos et al. 2001), thus putting to rest the suspicion that WC+O binaries have longer periods (L. F. Smith, priv. comm.).

Examples of rare massive RLOF W Ser systems in action possibly on their way to becoming WR+O systems include β Lyr, RY Scuti and more recently HDE 326823 (Richardson et al. 2011), for which $P = 6.1\,$d, $e = 0.19$, $f(M) = 7\,M_\odot$. In this case, the visible star (which has a spectrum similar to that of a B-supergiant despite its low mass, $\sim 6\,M_\odot$) is the mass donor, and is transferring mass to a more massive gainer star of $\sim 30\,M_\odot$ that is enshrouded in a thick accretion torus.

4 Population I WR inventory and relevance for supernovae

The current number of known (i.e. spectroscopically confirmed) WR stars in the Galaxy now stands at 642 (June 2015: P.A. Crowther's on-line catalogue: http://pacrowther.staff.shef.ac.uk/WRcat/), somewhat short still of the expected 1900 total (Rosslowe & Crowther 2015). The number of known extragalactic WR stars is ca. 700 (Massey, priv. comm.), excluding unresolved WR galaxies, where severe crowding occurs.

The expected average time till the next core-collapse WR supernova in a random sample of N WR stars will be $t = \tau({\rm WR})/(2N) = 2 \times 10^5\,{\rm yr}/N$. Thus, for an average total WR lifetime $\tau({\rm WR}) \sim 0.4\,$Myr, one has the results in Table 2:

Tab. 2: Time until next SN in a sample of N WR stars

N	t [yr]
10^3	200
10^4	20
10^5	2

Of course the last row is the most interesting, but requiring some 50 giant spirals each with 2000 WR. But if WR stars collapse into BHs taking everything with them without a SN, then the task of finding which WR stars have actually done this clearly becomes much more challenging, i.e. looking for missing WR stars without the signal of a preceding explosion.

Interestingly in this context, the proof that WN stars actually do explode as SN Ib and WC stars explode as SN-Ic in spiral galaxies, including e.g. NGC 7793, is intimated by their similar respective distributions (Bibby & Crowther 2010). Note that $\sim 20\,\%$ of all SNe are of type Ib, c, with the majority (type II) coming from more numerous lower-mass RSG.

5 WR models: winds and internal structure

How have spectral models (mainly CMFGEN and PoWR) faired over the years? A sample PoWR model fit to the weak-line (requiring a less dramatic extrapolation down through the wind to the hydrostatic surface, and thus a more likely fit) WN5-w star WR61 (Hamann et al. 2006) exhibits a good, although not perfect fit. Even if the fit were perfect though, one always wonders about the uniqueness of the model, given the large number of parameters involved. Fortunately, due to proper inclusion during the past decade of line blanketing, model atmospheres have become more realistic, with O stars now cooler and fainter, while WR stars are estimated to be hotter and brighter. In M_v, WNL stars are always the brightest, while WNE stars become increasingly fainter for progressively hotter subtypes. But despite the large progression in M_v with subtype, all WNE have $L \sim$ const., due to enhanced bolometric corrections for hotter stars.

Overall, the position in the CMD of single Galactic WN stars follows a distinct trend with a few exceptions: those with H (mostly WNL) are brighter in bolometric luminosity L by 0.5 dex (factor 3) on average than those without H (mostly WNE). But still, a problem remains: Why are there not more WN on/near the He-ZAMS as expected from internal models? Model atmospheres carry a high degree of uncertainty due to the required extrapolation to what is considered something close to their hydrostatic core radii $R_\star$, assuming $\tau_\star = 20$ and $\beta = 1$.

Things appear to get even stranger when the WC model atmospheres are examined (Sander et al. 2012). While WC4 stars may lie close to the He-ZAMS, cooler WC stars lie further towards the H-ZAMS, with WC9 stars clearly lying apart from the remaining WC stars, essentially on the H-ZAMS at luminosity lower by ca. 0.2 dex than their WC4–8 cousins. Perhaps this is due to their lower initial mass, being formed at higher initial Z, which allows lower-mass stars to become WR, in this case eventually ending up as WC9, although why so far from the He-ZAMS?

Comparison of wind models with evolutionary models (Meynet & Maeder 2003) for two groups of initial rotation $V_\mathrm{rot}(\mathrm{init}) = 0$ vs. 300 km/s shows that neither gives satisfactory agreement. The possibility of cooler cWR surface/wind models with inflated envelopes has been conjectured (Moriya et al. 2015), as will be discussed later in these proceedings. Ultimately one might need consistent models from basic principles starting with 10^{58} atoms + basic laws of physics! Of course that is a totally unrealistic pipe dream and we'll have to wait and see what gradually improved models bring as more realistic physics is included.

6 Conclusions

I originally wanted to zero in on a few topics in more detail, such as binaries, colliding winds and wind structures, but time and space limitations mean that I'll gladly defer to the excellent presentations to follow. Basically, I have given personal highlights, both subjective & not complete. E.g., not discussed much here have been: hybrid models (interiors + winds), abundances, ring nebulae, gamma rays, WR galaxies, etc. One thing is sure, though, and that is that future research will greatly benefit from highly advanced projects such as GAIA, JWST, EELT/TMT, Interferometry, and even pro-am collaborations.

And now let the real meeting begin!

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Peredur Williams: The figure comparing the ISO infrared co-added spectra of dust-making WCL stars with the PAH spectrum has corresponding emission features red-shifted by about 8000 km/s. This is greater than the outflow velocities of these stars or of the dust expansion velocities like that of the WR112 pinwheel. So these data do not show evidence for PAH emission in dust-making WCL stars.

Anthony (Tony) Moffat: The relative positions of the lines are consistent with each other and the strong red-shift can be understood in terms of published models in other contexts. A paper is in preparation on this and will be submitted soon.