Wolf-Rayet Stars
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Wolf-Rayet content of the Milky Way

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An overview of the known Wolf-Rayet (WR) population of the Milky Way is presented, including a brief overview of historical catalogues and recent advances based on infrared photometric and spectroscopic observations resulting in the current census of 642 (v1.13 online catalogue). The observed distribution of WR stars is considered with respect to known star clusters, given that $\leq$20% of WR stars in the disk are located in clusters. WN stars outnumber WC stars at all galactocentric radii, while early-type WC stars are strongly biased against the inner Milky Way. Finally, recent estimates of the global WR population in the Milky Way are reassessed, with 1,200$\pm$100 estimated, such that the current census may be 50% complete. A characteristic WR lifetime of 0.25 Myr is inferred for an initial mass threshold of 25 $M_{\odot}$.

1 Historical overview and current census

Wolf-Rayet (WR) stars are the evolved descendents of massive stars, with two main flavours: Helium-rich WN stars displaying the products of core H burning and Carbon-rich WC stars displaying the products of core He burning (Crowther 2007). An overview of the number of WR stars in the Milky Way is provided. The Galactic census tripled between the 1st (Campbell 1894) and the 6th catalogues (van der Hucht 1981), a century later (Table 1), and subsequently doubled by the Annex to the 7th catalogue (van der Hucht 2006) owing to deep narrow-band optical surveys (Shara et al. 1999), the discovery of rich star clusters (Crowther et al. 2006) and infrared surveys of the Galactic Centre region (Figer et al. 2002). Over the past decade, the number has doubled again, primarily through surveys arising from the advent of large format infrared detectors, with the census totalling 642[1], comprising 357 WN stars, 8 WN/C stars, 273 WC stars and 4 WO stars.

Tab. 1: Historical catalogues of Galactic WR stars

Catalogue	Reference	Number
I	Campbell (1894)	55
II	Fleming & Pickering (1912)	108
III	Payne (1930)	92
IV	Roberts (1962)	123
V	Smith (1968)	127
VI	van der Hucht et al. (1981)	157
VII	van der Hucht (2001)	227
VII	Current census v1.13	642[1]

Two complementary initiatives have dominated this improvement since the annex to the 7th catalogue (van der Hucht 2006). Mike Shara and collaborators have employed narrow-band imaging of the Galactic plane at 2-2.3μm to identify 150+ WR stars from follow-up spectroscopy (Shara et al. 2012). Since this approach relies upon the contrast between emission lines and the adjacent continuum, systems which are dominated by hot dust or a companion in the K-band will not be identified. A second method exploiting the unusual near- to mid-IR broad-band colours of WR stars has been exploited by Schuyler Van Dyk, Pat Morris and collaborators has identified 100+ WR stars (Hadfield et al. 2007; Mauerhan et al. 2011). This approach has successfully identified dusty WR stars, but would also prove problematic for systems whose IR energy distribution is dominated by a companion star.

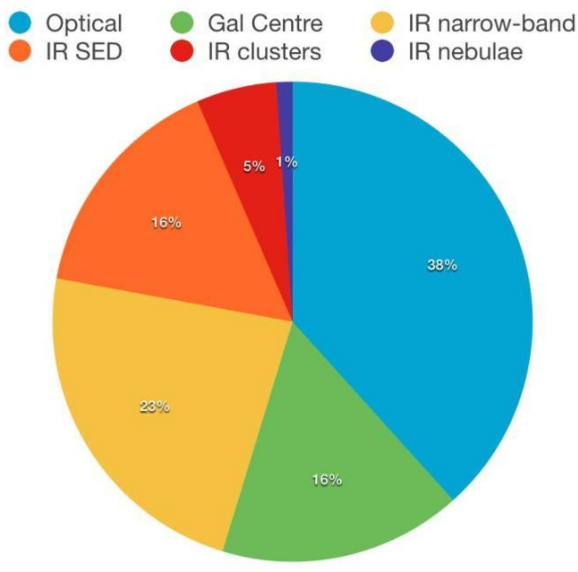

Fig. 1: Pie chart illustrating breakdown of discovery technique for WR stars in current census (v1.13 of online catalogue)

In addition, WR stars have been discovered from follow-up spectroscopy of members in star

[1]v1.13 of online WR catalogue http://pacrowther.staff.shef.ac.uk/WRcat/

clusters newly identified from IR surveys (e.g. Spitzer/GLIMPSE, VISTA/VVV) such as Chené et al. (2012). Other WR stars have been newly identified from follow-up spectroscopy of the ionizing stars in dusty mid-IR nebulae (Wachter et al. 2010). A chart illustrating the fraction of WR stars discovered by different techniques is illustrated in Fig. 1.

The binary frequency of O stars in young Galactic clusters is believed to be high: ∼71% will interact with a companion during their lifetime according to Sana et al. (2012). Since WR stars are the progeny of O stars, a high WR binary frequency will also be anticipated. The majority of searches for binarity in WR stars have been conducted via blue visual spectroscopic monitoring. Amongst the 25% of WR stars which are visually brighter than V=15 mag, 44 are close binaries (either SB1 or SB2), plus another 10 are dusty WC stars. It is now widely accepted that dusty WC stars are universally binary systems involving a WC star and an O star companion. Therefore, a strict lower limit to the binary frequency is 34% (= 54/160 stars). For comparison, a WR binary frequency of 38% (86/227) was estimated in the 7th WR catalogue (van der Hucht 2001), including long period systems (P > 1000 days) and X-ray bright systems - by way of example the X-ray bright system WR25 was subsequently identified as an SB1 by Gamen et al. (2006). These statistics undoubtedly represent lower limits to the WR binary frequency, although one would expect a lower binary frequency than for O stars since some WR stars will be merger products and others will become single following the (dynamical or post-supernova) disruption of initial binary systems.

2 WR stars and star clusters

If we adopt a lower mass limit to the production of WR stars of ∼25 $M_\odot$, and if massive stars only form in clusters, whose upper mass limit follows the relationship of Weidner et al. (2010), one would expect $10^3 M_\odot$ clusters to host the majority of WR stars. In reality only 27% of WR stars in the Milky Way are in known star clusters (Rosslowe & Crowther 2015). Of these, the majority of known WR stars in the Central Molecular Zone (CMZ) do lie within one of the three massive star clusters, the Arches, Quintuplet and the Galactic Centre cluster itself. Excluding the CMZ, only 18% of the WR stars located in the disk lie within star clusters. This is illustrated in Fig. 2.

Consequently, either the lower mass limit to the production of WR stars must be significantly lower (making birth clusters harder to identify), WR stars do not preferentially form in dense star clusters, or the majority of WR stars are no longer associated with their birth cluster.

OB stars are observed in a range of environments - low density star forming regions (e.g. ρ Oph), intermediate density OB associations such as Cyg OB2, and dense clusters such as NGC 3603. Indeed, the fraction of stars (of all masses) located in dense (Orion Nebula-like) clusters in the Solar Neighbourhood is <26% (Bressert et al. 2010). Wright et al. (2014) have established that massive stars in Cyg OB2 did not form in close proximity, nor in regions of higher density, so can form in regions of relatively low density.

Therefore, it is likely that typical massive stars arise from relatively loose OB associations, with only a small fraction born in dense star clusters, so the rarity of WR stars in star clusters naturally follows without resorting to a low threshold mass to the formation of WR stars or a high ejection frequency. This has relevance to the discussion of Smith & Tombleson (2015) regarding the relative masses of O, WR stars and Luminous Blue Variable (LBV) in the Large Magellanic Cloud from their spatial locations. One would expect relatively few O stars in close proximity to most WR stars/LBVs if the majority of massive stars originate in intermediate density environments, especially since most WR stars will arise from relatively modest $\sim 25 M_\odot$ progenitors.

3 Distribution of WR stars

Since the distance of the majority of Galactic WR stars is not well established, Rosslowe & Crowther (2015) have investigated the near-IR absolute magnitudes of different WR subtypes based on 108 stars whose distances have been estimated, either from cluster/association membership or other techniques. The spatial distribution of these, plus 246 field WR stars for which reliable spectral types have been obtained, are presented in Fig. 3.

Field WR populations include binary systems, providing the WR to OB light ratio can be estimated in the K-band or the WR star is thought to dominate the near-IR continuum flux. From a census of local (<3 kpc) WR systems, the WR star dominates the K-band flux in 82% of cases. In addition, dusty WC stars are omitted from this distribution because their K-band flux is typically dominated by hot dust rather than the WC continuum. For reference, dusty WC stars comprise ∼15% of the local (<3 kpc) WR population.

Generally, the near-IR classification of WR stars is rather coarser than at visible wavelengths. The majority of near-IR studies have followed the scheme of Crowther et al. (2006) who utilised IRTF/SpeX 1–5μm observations of ∼30 optically classified WR stars. In general robust near-IR classification requires observations at J, H and K, although the actual number of WN/C transition stars will be underestimated since no near-IR schemes have so far been implemented (efforts are currently underway to remedy this deficiency).

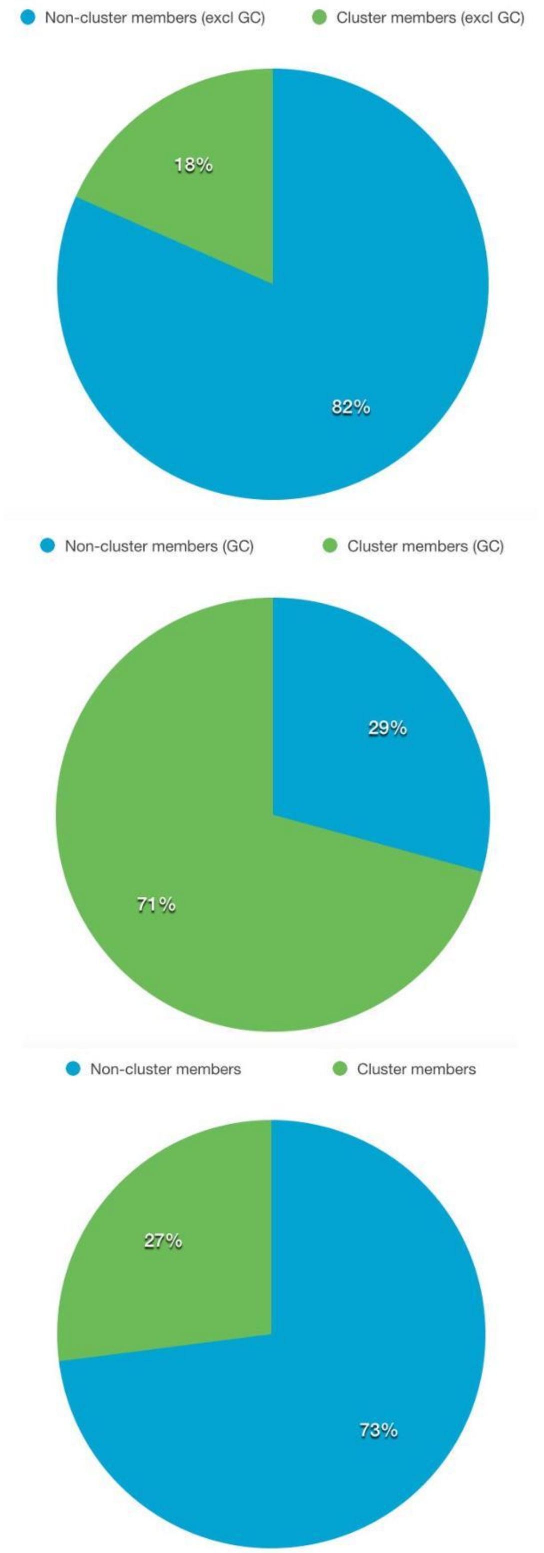

Fig. 2: Pie charts illustrating the fraction of Wolf-Rayet stars (v1.13 of catalogue) which are cluster members (green) or in the field (blue) for the Galactic disk (top), Galactic Centre region (middle) and combined pop (bottom).

The observed ratios of WR subtypes in the inner Galaxy at galactocentric distances of below 6 kpc (log O/H+12 $\sim$ 8.85), mid disk from 6–9 kpc (log O/H+12 $\sim$ 8.7) and outer disk beyond 9 kpc (log O/H + 12 $\sim$ 8.55) is presented in Table 2. Overall there is little variation between these regions with the exception of early to late WC stars, with the latter dominating in the inner disk owing to the metallicity dependence of WC classification diagnostics (Crowther et al. 2002). Incorporating results from the Magellanic Clouds, the observed WC to WN ratio is presented in Fig. 4, together with a variety of evolutionary predictions from single and binary models (see caption).

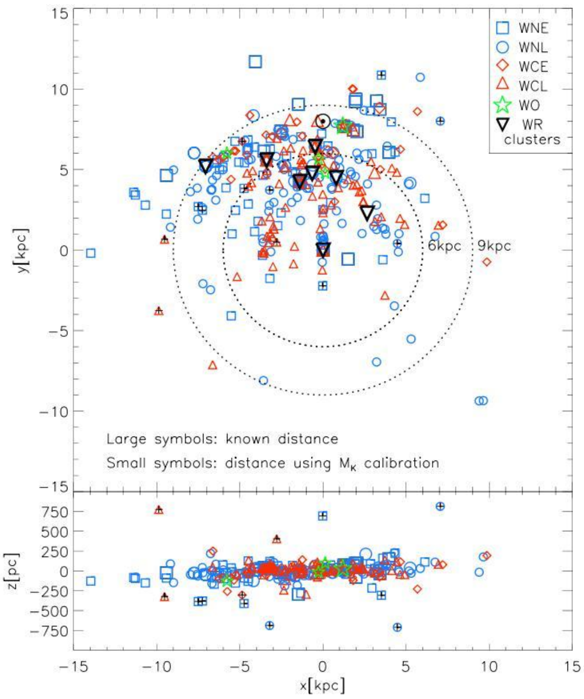

Fig. 3: Distribution of 354 WR stars in the Galactic disk from Rosslowe & Crowther (2015)

4 Global WR content

Various estimates of the global WR population in the Milky Way have been made, ranging from 1,200 (Maeder & Lequeux 1982) to 6,500 (van der Hucht 2001). We have constructed a toy model of the WR population in the Milky Way in an azimuthally symmetric disk following the radial HII distribution, atomic/molecular dust distribution and the observed WN/WC distribution (Rosslowe & Crowther 2015).

If we assume that the observed WR distribution is complete to K=8 mag (though see below), $\sim$550 WR

Tab. 2: WR subtype distribution in the Milky Way (Rosslowe & Crowther 2015) for three galacto-centric distances ($R_{\rm GC}$).

Region	N(WR)	N(WC)/N(WN)	N(WC+d)/N(WN)	N(WCE)/N(WCL)
Inner ($R_{\rm GC} < 6$ kpc)	187	0.51	0.69	0.05
Mid ($6 \leq R_{\rm GC} \leq 9$ kpc)	132	0.53	0.73	1.0
Outer ($R_{\rm GC} > 9$ kpc)	35	0.40	0.57	1.5

dominated stars in the Galactic disk reproduce the observed WR distribution. In addition, over 100 WR stars are currently known with $-2.5° \leq l \leq +3.5°$ so the total CMZ population may be as large as 250. Such a large population is surprising given that the CMZ accounts for perhaps 5% of the entire Milky Way star formation rate (Longmore et al. 2013), but the presence of three very massive clusters in the Galactic Centre region suggests WR stars may be disproportionately represented.

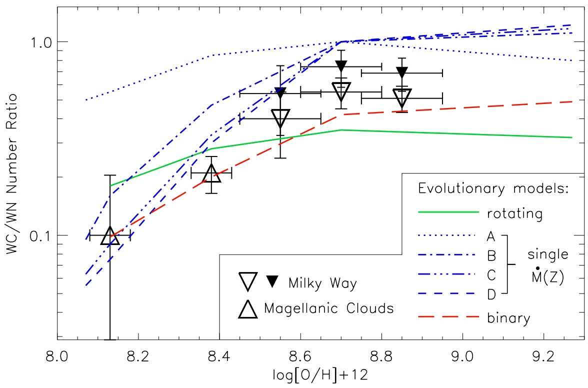

Fig. 4: Ratio of WC to WN stars in the Milky Way, for which dusty WC stars have been omitted (inverted open triangles) or included (inverted filled triangles), plus the Magellanic Clouds (open triangles) from Rosslowe & Crowther (2015). Predictions from rotating single star models (Meynet & Maeder 2005, green), binary models (Eldridge et al. 2008, red) and non-rotating single star models for various mass-loss metallicity dependencies (Eldridge & Vink 2006, blue) are also indicated.

A total of 550 + 250 = 800 stars would represent only 82% of the non-dusty WR population since 18% of systems are expected to be dominated by the WR companion in the K-band, so the non-dusty WR population inferred is ∼950. Finally, including dusty WC stars, which comprise 15% (150) of the whole population, we estimate N(WR) = 1,100, providing N(WCd)/N(WC) is uniform across all galactocentric radii. A histogram of the predicted JHK$_s$ magnitudes for this predicted WR population is presented in Fig. 5.

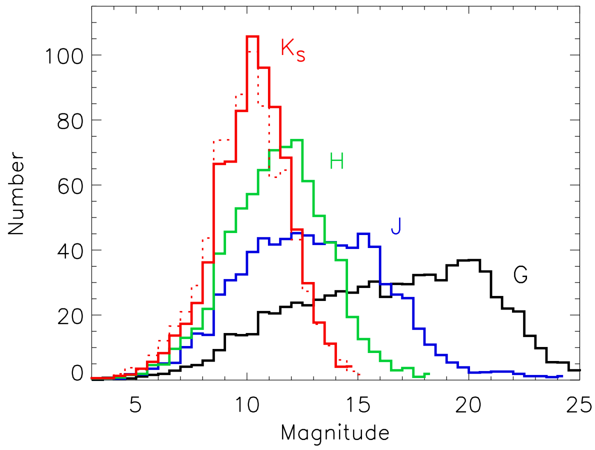

Fig. 5: Histogram of JHK$_s$ and GAIA G-band magnitudes predicted from the model WR population by Rosslowe & Crowther (2015).Thick lines represent populations consisting of WN and non-dusty WC stars, while the dotted-line illustrates a model population in which 28% of WC stars are dust-forming with $M_{\rm K} = -6.95$ mag.

Based on this global WR population of 1,100, if the lower mass threshold to WR stars is $25 M_\odot$, an average lifetime for the WR phase of 0.25 Myr is implied by the current Milky Way star formation rate of 1.9 $M_\odot$ yr^{-1} (Chomiuk & Povich 2011) and a standard Kroupa Initial Mass Function. This characteristic lifetime is in fair agreement with non-rotation evolutionary models, but is somewhat shorter than rotating model predictions (Georgy et al. 2012).

If the observed WR distribution is not complete to K=8 mag, the actual WR population will increase. By way of example, the two most recent additions to the on-line catalogue (v1.13) involve WR111-13[2], a WN6 star from Messineo et al. (2015) with K=8.02 mag and WR111-14, a WN7–8 star from Nebot Gómez-Morán et al. (2015) with K=7.7 mag. If the

[2] All WR stars discovered between the 6th catalogue and the Annex to the 7th catalogue follow the WRXXXa, WRXXXb nomenclature, whereas more recent additions utilise WRXXX-1, -2

WR-dominated disk population were 650 instead of 550, a global population of 1,300 would be inferred, so the current census may be 50% complete.

5 Summary

A brief overview of the Wolf-Rayet population in the Milky Way is presented. The current census of 642 (v1.13 of online catalogue) represents a doubling of the population since the Annex to the 7th WR catalogue only a decade ago, due to systematic searches from narrow-band surveys at 2μm and broad-band near to mid-IR surveys.

A strict lower limit to the binary fraction is 34% (SB1–2 systems plus dusty WC stars) for V$<$ 15 mag, but the actual fraction will undoubtedly be significantly higher. Spectroscopic monitoring of WR stars in the near-IR is now feasible owing to multi-object IR integral field units (e.g. KMOS at ESO's VLT).

Excluding the Galactic Centre region, $\leq$20% of WR stars are located in star clusters, adding weight to the formation of most massive stars in OB associations, i.e. away from dense clusters. The current WR census may be 50% complete, in which case the average duration of the WR phase is 0.25 Myr for a lower mass limit of 25 $M_{\odot}$ to the formation of WR stars.

The majority of systems hosting WR stars are dominated by the He-rich component in the K-band, so these are fundamentally high luminosity (high mass) stars. In contrast, typical progenitors of stripped envelope core-collapse supernovae are relatively low mass stars, having transferred the majority of their H-rich envelope to a close companion. Such systems would not be recognised as conventional WR stars since the He-rich mass donor would be masked by the H-rich mass gainer at optical and near-IR wavelengths.

Finally, the online WR catalogue is maintained in Sheffield on a best efforts basis so authors are encouraged to provide Paul Crowther with preprints as soon as they are accepted for publication.

References

Bressert, E., Bastian, N., Gutermuth, R., et al. 2010, MNRAS, 409, L54

Campbell, W. W. 1894, Astronomy and Astro-Physics (formerly The Sidereal Messenger), 13, 448

Chené, A.-N., Borissova, J., Clarke, J. R. A., et al. 2012, A&A, 545, A54

Chomiuk, L. & Povich, M. S. 2011, AJ, 142, 197

Crowther, P. A. 2007, ARA&A, 45, 177

Crowther, P. A., Dessart, L., Hillier, D. J., Abbott, J. B., & Fullerton, A. W. 2002, A&A, 392, 653

Crowther, P. A., Hadfield, L. J., Clark, J. S., Negueruela, I., & Vacca, W. D. 2006, MNRAS, 372, 1407

Eldridge, J. J., Izzard, R. G., & Tout, C. A. 2008, MNRAS, 384, 1109

Eldridge, J. J. & Vink, J. S. 2006, A&A, 452, 295

Figer, D. F., Najarro, F., Gilmore, D., et al. 2002, ApJ, 581, 258

Fleming, W. P. S. & Pickering, E. C. 1912, Annals of Harvard College Observatory, 56, 165

Gamen, R., Gosset, E., Morrell, N., et al. 2006, A&A, 460, 777

Georgy, C., Ekström, S., Meynet, G., et al. 2012, A&A, 542, A29

Hadfield, L. J., van Dyk, S. D., Morris, P. W., et al. 2007, MNRAS, 376, 248

Longmore, S. N., Bally, J., Testi, L., et al. 2013, MNRAS, 429, 987

Maeder, A. & Lequeux, J. 1982, A&A, 114, 409

Mauerhan, J. C., Van Dyk, S. D., & Morris, P. W. 2011, AJ, 142, 40

Messineo, M., Clark, J. S., Figer, D. F., et al. 2015, ApJ, 805, 110

Meynet, G. & Maeder, A. 2005, A&A, 429, 581

Nebot Gómez-Morán, A., Motch, C., Pineau, F.-X., et al. 2015, MNRAS, 452, 884

Payne, C. H. 1930, Harvard Observatory Monographs, 3, 1

Roberts, M. S. 1962, AJ, 67, 79

Rosslowe, C. K. & Crowther, P. A. 2015, MNRAS, 447, 2322

Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444

Shara, M. M., Faherty, J. K., Zurek, D., et al. 2012, AJ, 143, 149

Shara, M. M., Moffat, A. F. J., Smith, L. F., et al. 1999, AJ, 118, 390

Smith, L. F. 1968, MNRAS, 138, 109

Smith, N. & Tombleson, R. 2015, MNRAS, 447, 598

van der Hucht, K. A. 2001, New A Rev., 45, 135

van der Hucht, K. A. 2006, A&A, 458, 453

van der Hucht, K. A., Conti, P. S., Lundstrom, I., & Stenholm, B. 1981, Space Sci. Rev., 28, 227

Wachter, S., Mauerhan, J. C., Van Dyk, S. D., et al. 2010, AJ, 139, 2330

Weidner, C., Kroupa, P., & Bonnell, I. A. D. 2010, MNRAS, 401, 275

Wright, N. J., Parker, R. J., Goodwin, S. P., & Drake, J. J. 2014, MNRAS, 438, 639

Dany Vanbeveren: In most of the WR+O binaries the O star is the brighter component. How many O-type stars could be WR+OB binaries but unrecognized because the WR star is too faint?

Paul Crowther: Indeed many WR+O systems are dominated by OB (supergiant) companions at optical wavelengths, but the IR continuum excess from dense WR winds tends to ensure that a fraction of such systems are WR dominated in K band. Still, we estimate 1/6 of nearby WR+O systems (<3 kpc) are dominated by companions (Rosslowe & Crowther 2015).

Ted Gull: Your presentation suggests a bias of detection for WC stars, especially in the IR. Please elucidate how WN stars are identified.

Paul Crowther: IR selected Wolf-Rayet stars span WC, WN subtypes since both subtypes possess K-band emission lines and a continuum excess at 1 – 10 μm with respect to “normal” stars.

Anthony (Tony) Moffat: Are the 24 WRs in Wd1 confirmed binaries (e.g. by periodic RV variations)?

Paul Crowther: Only a few have orbital periods from RV variations to date, although Simon Clark is using VLT/FLAMES to search for more. Still, many more Wd1 WR stars are likely to be binaries owing to either being dusty WC stars or bright X-ray emitters (or both), so a very high binary WR fraction can’t be ruled out,