Wolf-Rayet Stars
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Finding Wolf-Rayet Stars in the Milky Way: Inputs to Star Formation and Stellar Evolution

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The total population of Wolf-Rayet (WR) stars in the Galaxy is predicted by models to be as many as ~6000 stars, and yet the number of catalogued WR stars as a result of optical surveys was far lower than this (~200) at the turn of this century. When beginning our WR searches using infrared techniques it was not clear whether WR number predictions were too optimistic or whether there was more hidden behind interstellar and circumstellar extinction. During the last decade we pioneered a technique of exploiting the near- and mid-infrared continuum colours for individual point sources provided by large-format surveys of the Galaxy, including 2MASS and Spitzer/GLIMPSE, to pierce through the dust and reveal newly discovered WR stars throughout the Galactic Plane. The key item to the colour discrimination is via the characteristic infrared spectral index produced by the strong winds of the WR stars, combined with dust extinction, which place WR stars in a relatively depopulated area of infrared colour-colour diagrams. The use of the Spitzer/GLIMPSE 8μm and, more recently, WISE 22μm fluxes together with cross-referencing with X-ray measurements in selected Galactic regions have enabled improved candidate lists that increased our confirmation success rate, achieved via follow-up infrared and optical spectroscopy. To date a total of 102 new WR stars have been found with many more candidates still available for follow-up. This constitutes an addition of ~16% to the current inventory of 642 Galactic WR stars. In this talk we review our methods and provide some new results and a preliminary review of their stellar and interstellar medium environments. We provide a roadmap for the future of this search, including statistical modeling, and what we can add to star formation and high mass star evolution studies.

1 Motivation for finding Wolf-Rayet stars in the Milky Way

At the start of our studies in 2003, we considered the distribution and numbers of Wolf-Rayet (WR) stars in the Milky Way. There were a number of motivating factors for finding more. A limited number of Wolf-Rayet stars were known, 227 in 2001, while around 20 times more than this were predicted to exist in the Galaxy (see van der Hucht (2001). Sample groups of particular WR subtypes made evolutionary studies more difficult. WR to O star and WN versus WC sublass ratios are key for stellar evolution model tests. These values and their variation across the Galaxy were unclear. WR population estimates are major constraints for predicted evolutionary lifetimes (e.g., Maeder et al. 2014; Shenar et al. 2014). While studies of a larger sample of WR star ejecta nebulae could also provide information on evolutionary sequences and linkages to other high mass stars such as Luminous Blue Variables (LBVs).

Since 2001 more than 400 new WR stars have been discovered in the Galaxy. Predominantly due to new techniques in the infrared. A slew of estimates indicate a total number in the Galaxy as being between 1200 and 6000 stars (Shara et al. 2009; Rosslowe & Crowther 2015). More than 100 of these new discoveries come directly or indirectly from our work. We describe our methods and we indicate how our work is expected to continue in the future.

2 Defining WR candidates

2.1 Spitzer/GLIMPSE survey candidates

The best means of finding new stellar populations in the Galaxy is via infrared observations. The GLIMPSE legacy program on board the *Spitzer Space Observatory* allowed 4-colour broadband infrared imaging between 3.6 and 8.0μm covering the whole Galactic plane between galactic latitudes of -1 and +1 degrees. The extracted GLIMPSE point source catalogue and associated 2MASS sources provide the potential for identifying previously obscured and distant stellar populations Benjamin et al. (2003). It also provides an unbiased sample across the galactic plane, not just covering the dense massive star clusters where many WR stars have been found previously.

Strong winds from WR stars are responsible for producing free-free emission which shows as an infrared excess in the spectral energy distribution (SED). Morris et al. (1993) showed the observed wavelength spectral index of WR stars is -2.95 ± 0.25, providing a shallower spectral index than that of a pure photosphere. With a limited range of spectral indices, there is a narrow range of possible infrared colours. Results from fields observed early in the GLIMPSE survey were used to distinguish candidate objects, including the field around Westerlund 2 and RCW49 (see Figure 1). Candidate WR stars were defined by those objects in the colour-colour plot box shown in Figure 1 which contained all previously known WR stars. A similar candidate selection process was done for two less remarkable parts of the Galaxy at longitudes of 312 and 321 degrees.

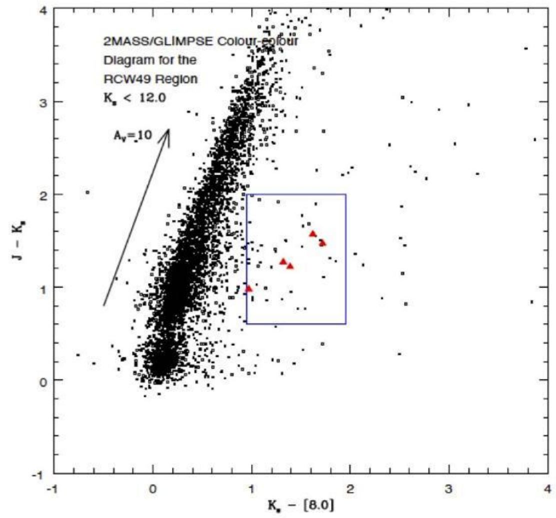

Fig. 1: Original colour-colour plot for objects in the RCW49 region for GLIMPSE identified objects with 2MASS K_s band magnitudes < 12.0, used in our NTT proposal. WR stars from the van der Hucht (2001) catalogue are shown as red triangles, while the blue box provides the boundary conditions used for identifying potential new WR candidates. A similar selection was done for 2x2 degree regions at galactic latitudes of 312 and 320 degrees. The reddening vector is based on Indebetouw et al. (2005).

Two main surprises of the work were: (a) the fact that WR stars were found well away from stellar clusters; (b) approximately 85% of all candidates showed emission lines, most of which appear to be lower mass Be stars.

2.2 Further WR discoveries

A larger followup of the galactic plane around l=312 degrees by Hadfield et al. (2007) provided 15 more WR star discoveries, while Mauerhan et al. (2011) provided a further 60 with somewhat improved candidate selection through GLIMPSE colour selections (see Figure 2).

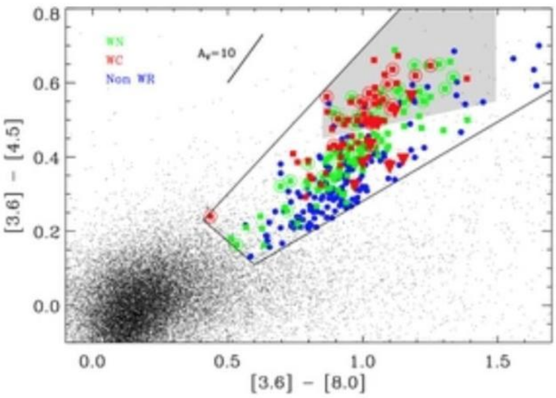

Fig. 2: WN and WC objects are seen in green and red in this colour-colour plot taken from Mauerhan et al. (2011). Candidate objects turning out not to be WR stars are shown blue. The gray shaded area indicates a 50%+ rate of WR detection from the candidate list. Dusty WC stars are shown by inverted red triangles.

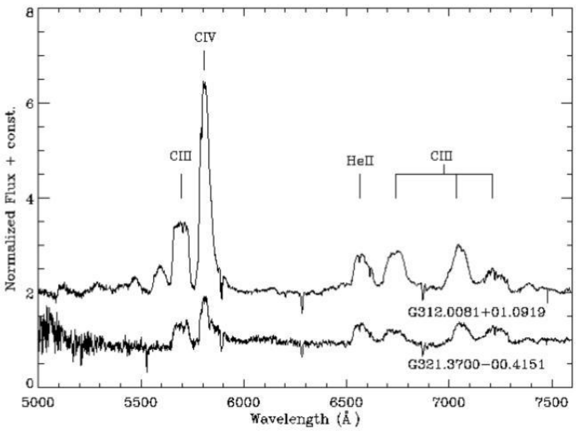

Fig. 3: CTIO/SOAR optical spectra taken by P. Morris and S. Van Dyk as confirmation to the SOFI near-infrared discoveries of WR60-5 and WR67-2.

2.3 Optical and Near-Infrared Spectra of WR candidates

Confirmation of WR candidates was achieved initially by near-infrared H and K band SOFI spectroscopy at the NTT on La Silla, Chile in 2004. Further optical spectroscopy of confirmed candidates was done in follow-up observations on the CTIO/SOAR telescope. Six WR stars have been discovered from this early work (see Marston et al. 2013; Roman-Lopes 2011b; Roman-Lopes 2011a; Roman-Lopes 2012). Optical spectra of two new WC stars found in this early work are shown in Figure 3.

2.4 Future candidate selection

We are currently looking into improving candidate selection criteria based on near- and mid-infrared colours (including MIPSGAL/Spitzer and WISE fluxes). We can start to make knowledge-based estimates of the probability/confidence level of and object's classification based on its colours. In this way we can potentially determine a statistical value of WR numbers in the galaxy – assuming a reasonable probability estimate is able to be done. To this end we have considered nearest-neighbour tests in infrared colour space. Potentially this could improve WR candidate identification considerably, but requires hypothesis testing via follow-up IR spectroscopic observations that we expect to make in the summer of 2015.

3 Followup of new WR stars - origins of isolated WR stars

Of the more than 100 WR stars discovered in follow-up spectroscopy of infrared colour-selected candidates, a large fraction of them are found well away from stellar clusters. In general, we have a bias against objects being found in clusters due to Spitzer confusion, our work therefore complements surveys such as those done in Westerlund 1 (Crowther et al. 2006). A number of new WR stars have been found towards the edges of stellar clusters (e.g. see Roman-Lopes 2011b; and the Danks clusters objects in Mauerhan et al. 2011). This hints at significant numbers of runaway stars from central dense stellar clusters.

Further out in the galaxy, a number of apparently isolated WR stars may well be scattered out from stellar clusters at earlier times (e.g., see Mackey et al. 2013) and indeed 25% of local O stars may be runaways (Blaauw 1993). GAIA results will help with determining proper motions of WR stars in the future.

But some objects appear too far from star forming areas to have been scattered from high density star forming sites within an average WR lifetime and suggest the possibility of *in situ* star formation, possibly associated with looser stellar associations. Although the lack of stellar clusters may simply be due to elusive lower mass clusters lost in infrared galactic confusion – "false negative clusters" Hanson et al. (2010).

4 Conclusions

Broad-band infrared colours have been successful in finding obscured and distant WR stars in our Galaxy. We plan to extend the work to better provide numbers and distributions of WR stars and their subclasses. Such information helps to constrain stellar evolutionary models of high mass stars and the current assumptions they make.

An alternative narrow-band infrared imaging technique, centred on the wavelengths of key spectral line features in WR spectra, has been performed in the Galactic plane and new WR discoveries have been reported in several papers including Shara et al. (2009) and Faherty et al. (2014).

Our studies show that WR stars are not all grouped in dense stellar clusters but many may be runaways or possibly created in relatively isolated regions or loose associations. Many of the objects also have nebulae (including a number of apparent ejecta nebulae) associated with them which provide a better statistical basis for the study of WR subclasses and ejecta plus timing of ejecta events.

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Phil Massey: You've done well in eliminating false positives among your candidates, but what about false negatives? In other words, how sensitive are you to weak-lined WRs?

Anthony Marston: The broad-band selection technique should pick up all, since it depends on the free-free spectral index only (plus reddening) and *not* emission-line strength. So our only problem is recognizing the weak-lined WR stars in our candidate spectroscopy (as per narrow-band technique). Possible issues in spectroscopy are: hot dust emission, companion emission causing spectral feature dilution.

Lidia Oskinova: Integral field spectroscopy with SINFONI@ESO-VLT of an area around WR 102ka did not reveal a hidden low-mass cluster. It seems that some of the massive WRs are indeed quite isolated, just as you pointed out.

Anthony Marston: Thanks for this point, I am very aware of this case. We need to do a lot more work on possible isolated star formation (or massive star formation).

Anthony (Tony) Moffat: Tony (nice name, BTW), this is just a nit-pick, but on one of your opening slides you have O $\rightarrow$ RSG $\rightarrow$ WR for $M_\mathrm{i} = 25 - 40\,M_\odot$. But no one believes (does he?) that this happens; rather one has O $\rightarrow$ LBV $\rightarrow$ WR for such stars (just like the range $M_\mathrm{i} = 40-75\,M_\odot$), with only a few at the low-mass end going through a RSG stage.

Alexandre Roman Lopes: Concerning the "isolated formation" vs. "ejection" process, WR 67a is an interesting case. Do you have considered it in your studies? (Please see the figure with the cavity (NIR) and the "isolation" of the source.)

Anthony Marston: At present we have not properly looked at isolation and cluster ejection. It appears (at first glance) that these are both in the data. But this requires more checks and follow-up than we have done so far. WR 67a will be considered when we do this work.