ESLAB #53: The *Gaia* Universe
Unedited (Zenodo community curated by J.H.J. de Bruijne)

Unlocking Galactic Wolf-Rayet stars with Gaia DR2

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Abstract

Wolf-Rayet (WR) stars represent the final evolutionary stage of the most massive O stars and can reveal much about massive star origins and fates. We can study their formation and frequency of binary interaction, by measuring the fraction in clusters and associations and identifying runaways far from the Galactic plane. Additionally, their absolute magnitudes and luminosities remain poorly constrained in the Milky Way. Accurate distances to individual stars are required to improve our knowledge of WR stars. Past work relied upon absolute magnitude calibrations to find distances, with large associated uncertainties. Parallaxes give more precise results and Gaia DR2 (Gaia Collaboration *et al.*, 2018) expands the number of WR stars with parallaxes from one star to several hundred. Here we have calculated new distances to 382 WR stars using DR2 astrometry. We also calculate absolute magnitudes for stars with distances. 184 are plausible, confirming these stars have reliable distances. Recalculated luminosities are found to be lower than expected, potentially indicating binary interaction or requiring improved single star models. We confirm only a small proportion (13%) of WR stars are definitely members of clusters or associations, implying many WR stars may form in relatively sparse environments. We also search for runaways by applying a vertical cutoff distance of 156pc from the Galactic midplane. 31 stars (8%) exceed this distance and so are likely runaways. The low fraction of binary companions, combined with the low frequency of clusters and association membership, leads us to conclude that supernovae from close binary companions are the dominant source of runaways.

1 Introduction

Massive stars are born with >8M$_\odot$ and therefore have high luminosities (10^3 to 10^6 L$_\odot$) and correspondingly high temperatures (>20,000K). Being located at the upper end of the IMF, they have short lifetimes (<50Myr) and form <1% of all stars at birth. Despite their rarity, massive stars have a significant effect on the galactic environment. They produce α process elements (Oxygen) via core fusion and supernovae, and inject mechanical feedback into the interstellar medium, which can quench star formation. They also produce large numbers of lyman continuum photons, which can ionize H II regions. Finally, massive stars are progenitors for a variety of phenomena, including stripped supernovae, long gamma ray bursts and compact binaries which can produce gravitational waves.

Wolf-Rayet (WR) stars are the helium core burning descendants of the most massive O stars (>25M$_\odot$). They have high mass loss rates ($\sim10^{-4}$ to 10^{-5}M$_\odot$/yr Sander *et al.* (2019), Hamann *et al.* (2019)), which results in a low fraction ($< 40-50\%$) or absence of atmospheric hydrogen. Their high temperatures and eddington ratios lead to broad emission lines exhibiting nuclear core burning products. These create two main WR subtypes; Helium, Nitrogen for the WN type and Carbon for WC stars. Due to their extremely high masses and thus short lifetimes (<5Myr), WR stars are a good tracer of recent star formation and can thus reveal information about massive star origins. Their rapid deaths can also help us to probe massive star fates.

Well constrained distances are required to properly study WR. Parallaxes were previously unavailable for all but the closest WR star (γ Velorum). Previous work therefore relied on the small number of WR stars which were members of Galactic clusters or associations (e.g Lundstrom & Stenholm (1984)), or in the Magellanic Clouds (e.g Smith (1968)). These were used to estimate typical absolute magnitudes for WR subtypes (e.g van der Hucht (2001), Rosslowe & Crowther (2015)), which could then be applied to obtain distances to field stars. However, this method produces large uncertainties on the resulting distances (up to 50% from van der Hucht (2001)). Parallaxes would provide a much better alternative and remove the reliance on these calibrations.

The second Gaia Data release (DR2) (Gaia Collaboration *et al.*, 2018) increases the number of WR with parallaxes from 1 to almost 400 (see Figure 1). Here, we present the distances calculated using these parallaxes and the resulting insights into our Galactic WR population, including absolute magnitudes, luminosities, cluster and association membership and the proportion of WR which are runaway candidates.

2 Distances and Absolute Magnitudes

We calculate distances using the Bayesian inference method recommended by Luri *et al.* (2018). WR stars are mainly found in the Galactic plane and at large (>1kpc) distances. Therefore we construct a prior with a focus on massive stars, combining a radio map of H II regions (Paladini *et al.* (2003) (2004)) and a dust extinction model (Rosslowe & Crowther (2015) and Fritz *et al.* (2011)). The combined prior approximates the distribution of massive stars which are visible in the Gaia G band. As uncertainties from the Gaia catalogue are

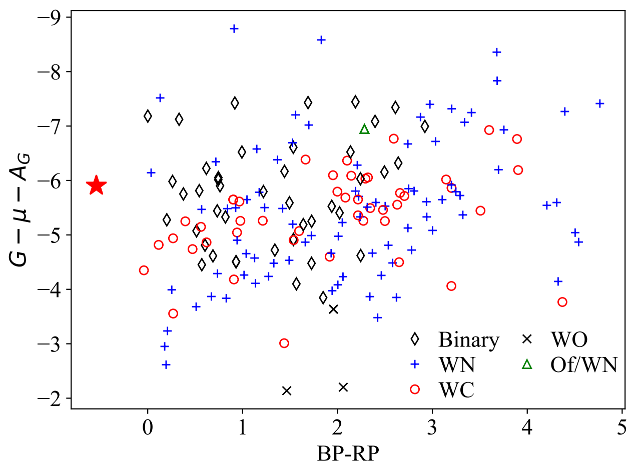

Figure 1: The HR diagram for WR stars with reliable distances, including approximate extinction A_G (from E(BP-RP)$\sim$1/2A_G (Andrae *et al.*, 2018)). Prior to DR2, only the filled star, γ Velorum, had a measured parallax.

likely to be underestimated (Gaia Collaboration *et al.*, 2018), we use relations from Arenou *et al.* (2018) to inflate them. Our sample is spread over the sky, so we apply the QSO zero point correction to our input parallaxes (Arenou *et al.*, 2018). This gives us a gaussian likelihood distribution which peaks at the parallax value. The parallax error is the standard deviation.

We find 382 stars (58% of the known Galactic WR population) with DR2 parallaxes and we obtain posterior distributions for all of them. Figure 3 shows the remainder of WR stars were not observed because they were too heavilly reddened for Gaia. However, a significant fraction of the distances we calculated are potentially unreliable; with negative parallaxes, an error to parallax ratio >1 or astrometric excess noise >1 (contaminated by nearby bright sources, which may affect astrometry).

Absolute magnitudes can help us assess the plausibility of these distances and generate new absolute magnitude calibrations. We use the final distance posterior, existing apparent magnitude measurements (van der Hucht (2001) and Torres-Dodgen & Massey (1988)) and calculate extinctions.

A Monte Carlo selection from these distributions to generate the absolute magnitude distribution and accept the most likely value as the absolute magnitude.

Absolute magnitudes from each WR star are then averaged to obtain typical values for a star of a given subtype. This allows us to see outliers, with innacurate absolute magnitudes. Such outliers are likely to be have incorrect distances. Figure 2 shows narow band v results (Smith, 1968), selected to minimize WR emission lines. We also have calculated corresponding results in the K band.

From this, we find 184 WR have plausible absolute magnitudes, indicating their distances are reliable.

Figure 2 shows the WR have a clear progression in magnitudes, with later subtypes being brighter than early subtypes, as expected. The observed spread of absolute magnitudes is also larger than previous v band measurements for WC stars. These are typically around 0.6mags, compared to $\sim$0.5mags for previous results (van der Hucht (2001), which have fewer samples). As in Sander *et al.* (2019), these results suggest WC star absolute magnitudes are less homogenous than previously thought. This in turn suggests their parameters, such as luminosity, mass and radius, also vary more.

3 WR luminosities

We convert our absolute magnitudes to luminosities, using calibrations from Sander *et al.* (2012), Hamann *et al.* (2006) and Tramper *et al.* (2015) to obtain bolometric corrections for each WR subtype.

Figure 4 shows new values have little relation to the previous results. This reveals that many previous distances to WR stars were inaccurate. A subset of stars posess low luminosities of log(L/L$_\odot$) $\sim$ 5. A possible explanation is that these stars are created by binary interaction. However, very few of these stars are in known binaries and bright OB companions should be visible. Therefore, it is not clear how a single WR star with a low luminosity could be created and, as also discussed by Hamann *et al.* (2019) and Sander *et al.* (2019), this suggests our understanding of WR evolution needs further consideration.

4 Cluster and Association Membership

It is believed that stars are mainly formed in clusters Lada & Lada (2003), and that WR stars would not live long enough to survive dissolution into the field. Therefore, we would expect to preferentially find WR stars in clusters or associations.

To better understand massive star origins, we reassess the membership of 91 WR which were supposedly in clusters and associations. Other known members (mainly OB stars) are used to identify the typical proper motion of the cluster by eye. We can then assess whether the WR stars are close enough in proper motion space to be associated with the cluster or association. Distances are used as a secondary check to remove any foreground or background stars. Due to their smaller uncertainties we give extra weight to the proper motion measurements.

Only 10% of the WR population visible to Gaia could be definitvely confirmed as members of clusters. This fell to just 3% for association members. Our search was hampered by a large degree of scatter in proper motion space and some associations had very few members. This made locating the centre of the cluster or association difficult and meant that many stars could only be considered 'possible members'.

Despite these difficulties, the extremely low membership fraction suggests WR stars may form in more isolated environments than currently expected.

5 Runaway candidates

Massive stars are mainly born in binaries (Mason *et al.*, 2009) and a majority of O stars possibly undergo interaction (Sana *et al.*, 2012). Such interaction can substantially affect stellar evolution (such as via Roche Lobe Overflow, (Kippenhahn & Weigert, 1967)). We can probe

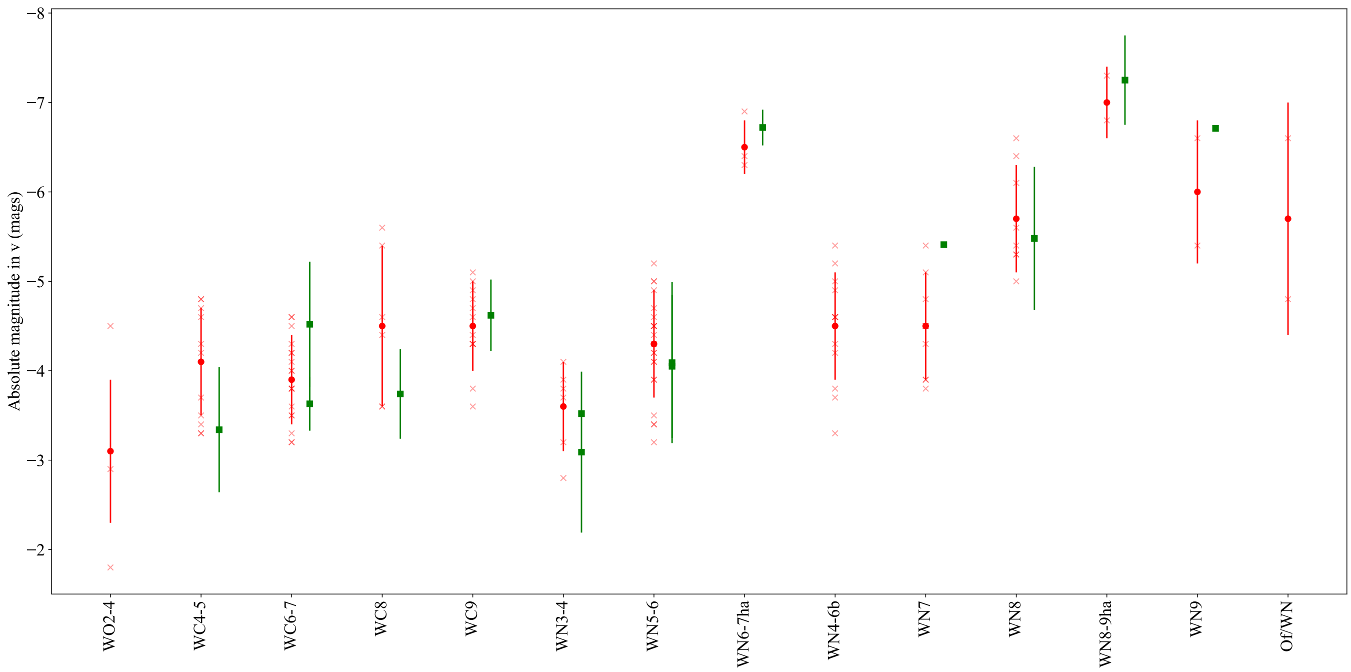

Figure 2: Absolute magnitudes in v band. The red circles are from this work and the green squares are previous values from van der Hucht (2001).

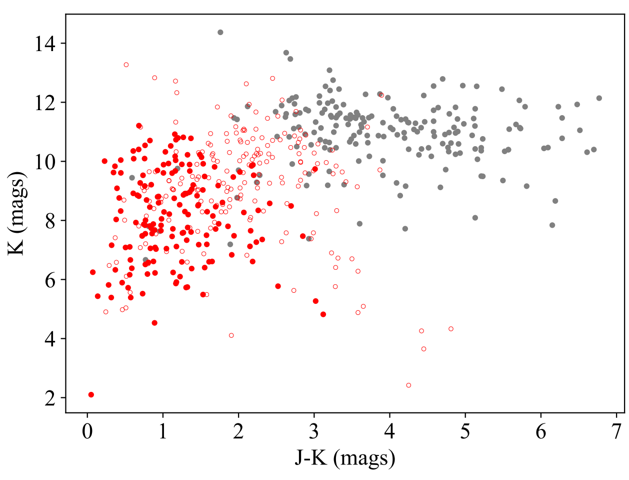

Figure 3: Plot showing WR stars visible in Gaia (red markers) and stars only observable at IR wavelengths (grey markers). The latter have large J-K colours (>4), due to high extinction. Filled red markers indicate stars with reasonable absolute magnitudes.

binary interaction of WR stars using runaways, identified as having a peculiar spatial velocity >30km s^{-1}. Two mechanisms that produce runaways are ejection from a dense cluster or a binary being given a 'kick' if its primary star explodes as a supernova. The former produces either a single WR, if the binary is unbound or a WR and compact companion. The latter again can produce either a single WR, or a WR and OB companion.

Figure 5 shows the majority of stars are found very close to the galactic midplane. Using H II region scale heights (52pc, based on Paladini *et al.* (2004)), we apply a 3σ cutoff of 156pc to indicate runaway status. Assuming the star is born in the midplane and travels vertically upwards, this corresponds to a WR star with typical age of 5Myr travelling at 30km s^{-1}.

We find that only 31 stars, 8% of the Gaia detected WR population, are located above the cutoff. 11 of these are runaways previously recorded by Rosslowe & Crowther (2015), but the rest are new candidates. Only 2 have known OB companions, meaning the rest are likely to be single. We therefore conclude that both mechanisms contribute to runaway production, but the low fraction of WR stars detected in clusters and associations means that supernovae likely dominate.

This is still only a minimum estimate, as it does not account for any runaways which are ejected within the plane.

6 Conclusions

We have calculated distances to 382 Galactic WR using Gaia DR2 parallaxes. These were found using a prior which was based on H II regions and dust extinction. We also check these distances for plausibility by calculating

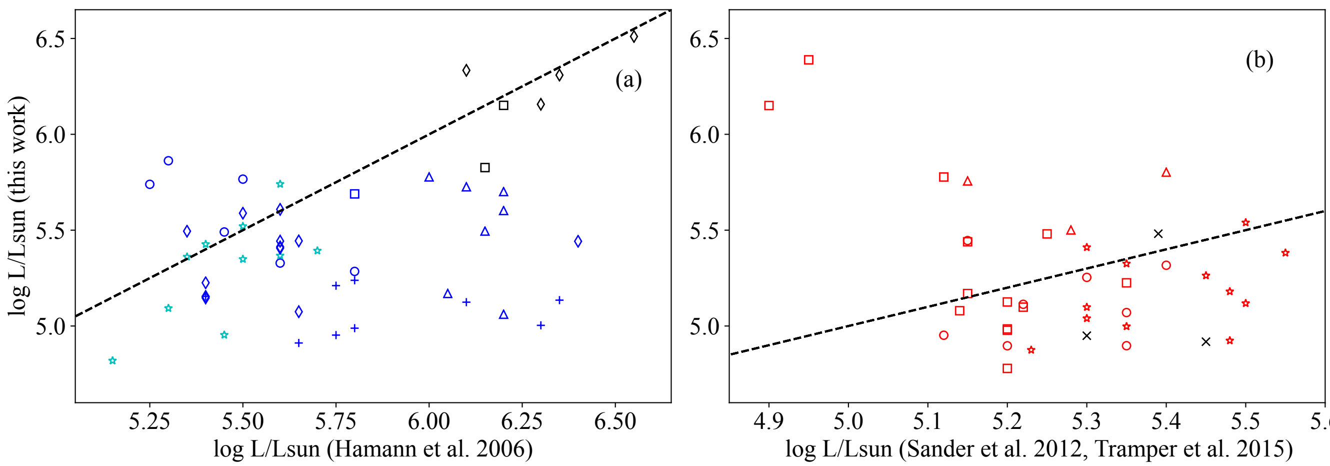

Figure 4: Comparison between previous luminosities and results from this work, for WN in (a) (Hamann *et al.*, 2006), WC in (b) (Sander *et al.*, 2012) and WO (crosses in (b) Tramper *et al.* (2015)).

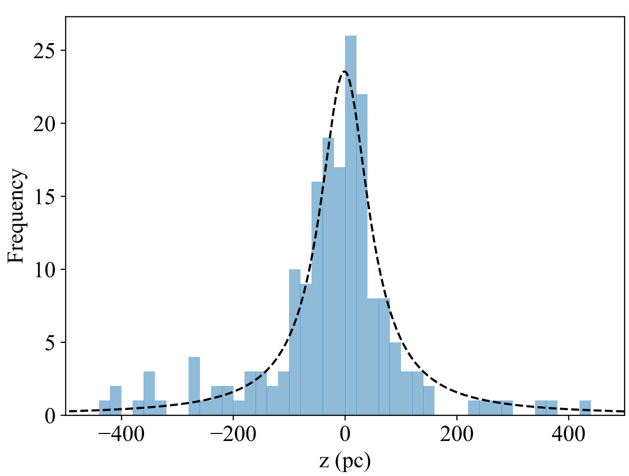

Figure 5: A histogram distribution of WR heights. The dotted line shows the cauchy distribution fit used to obtain the WR scale height.

the absolute magnitudes of each WR, using Monte Carlo selection to obtain a distribution of results with the uncertainties. 184 WR have plausible absolute magnitudes and so reliable distances. The average absolute magnitudes for different WR subtypes can be used to obtain future distances and follow the expected pattern of being higher for later type WR than early types. In common with Sander *et al.* (2019), we find WC stars cover a larger absolute magnitude range than expected. Other parameters that on this, such as luminosity are also more varied.

We have also converted our absolute magnitudes to luminosities, finding that many stars have low luminosities of $\log(L/L_{\odot}) \sim 5$. These unusually low luminosities may result from binary interaction, or an incomplete understanding of single star evolution.

We find that due to the low fraction (13%) confirmed as members of clusters and associations, WR stars may be born in more isolated environments than anticipated. The production mechanisms of runaways, supernovae or cluter interactions, are exlored. 31 stars are found above the 156pc cutoff, based on H II region scale heights. Only 2 have OB compaions, meaning both mechanisms contrivute to runaway production. However, few WR stars are in clusters, which suggsts that supernovae are the dominant producers of runaways.

Gaia DR3 is predicted to improve the accuracy of parallaxes by 1.2 (Brown, 2019). As distance uncertainties for remote WR stars are still substantial (kpc scale), even a small percentage improvement will lead to a greater accuracy of distances and absolute magnitudes. Later data releases will also improve the quality of the data, reducing the level of astrometric excess noise. This will correspondingly increase the number of reliable distances. Future work may also better constrain the variation of the parallax zero point with colour, magnitude and position noted by Lindegren *et al.* (2018). This will allow us to apply different zero points to individual stars, further improving distance accuracy.

Acknowledgments

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This publication also makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. The code used in this research made use of Astropy,[1] a community-developed core Python package for Astronomy (Astropy Collaboration *et al.*, 2013, 2018).

Some work is based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 177.D-3023, as part of the VST Photometric Hα Survey of the Southern Galactic Plane and Bulge (VPHAS+, www.vphas.eu). Additionally, this paper makes use of data obtained as part of the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS, www.iphas.org) carried out at the Isaac Newton Telescope (INT). The INT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. All IPHAS data are processed by the Cambridge Astronomical Survey Unit, at the Institute of Astronomy in Cambridge. The band-merged DR2 catalogue was assembled at the Centre for Astrophysics Research, University of Hertfordshire, supported by STFC grant ST/J001333/1.

Finally, Gemma Rate wishes to thank the Science and Technology Facilities Council (STFC), for their financial support through the Doctoral Training Partnership.

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[1] http://www.astropy.org