Wolf-Rayet Stars
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The importance of getting single-star and binary physics correct.

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We discuss the uncertainties that need to be considered when creating numerical models of WR stars. We pay close attention to inflation and duplicity of the stellar models, highlighting several observational tests that show these are key to understanding WR stellar populations.

1 Introduction

There are several groups making stellar evolution models today, with a number of them also represented within these proceedings (e.g. Geneva, Bonn and Brussels). In general the predictions of various groups are consistent. However, there are important differences of approach regarding uncertainties that still affect the results of stellar models.

In this review we outline the major uncertainties that have important effects on the evolution of Wolf-Rayet stars. Then we will discuss how these could be reduced by comparisons between observations and theoretical predictions for single stars and interacting binaries. We highlight the importance of binary interactions that are not normally full appreciated.

Throughout this review we have used our own stellar models to create the relevant figures. These are calculated with the Cambridge STARS code, the version employed here is described in Eldridge et al. (2008). These models of single stars and interacting binaries were used to create our Binary Population and Spectral Synthesis code, BPASS. In the examples below we outline the observational tests that BPASS has confronted. These models are available at `http://bpass.auckland.ac.nz`. Those described below are mostly based on the Version 1.1 results. However, we have now released the highly improved Version 2.0 of BPASS. The improvements include a new faster synthesis code that has been thoroughly debugged, a larger number stellar evolution models and, importantly, new stellar atmosphere spectra. Key to the latter has been the release of a large number of new atmosphere models by the Potsdam Wolf-Rayet group, PoWR. These include calculations at lower metallicities where before we had extrapolated. This has greatly improved the accuracy of the low metallicity predictions of BPASS. The new version will be fully described and compared to many observational tests in the forthcoming instrument paper, Eldridge et al. (in prep.).

2 Stellar uncertainties

There are five key uncertainties of stellar evolution relevant for Wolf-Rayet stars. The evidence that standard single-star evolution models are not sufficient to reproduce the observed Wolf-Rayet population is demonstrated by Figure 1. The primary issue is that WC stars are less luminous and cooler than predicted by single-star evolution models, while WN stars are cooler than stellar evolution predictions. These results were first shown in Hamann et al. (2006) and Sander et al. (2012). Georgy et al. (2012) showed that even the latest stellar evolution models including rotation were unable to remove these issues. Reproducing these observed locations of WR stars in the HR diagram is the key point we use in discussing how the uncertainties can drive a match or mismatch between observation and theory.

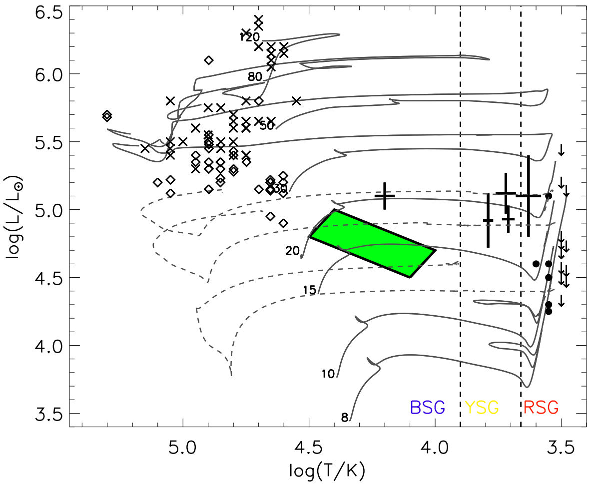

Fig. 1: HR diagram comparing stellar evolution tracks to observed WR stars. The solid lines are for single stars and dashed lines for interacting binary stars. The numbers give the initial masses in $M_{\odot}$. The circles, arrows and points with error bars represent the locations of observed type II, hydrogen rich, supernova progenitors, data taken from Smartt et al. (2009) and Eldridge et al. (2013). The location of the type Ib supernova progenitor for iPTF13bvn is indicated by the green box (Eldridge et al. 2015). The crosses are the locations of Galactic WN stars from Hamann et al. (2006) while the diamonds are the locations of Galactic WC stars from Sander et al. (2012).

2.1 Composition and opacity

In the last century it was thought that the standard Solar mass fraction of metals was about 2% (Grevesse & Sauval 1998). However, in reanalysis of the Solar atmosphere with updated 3D models, a new lower value of the metal content was found. Initially it dropped as low as 1.2% before increasing to somewhere around 1.4% (Asplund et al. 2009; Caffau et al. 2011). The main reason for this large drop was a decrease in the amount of oxygen inferred in the Sun's atmosphere. However, the new composition from looking at the surface did not agree with the composition inferred from the interior by helioseismology, e.g. Basu & Antia (2008), which was more inline with the original old Solar composition. This mismatch has yet to be resolved. Despite this, in the last few years, many groups have switched to the new Solar composition, creating stellar models with the lower oxygen abundance so that the metallicity, $Z = 0.014$.

The question, however, may not be, "what is the correct Solar abundance?", but "should we be using the Sun as our abundance standard at all?". The Sun is around 4.5 billion years old and is unlikely to have been formed in its current location in the Galaxy. The massive stars we observe in the Galaxy formed much more recently and thus we should use those stars as our abundance standard instead. This was suggested by the work of Nieva & Przybilla (2012) who have provided an alternative Galactic abundance standard that lies between the old and new Solar compositions.

The abundance that modellers should be using is still uncertain, and in essence it comes down to how much oxygen we use in our stellar models of the Galaxy. The amount of iron in the different compositions is almost identical and it is this that is key to determine the mass-loss rates in the stars from stellar winds. The key point is that we should not be too keen to use the new Solar composition for modelling anything other than the Sun.

2.2 Mass-loss rates

The main way to form a WR star in the Galaxy and in most other environments is via mass loss. Nuclear fusion creates a helium core at the centre of a star during the main-sequence. The surface hydrogen then needs to be removed to expose this helium core for it to become a WR star. The mass-loss probably happens during the red supergiant (RSG) or luminous-blue variable (LBV) stages of evolution. The mass-loss rates, however, are quite uncertain and there is still the possibility that they could be in error (Smith 2014). An open question is also how should mass-loss rates be scaled with metallicity. We know that mass-loss rates decrease with metallicity but exactly how quickly they vary has yet to be accurately determined.

The only way to remove this uncertainty is to test mass-loss rates by studying the period change in eclipsing binaries as in Shenar et al. (2015). Relevant samples are only now becoming available and these will be the most stringent tests in the future. However, there are few post-main sequence eclipsing binaries so these are difficult to constrain. Work by Georgy (2012) and Georgy et al. (in prep.) determine some of the impacts of varying RSG mass-loss rates within the range of observed values. The problem with this is that it is difficult to disentangle variation in the RSG mass-loss rates with varying the binary evolutionary pathways.

We note, however, once the WR star is formed the mass-loss rates appear to still be approximately consistent with Nugis & Lamers (2000) as shown in the work of the Potsdam WR group, e.g. Hamann et al. (2006) and Sander et al. (2012).

2.3 Convection and inflation

Energy transport by convection is normally parametrised in stellar models by mixing-length. We calibrate the mixing length to the Sun and then recklessly apply it to all other stars in the Universe. However for WR stars simple tests show that adjusting the mixing-length parameters has only a small effect on the surface temperatures and radii. The convective envelopes of WR stars are atypical, being extended and almost constant density, with a small density inversion near the surface. In addition most of the energy transport is by radiation despite stellar models indicating these envelopes are convective. This is why varying the mixing-length parameter has little effect on a model's radius.

Clearly there is something else wrong with our models of convection if we are to move our stellar models closer to the temperatures inferred from the Potsdam WR group's observations. As discussed by others, the convective zones may have typical convective velocities that exceed the sound speed of the stellar interior. Therefore they may be highly turbulent and clumped. Gräfener et al. (2012) suggest that clumping of the convective flows in outer parts of the star could be what seeds the clumping in stellar winds. In stellar models they increase the opacity of the material due to this clumping but shift the average opacity to a higher density. This increase in opacity, inflates the envelope further leading to cooler temperatures, as shown by models in Figure 2 that have had this effect included.

We can conclude from this that we need to include this inflation effect, which is present in most stellar models, but also increase it beyond what is already found from the evolution models. This is work in progress.

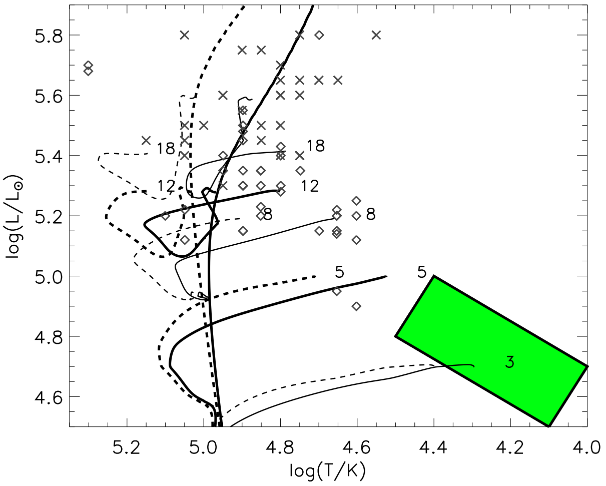

Fig. 2: Similar to Figure 1 but now showing models based on helium star only models (see McClelland this proceedings). The numbers give the initial helium star masses in $M_\odot$ Crosses represent the locations of Galactic WN stars and diamonds the Galactic WC stars. The dashed lines are standard models, the solid lines are stellar models including the clumping factor for stellar opacity in the inflated envelope given by Gräfener et al. (2012).

2.4 Rotation and magnetic fields

Rotation and magnetic fields are both important in stellar evolution, although how important is an open question. It is summarised in these proceedings by Meynet and Georgy. Rotation has two effects. First it will extend the main-sequence lifetimes. Second it will increase mass loss and therefore produce WR stars from lower initial mass stars. However, as shown, in Georgy et al. (2012) such single star models cannot reproduce the bulk of the WC stars.

As suggested by de Mink et al. (2013) the most rapidly rotating stars are produced during binary interactions. The accreting companion in a binary can accrete mass and angular momentum and be left rapidly rotating. However, rapid rotators are relatively rare with the majority of stars rotating too slowly to lead to significantly observable effects. However, including rotation accurately is still important.

2.5 Duplicity

Why duplicity and not binarity? Binarity typically indicates something that can be switched on/off. This does not apply to binary evolution as it encompasses a range of behaviour of different strengths. In the dictionary definition, duplicity is the state of being double. Fortunately the more modern use of implying deceitfulness is also apt as binaries are confusing and make our task of understanding their evolution more difficult.

As described by Vanbeveren in these proceedings, the history of massive stars is an interesting story of research pathways taken by the field. For various reasons the community first considered binary evolution important, then moved away to considering only single stars and rotation and now are returning to taking account of interacting binaries.

An important point to make is that there are several groups worldwide creating binary evolution models and performing population synthesis including interacting binaries; Brussels, Yunnan, Amsterdam, Auckland and many more. All these groups demonstrate that interacting binaries have an important effect on stellar populations that must be taken into account. Their results are broadly consistent. This is an important point as it is normally assumed that with the large number of free-parameters that binary evolution is somehow untrustworthy. However, similar results obtained with different methods lend some confidence to the results of binary evolution codes.

In Figure 1 the tracks where the stars have experienced a binary interaction and lost their hydrogen envelope are able to reproduce the luminosities of the observed Galactic WC stars. While the temperatures are still slightly too hot we have not yet included the inflation effect of effect Gräfener et al. (2012) into these models.

Achieving the correct luminosity is a positive step. Assuming these stars are in binaries is a preferable assumption to having to arbitrarily boost the mass-loss rates of these lower-luminosity RSGs to produce the WR stars. In fact many RSGs with boosted mass-loss rates are likely to be binary systems where the RSG has an unobservable low-mass companion.

The best evidence that we must take account of binaries comes from the work of Sana et al. (2012, 2014) who directly measured the binary fraction of stars and their periods and mass ratios. They find that 70% of O stars are in an orbit where they will have the evolution altered by a binary interaction.

3 Resolved WR populations

Duplicity and inflation then are the key uncertainties to consider in attempting to reproduce the observed WR population in our Galaxy. While we are still currently working on inflation, we now discuss observational tests for synthetic binary populations highlighting their importance. We divide these into those considering resolved stellar populations and those with unresolved populations in more distant galaxies.

The next step beyond matching the location of WR stars on the HR diagram is to model the relative numbers of different WR subtypes and the relative numbers of massive stars in other phases of evolution such as the main-sequence and red supergiants. For a complete test these must be reproduced in galaxies with various metallicities such as the Magellanic clouds. The problem with such tests is they have been plagued by observational selection effects as discussed by Massey in these proceedings. However, as also discussed by Massey and Neugent, at least for some samples, progress has been made and models face more stringent tests.

The three main population number ratios to test are the ratios of the number of WR to O stars, RSG to WR stars and the WC to WN. In calculating these for a theoretical population a constant star-formation rate and fully sampled initial-mass function are assumed. Populations including single star evolution models only are not able to reproduce the observed ratios, however, binary models are able to, e.g. Eldridge et al. (2008). While the RSG/WR ratio is difficult to reproduce, new observed ratios from Massey in these proceedings indicate the disagreement is not as bad as suggested previously. Both Vanbeveren et al. (2007) and Eldridge et al. (2008) predicted similar WC/WN ratios from binary populations that were lower than the available observed samples at the time the work was done. The newer, lower, ratios as the various metallicities given in these proceedings by Massey are in agreement with these predictions.

We stress, however, that further refined comparisons must be performed, for example the relative rates of early to late WR stars. This will be dependent on the importance of inflation. One detail that is insensitive to inflation will be the luminosity distribution of the WR stars in the HR diagram.

Another test that involves resolved populations is the SN progenitors observed in pre-explosion images (Smartt et al. 2009; Eldridge et al. 2013; Smartt 2015). WR stars were long expected to be the progenitors of type Ib/c SNe (these are supernovae with no hydrogen observed). However, as discussed by Yoon et al. (2012) and Yoon (2015), the brightest and most visible type Ib/c progenitors are in fact helium giant stars that are not WR stars at all. However, such helium giants have still not been observed in our Galaxy so their exact numbers are only theoretically predicted. The one progenitor observed for a type Ib SN is most likely to have been a helium giant, see Bersten et al. (2014); Eldridge et al. (2015) and references therein.

WR stars are likely to still produce some type Ib/c SNe but their observability as SN progenitors is uncertain and model dependent. Inflation will actually make it easier to observe progenitors (if it occurs). Interestingly to explain the relative ratios of type Ib/c to type II SNe some WR stars must explode and give rise to type Ib/c SNe as well as long-Gamma-ray bursts. Also their contribution to the rate may be reduced if most of them form black holes at core-collapse and not give rise to a luminous explosion (Smartt 2015).

4 Unresolved WR population

For more distant galaxies individual WR stars cannot be resolved but their contribution to the integrated light can be estimated. The most easily identifiable features are the Blue and Red WR bumps. A large sample of SDSS galaxies were studied by Brinchmann et al. (2008). In their study they used optical fluxes to infer the ratio of WR to O stars and compared these to theoretical predictions from various models, finding binary models and those including rotation performed best.

In Eldridge & Stanway (2009) we took the alternative approach and attempted to model the observed WR bump fluxes directly using stellar population models linked to atmosphere models. Using the resultant BPASS models we found that a population including interacting binaries could reproduce the observed range of equivalent widths for the WR features of SDSS galaxies versus metallicity. In effect this is equivalent to matching both the observed WR/O and WC/WN ratios in nearby galaxies. Similar studies have been performed by others using the same population models, e.g. Miralles-Caballero et al. (2014).

In Eldridge & Stanway (2012) we took this one step further and attempted to reproduce the ultraviolet O star and WR lines in the observed spectra of galaxies at redshifts greater than 2. Interestingly here we found the binary interactions were not sufficient to produce the WR lines but we also needed to account for the spin-up of the companion stars during the mass-transfer events to reproduce the observed He II 1640Å line.

The population model predictions used in the above studies are summarised in Figure 3. It can be seen that binary populations do not just produce more WR stars and therefore more ionising flux, they do so at a later age than a single star population. As the observed WC stars are from stars of a lower initial mass, these can only appear at a later phase of evolution.

This difference in behaviour means more ionising flux, and significantly harder ionising flux at later ages. This fact was used by Stanway et al. (2014) to explain the surprisingly strong ionisation state of high redshift Lyman-break galaxies as well as their nearby analogues. While single star models could almost reproduce them they are limited to ages less than 10Myrs, binary models can match the observed galaxies over a broader age range of up to 100Myrs. In addition Kehrig, Sokal and Walsh discuss how there are clusters and galaxies observed with strong ionising lines but no WR features. The predictions of binary evolution models may be able to explain these features too.

The evidence that binary stars are important and key to many observational signatures cannot be ignored. As shown in Figure 3 the binary models can

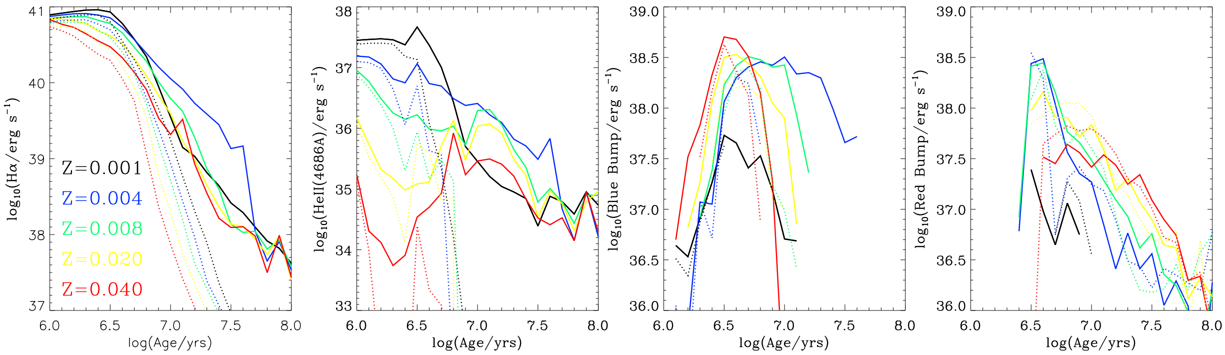

Fig. 3: Predictions for emitted fluxes from stellar populations of single stars (dotted lines) and interacting binaries (solid lines). Left to right the panels are Hα flux, He II flux at 4686Å, the blue WR bump and the red WR bump. The models are for an instantaneous starburst of 10^6 $M_\odot$ at five different metallicities.

produce strong He II ionising fluxes with and without WR emission.

5 Summary

In summary, the modelling of stellar evolution is still subject to many uncertainties. Key amongst these are the role and impact of interacting binary evolution, inflation of WR envelopes and rapid rotation. However, we are now reaching an epoch in which models and observations are tending towards agreement. Refining the uncertainties on both models and the observational data will be essential to future progress.

References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481

Basu, S. & Antia, H. M. 2008, Phys. Rep., 457, 217

Bersten, M. C., Benvenuto, O. G., Folatelli, G., et al. 2014, AJ, 148, 68

Brinchmann, J., Kunth, D., & Durret, F. 2008, A&A, 485, 657

Caffau, E., Ludwig, H.-G., Steffen, M., Freytag, B., & Bonifacio, P. 2011, Sol. Phys., 268, 255

de Mink, S. E., Langer, N., Izzard, R. G., Sana, H., & de Koter, A. 2013, ApJ, 764, 166

Eldridge, J. J., Fraser, M., Maund, J. R., & Smartt, S. J. 2015, MNRAS, 446, 2689

Eldridge, J. J., Fraser, M., Smartt, S. J., Maund, J. R., & Crockett, R. M. 2013, MNRAS, 436, 774

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

Eldridge, J. J. & Stanway, E. R. 2009, MNRAS, 400, 1019

Eldridge, J. J. & Stanway, E. R. 2012, MNRAS, 419, 479

Georgy, C. 2012, A&A, 538, L8

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

Gräfener, G., Owocki, S. P., & Vink, J. S. 2012, A&A, 538, A40

Grevesse, N. & Sauval, A. J. 1998, Space Sci. Rev., 85, 161

Hamann, W.-R., Gräfener, G., & Liermann, A. 2006, A&A, 457, 1015

Miralles-Caballero, D., Rosales-Ortega, F. F., Díaz, A. I., et al. 2014, MNRAS, 445, 3803

Nieva, M.-F. & Przybilla, N. 2012, A&A, 539, A143

Nugis, T. & Lamers, H. J. G. L. M. 2000, A&A, 360, 227

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

Sana, H., Le Bouquin, J.-B., Lacour, S., et al. 2014, ApJS, 215, 15

Sander, A., Hamann, W.-R., & Todt, H. 2012, A&A, 540, A144

Shenar, T., Oskinova, L., Hamann, W.-R., et al. 2015, ArXiv e-prints

Smartt, S. J. 2015, PASA, 32, 16

Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, MNRAS, 395, 1409

Smith, N. 2014, ARA&A, 52, 487

Stanway, E. R., Eldridge, J. J., Greis, S. M. L., et al. 2014, MNRAS, 444, 3466

Vanbeveren, D., Van Bever, J., & Belkus, H. 2007, ApJ, 662, L107

Yoon, S.-C. 2015, PASA, 32, 15

Yoon, S.-C., Gräfener, G., Vink, J. S., Kozyreva, A., & Izzard, R. G. 2012, A&A, 544, L11

Norbert Langer: Can rotation affect the mass transfer efficiency in binaries and what do you assume for that in your models?

J. J. Eldridge: Yes, this is the most uncertain thing in the models. We assume that the accreting star can only accrete at a rate determined by the thermal timescale. The star puffs up if it accretes material too fast. We also assume that a star is spun up to rapid rotation if it accretes 10% of its initial mass.

Paul Crowther: Many more parameters are required for massive binary models, (period distributions, mass ratio, etc. . . .) than single ones, which have been revised recently by Sana et al. (2012, 2013). Are your models consistent with these?

J. J. Eldridge: Yes they are consistent with them, although I chose flat mass ratio and log(separation) distributions, but these are similar. The key point is I do not vary any parameters. My models take time so I only have one set that I compare to observations. Which is nice as it appears I don't have to fudge anything to get a better agreement with binaries.