Massive Stars Near and Far
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Constraining physical processes in pre-supernovae massive star evolution

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Abstract. While we have growing numbers of massive star observations, it remains unclear how efficient the key physical processes such as mass loss, convection and rotation are, or indeed how they impact each other. We reconcile this with detailed stellar evolution models, yet these models have their own drawbacks with necessary assumptions for 3-dimensional processes like rotation which need to be adapted into 1-dimensional models. The implementation of empirical mass-loss prescriptions in stellar evolution codes can lead to the extrapolation of base rates to unconstrained evolutionary stages leading to a range of uncertain fates. In short, there remain many free parameters and physical processes which need to be calibrated in order to align our theory better with upcoming observations. We have tested various processes such as mass loss and internal mixing, including rotational mixing and convective overshooting, against multiple observational constraints such as using eclipsing binaries, the Humphreys-Davidson limit, and the final masses of Wolf-Rayet stars, across a range of metallicities. In fact, we developed a method of disentangling the effects of mixing and mass loss in the 'Mass-Luminosity Plane' allowing direct calibration of these processes. In all cases, it is important to note that a combined appreciation for both stellar winds and internal mixing are important to reproduce observations.

Keywords. stars: evolution, early-type, interiors, mass loss, winds, outflows, Wolf-Rayet

1. Introduction

In the first instance, we expect that the effects of internal mixing dominate the evolution of the lower mass range of massive stars (∼10-30 $M_\odot$) and mass loss dominates the upper mass range (∼30-60 $M_\odot$), however, the picture is much more complex than this. For instance, the effects of stellar winds on the surface properties of massive stars directly impacts the subsurface convective layers, including semiconvective regions which induce mixing in the envelope. Moreover, for the most massive stars it may be the case that internal mixing – in particular very low internal mixing – allows for smaller convective cores which collapse to form heavy black holes on the order of 80-90 $M_\odot$. It is therefore important to note that while in certain regimes we can focus on the effects of mixing *or* mass loss, in reality it will be important to have a real appreciation for how both interact with and counteract each other. This may be key in understanding the nature of how

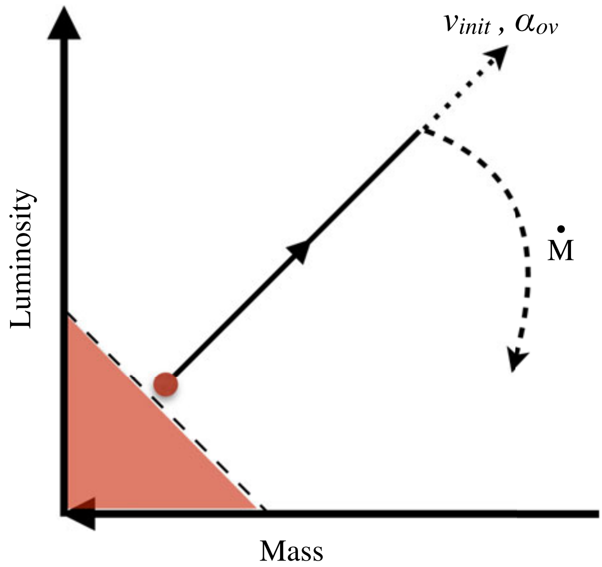

Figure 1. Illustration of the 'Mass-Luminosity' plane with an evolutionary track starting at the ZAMS with the red dot, evolving along the black vector. The dotted line extending the vector suggests how much additional mixing via increased rotation and/or convective overshooting should be applied to extend the $M - L$ vector. The curved dashed line represents the gradient of the vector, dominated by the mass-loss rates. The red solid region represents the boundary set by the mass-luminosity relationship, and as such is forbidden.

and where certain massive star evolutionary channels split towards becoming black holes (BHs), neutron stars (NS), Wolf-Rayets (WRs) and Red supergiants (RSGs).

2. Main Sequence Evolution

We have developed a new method of calibrating various physical processes in Higgins & Vink (2019), called the Mass-Luminosity Plane. From our analysis of a detached eclipsing binary in the Galaxy (HD166734, see Mahy *et al.* 2017) we determined that individual processes such as rotational mixing or core overshooting could not be calibrated in a standard Hertzsprung-Russell diagram (HRD). In this study we used the M-L plane to reproduce the observed stellar parameters, however with continued use and development we have found that it may be an extremely powerful tool in disentangling physical processes.

Just like in a HRD, models evolve to cooler effective temperatures along the vector towards the right-hand side, but we find that the length of the vector can be extended by extra mixing (see Fig.1). In the first instance rotation is the dominant factor, with core overshooting as a secondary extension after rotation has been constrained by, for example, the surface Nitrogen abundances ([N/H]). The key feature is that we can separate these internal mixing effects from the effects of mass loss, whereby the gradient of the vector track shows the effects of winds, with stronger mass-loss rates leading to a shallow gradient and weak winds leading to a steep gradient. This effect will also be seen in different metallicities (Z) since the gradients will be steeper in low Z environments due to Z-dependent winds.

With the M-L plane we found that the eclipsing binary required additional internal mixing by core overshooting of up to α_{ov}= 0.5 for the 30-40 $M_{\odot}$ components. While simultaneously we were able to hone in on the extent of mass loss to a factor of unity

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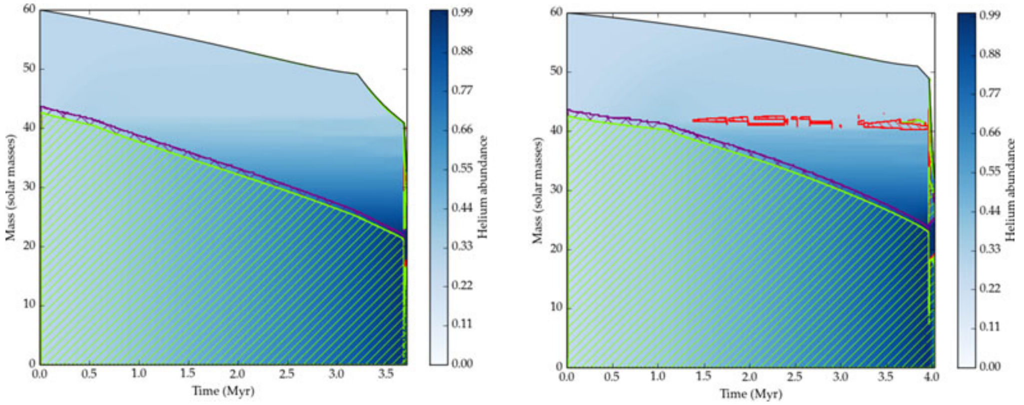

Figure 2. Kippenhahn diagrams illustrating the structure of 60 $M_{\odot}$ models with $\alpha_{\rm ov}$= 0.1, $\alpha_{\rm semi}$= 100 and $\Omega/\Omega_{\rm crit}$ = 0.4. The colourbar represents Helium abundance, while the green hatched region denotes convection. The model which evolves at Galactic metallicity (which experiences increased mass loss due to Z-dependent winds) is shown on the left. The model which has evolved at $Z_{\rm LMC}$ is shown on the right, where red semiconvective regions are seen as a consequence of lower mass-loss rates and subsequently a larger envelope mass.

of the standard Vink *et al.* (2001) rates, excluding for this range of models any large amplifications or reductions (within a factor of two) in the mass-loss rates. We also find in Higgins & Vink (2019) that by calculating a large grid of models with varied core overshooting that due to the relative compactness of our pre-supernovae models, that BHs were more likely to form with lower overshooting, which has remained important for our follow up studies, including Vink *et al.* (2021).

3. Post-Main Sequence Evolution

Considering the idea of 'turning points' in evolutionary channels, we probed the post-Main Sequence (post-MS) evolution towards red and blue supergiants (RSGs and BSGs), considering what we had learnt from the Galactic eclipsing binary and the M-L plane. The upper RSG luminosity or Humphreys-Davidson (HD) limit points towards a tipping point at which stars stop evolving to RSGs and start evolving to hotter temperatures as WRs. This change in evolutionary channels is important for comparing populations of BSGs and RSGs or various SNe progenitors with population synthesis models. But this turning point is also considered to be highly sensitive to mass loss. In Higgins & Vink (2020), we found that while mass loss did play a key role, it was actually in its indirect effect on the envelope structure which prohibited semiconvective regions forming, which would promote blueward evolution above the RSG limit. In this study, it was important that we maintained a low convective core mass to allow for additional, or in this case, semiconvective mixing to take place, and the standard Z-dependent mass loss naturally reproduced the observed HD limit at each Z. However, recent work by Sabhahit *et al.* (2021) suggests that if the HD-limit is in fact Z-independent, then the effects of envelope mixing and Z-dependent winds may balance to produce an upper RSG luminosity of log L/ $L_{\odot}$ = 5.5 regardless of host galaxy Z.

Figure 2 showcases the effect of stellar winds on internal mixing processes. Due to increased winds at $Z_{\odot}$ compared to lower Z environments, such as the LMC (50% $Z_{\odot}$), the envelope mass is reduced such that semiconvective regions do not develop. We find that increasing the convective core by overshooting has a similar effect on envelope mixing. This shows that while the M-L plane can disentangle each process to better calibrate our prescriptions to reproduce observations, the indirect effects of stellar winds

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on the interior structure and efficiency of mixing processes also plays a key role in our understanding of massive stars.

Since it was the higher mass models which set the HD limit, and with prior knowledge of having a low core overshooting parameter to produce more BHs from our study of HD166734, we could actually use these results in reproducing heavy BHs. When the announcement of an 85 and 65 $M_{\odot}$ BH merger was detected by LIGO, we aimed to reproduce the heaviest BH from first generation black holes which have not had previous merger events. In fact, with this prior work on massive star evolution, and in particular a combined appreciation for how mixing can impact mass loss and vice versa, we were able to form an 85 $M_{\odot}$ BH with a moderate Z (10% solar) and an initial mass of $\sim$100 $M_{\odot}$ (see Vink *et al.* 2021).

4. Wolf-Rayet stars as black hole progenitors

Now we look at the point at which stars stop evolving to cooler effective temperatures as RSGs, above which the upper mass range is dominated by WR stripped Helium stars. Since these stars dominate the upper mass range, they also will dominate the BH mass spectrum across different metallicities. As a result, it is important to know how much mass they lose over their He-burning lifetime, since the remaining stages are exceedingly short. WR stars have very strong, Z-dependent winds which dominate the final masses of the most massive stars. It is important therefore to correctly measure the extent of these winds if we are to probe the full mass spectrum of stellar BHs.

More recently, in Higgins *et al.* (2021) we have developed a study of Helium star evolution for three commonly-used wind prescriptions, including the recent hydrodynamically-consistent rates by Sander & Vink (2020), at 5 metallicities from Solar down to 2% solar, and Helium ZAMS masses of 20 to 200 $M_{\odot}$. Our models show a qualitative difference in mass-loss behaviour of the various prescriptions in terms of "convergence" on the upper BH mass. Using the prescription from Nugis & Lamers (2000) the maximum stellar black hole below the pair instability gap is found to converge to a value of 20-30 $M_{\odot}$, independent of metallicity. We also provide a comparison of the Helium star mass-loss rates utilised in population synthesis codes such as COMPAS, see Belczynski *et al.* (2010). This mass-loss prescription is based on the Hamann *et al.* (1995) rates (denoted here as H95+), which are then reduced by a factor of ten to account for wind clumping and implemented with a Z-scaling from Vink & de Koter (2005), see also Yoon *et al.* (2006).

We find that when implementing the new prescription from Sander & Vink (2020) there is no convergence to a maximum black hole mass value across all Z, but the final mass is larger for larger initial He star mass, in which case the upper black hole limit is set by prior main sequence evolution and mass loss or by the pair instability. Interestingly, the upper black hole mass limit for each Z also corresponds here to the Z-limit of pair instability supernovae, with our results reaching the pair instability gap at a higher metallicity limit (50% $Z_{\odot}$) than previously predicted. Finally, we show in Fig. 3 that above the second black hole mass gap, the Nugis & Lamers (2000) prescription would not predict any black holes, whereas the most massive He stars with Sander & Vink (2020) winds included, demonstrate a channel for very massive stars to form black holes above the $\sim$130 $M_{\odot}$ Pair instability supernova limit at $\sim$2% $Z_{\odot}$ or below.

These studies have shown that in order to predict evolutionary channels for the relevant mass ranges with realistic final masses and fates, we must have a combined understanding of metallicity-dependent mass loss – both on the main sequence and for WRs – and internal mixing efficiencies. In summary, our implementation and understanding of these key processes will be aided with further studies of eclipsing binaries, alongside the advancement of asteroseismology and updated wind prescriptions.

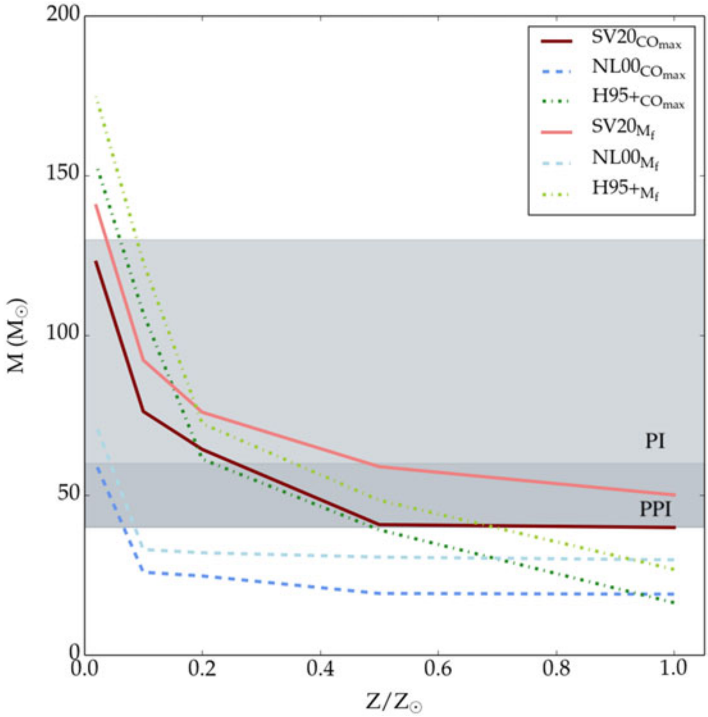

Figure 3. Final CO masses at core He-exhaustion as a function of initial metallicity for each wind recipe. Models which implement Sander & Vink (2020) are represented by solid red lines, H95+ in dashed-dotted green lines and Nugis & Lamers (2000) in dashed blue lines. The maximum final mass (M_f) models, for each metallicity, which include mass-loss rates from SV20 are represented by solid light red lines, H95+ in dashed-dotted light green lines and NL00 in dashed light blue lines. The grey shaded region highlights the region where pulsational pair-instability supernovae occur, with CO core masses above 40 $M_\odot$.

5. Conclusions

These studies have shown that in order to predict evolutionary channels for the relevant mass ranges with realistic final masses and fates, we must have a combined understanding of metallicity-dependent mass loss – both on the MS and for WRs – as well as internal mixing efficiencies.

We find that while high values (α_{ov}=0.5) of core overshooting were needed to reproduce a galactic eclipsing binary with masses of 30-40 $M_\odot$. However, we find that lower values of α_{ov}=0.1 were required for reproducing the 85 $M_\odot$ BH. This means that there may be a variation of internal mixing efficiencies at different masses or metallicities.

The M-L plane is an important tool for calibrating stellar evolution models since it can disentangle the effects of internal mixing and mass loss allowing for constraints on each process. We find that MS mass loss cannot be increased or decreased by extreme factors of the standard Vink *et al.* (2001) rates for the 20-60 $M_\odot$ range due to the resulting gradient in M-L plane which would not be able to reproduce observed luminosities simultaneously with stellar masses. Furthermore, WR mass loss may be the decisive feature in setting the BH mass spectrum across multiple metallicities. Though our studies show that the pre-Helium evolution and Pair instability also play an important role.

We find that stellar winds have a direct impact on the efficiency of mixing in stellar interiors as the envelope is depleted, thereby altering the subsurface regions where mixing

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such as semiconvection or subsurface convection occurs. It will be important to have a combined view of both mixing and mass loss in reproducing future observations.

In summary, our implementation and understanding of these key processes will be aided by further studies of eclipsing binaries, alongside the advancement of asteroseismology for the most massive stars and updated wind prescriptions, as well as follow up studies of BH progenitors and merger events.

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Discussion

TOMER SHENAR: I have a question regarding the HD limit, how do you define the limit in terms of luminosities?

ERIN HIGGINS: Prior to updated observations in 2020, the upper RSG luminosity of the Milky Way was log $L/L_\odot = 5.8$, but has now been revised to 5.5. While the LMC and SMC maintained an upper RSG luminosity of log $L/L_\odot = 5.5$.

JON SUNDQUIST: How do you evolve the stars towards WRs at low metallicity rather than evolving stars which inflate towards the red?

ERIN HIGGINS: We evolve our Helium star model grid in two ways, with increased rotation or with increased core overshooting to fully mix the models towards the Helium ZAMS. We also test models with main sequence mass loss, and without. This allows for the entire mass range to be tested at each metallicity.

JON SUNDQUIST: Do you assume the enhanced convective efficiency by MLT++?

ERIN HIGGINS: No, we don't include MLT++ during core He-burning, but to evolve the high mass Hydrogen-burning stars towards the Helium ZAMS we implement MLT++ and then disable this at the He ZAMS.

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