Massive Stars Near and Far
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On the Z-(in)dependence of the Humphreys-Davidson Limit

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Abstract. The temperature independent part of the Humphreys-Davidson (HD) limit sets the boundary for evolutionary channels of massive stars that either end their lives as red supergiants (RSGs) or as the hotter blue supergiants (BSGs) and Wolf-Rayet stars. Recent downward revision of most luminous RSGs the Galaxy below $\log(L/L_\odot) \approx 5.5$, more in line with the Magellanic Clouds, might hint towards a metallicity (Z)-independent HD limit. We present MESA single star models in the 15-40 $M_\odot$ range and study the different Z-dependent processes that could potentially affect the location of the upper luminosity limit of RSGs.

Keywords. Hertzsprung-Russell diagram, stars: evolution, stars: late-type, stars: fundamental parameters

1. Introduction

The observed absence of supergiants in the Galaxy and the Magellanic Clouds above a certain luminosity threshold has been known for decades (Humphreys & Davidson 1979). The upper luminosity boundary for the supergiants in these galaxies consists of two parts: a temperature dependent part characterised by decreasing luminosity with decreasing temperature for the hottest supergiants which merges with a temperature independent part (at $\sim$ 10 kK) for Red supergiants (RSGs). Humphreys & Davidson (1979) found an upper magnitude of $M_{\rm bol} \approx -9.5$ to 10 mag in both the Galaxy and the Large Magellanic Cloud (LMC) which translates to a luminosity of $\log(L/L_\odot) \approx 5.8$.

Ever since supergiants were not detected above this luminosity threshold, the general absence of these stars above this limit was assumed to be due to stellar wind mass loss in close proximity to the Eddington limit. The shape of the temperature dependent part of the HD limit when reproduced in the temperature-gravity diagram closely resembles the Eddington limit (Lamers & Fitzpatrick 1988), and the reversal of the redward expansion of stars is due to high mass loss as deeper layers of the stars get exposed. Lamers & Fitzpatrick (1988) also explain the 'plateau'ing of the observed limit as below a certain critical luminosity the stars are stable against radiation pressure even at the location of the maximum opacity and the Eddington limit is not reached as the star expands redwards.

Line-driven mass loss inherently scales with the metal content: the lower the metal mass fraction Z, the smaller the content of line-driving ions such as iron and hence lower the mass loss rates. If the upper luminosity limit of supergiants is indeed set by mass loss, the critical luminosity would also scale with Z shifting it to higher luminosities at lower Z.

So it was quite a surprise when Davies et al. (2018) re-evaluated the luminosity limit of RSGs in the Magellanic Clouds and found no evidence for the limit to be higher in the Small Magellanic Cloud (SMC, $Z \approx 0.2 Z_\odot$) compared to the Large Magellanic Cloud (LMC, $Z \approx 0.5 Z_\odot$). In both these sub-solar metal content environments, Davies et al. (2018) report a RSG luminosity limit of $\log(L/L_\odot) \approx 5.5$. More recently, Davies & Beasor (2020) re-analysed some of the brightest known RSGs in the Galaxy and suggest a Galactic RSG limit also at $\log(L/L_\odot) \approx 5.5$, hinting towards a Z-independent upper luminosity limit. If this finding is confirmed this would imply that the physics setting the HD limit remains elusive, and mass loss is just part of the answer.

The luminosities of massive stars steeply increase with initial stellar mass resulting in large L/M ratios that could bring such stars on the brink of radiative instability where one could potentially have the outward radiative force exceed the inward pointing gravitational force locally. The ratio of radiative force to Newtonian gravity, given by the so-called Eddington parameter $\Gamma_{\rm rad}$, could potentially approach unity (and even cross it) in layers associated with the opacity bumps of hydrogen (H), helium (He) and metals (mostly iron) (Sanyal et al. 2015). The metallicity dependence of the Eddington limit being reached in the iron bump clearly predicts a growing luminosity limit with decreasing Z (Sanyal et al. 2017). This is because the iron bump opacities increase with the content of metals, allowing the stability of more massive stars, hence higher maximum luminosity at lower Z.

The uncertain single-star physics of stellar envelopes in close proximity to the Eddington limit is of key relevance to understanding both the HD limit as well as luminous blue variable (LBV) S Doradus variations (Grassitelli et al. 2021). Furthermore, it has direct implications on binary evolution involving the interaction probability of close binary systems and gravitational wave (GW) events (e.g. Klencki et al. 2021). A better understanding of supergiant envelopes is also critical for understanding the maximum black hole (BH) mass of blue supergiant (BSG) models up to approximately 85 $M_\odot$ (Vink et al. 2021).

2. Methods

The one-dimensional stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA version 12115) (Paxton et al. 2011, 2013, 2015) is used to compute our grid of stellar models. The initial mass in our grid ranges from 15 $M_\odot$ to 40 $M_\odot$ at intervals of 2.5 $M_\odot$, and three different initial metallicities corresponding to the Galaxy ($Z = 0.017$), LMC ($Z = 0.008$) and SMC ($Z = 0.004$). We also have over-shooting mixing immediately above (or below) convective zones with two different values for their efficiencies: low ($f_{\rm ov} = 0.01$) and high ($f_{\rm ov} = 0.05$), implemented using a diffusive approach with an exponential profile as described in Herwig (2000). We use the Ledoux criteria for convection, with a high semiconvective efficiency of $\alpha_{\rm sc} = 100$. Further models are run to test the effects of certain processes such as mass loss, rotation and semi-convection on our results. All the models are evolved until core helium exhaustion when the central helium mass fraction ($Y_{\rm c}$) drops below 0.01.

Convection is treated using the standard mixing length theory (MLT) developed by Cox & Giuli (1968) with the free parameter $\alpha_{\rm MLT} = 1.82$ (Choi et al. 2016). The exact value of $\alpha_{\rm MLT}$ can change the RSG temperatures by a few hundred Kelvin, but has negligible effects on the stars that evolve bluewards and on the RSG limit. While the existence of such density inversions and inflated envelopes is heavily debated, we can still study the Z-dependence of the opacity bumps by using standard MLT and understand the stability of massive stars based on the local $\Gamma_{\rm rad}$ in these bumps.

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Mass loss in our models is implemented similar to the "Dutch wind scheme" in MESA comprising of three different recipes. Hot O stars ($T_{\rm eff} > 10\,{\rm kK}$) with surface hydrogen mass fraction $X_s > 0.4$ use the metallicity-dependent mass loss recipe from Vink et al. (2001). The mass-loss rates used in our models scale with the surface iron abundance ($Z_{\rm Fe}$) instead of the total metal fraction at the surface. Cooler stars with $T_{\rm eff} < 10\,{\rm kK}$ use the dust driven mass loss recipe from de Jager et al. (1988). For temperatures $10\,{\rm kK} < T_{\rm eff} < 11\,{\rm kK}$, we interpolate between the rates derived from Vink et al. (2001) and de Jager et al. (1988). Post-main sequence stars that lose their envelope ($X_s < 0.4$) and evolve bluewards use the recipe adopted from Nugis & Lamers (2000), which only become relevant for stars towards the upper end of the initial mass range considered in our study.

3. Z dependent processes

Over the last few decades, theoretical efforts have been made to predict the radiation-driven mass loss as a function of fundamental stellar parameters such as luminosity, mass and metallicity (Lucy & Solomon 1970; Castor et al. 1975). Simulations such as Monte Carlo calculations in Vink et al. (2001) show the mass loss rate to scale with the surface iron abundance, $\dot{M} \sim Z_{\rm Fe}^{0.7}$. The mass loss-$Z$ scaling has also been verified empirically where the modified wind-momentum luminosity relation (WLR) $D_{\rm Mom}(L) = \dot{M} v_{\rm inf} R^{0.5}$ for the LMC stars lies in between the WLRs of Galactic and SMC stars. The Z-dependence of the mass loss causes the critical luminosity of the RSGs to grow at lower Z due to lower total mass being lost.

Internal mixing processes can potentially affect the surface temperatures of supergiants and set a limit on their luminosity. Gilkis et al. (2021) find the over-shooting above the convective core during MS to significantly affect the fraction of post-MS lifetime (core helium burning) spent as RSGs. Semi-covective mixing, that arises in layers with a chemical gradient that can potentially stabilize the convective instability, can also cause blueward evolution (Langer et al. 1985; Schootemeijer et al. 2019). Metallicity can indirectly affect the formation of semi-convective layers in the envelopes of massive stars through mass loss (Higgins & Vink 2020). Semi-convection only becomes relevant at low enough initial Z where massive stars can retain most of their envelopes thus allowing semi-convective regions to form. This lowered the maximum luminosity of RSGs in LMC and SMC models which agreed well with the then empirical limits in the respective galaxies reported by Davies et al. (2018).

As mentioned in the Introduction, radiative instability in opacity bumps inside massive stars also influences the maximum luminosity of supergiants, and depends on the host Z. Unlike pure He stars and hot O supergiants where the envelope density stratification follows the topology of the iron bump (Gräfener et al. 2012), it is the H opacity bump that dominates the physics of red supergiant envelopes. In Fig 1, we show the variation of Rosseland mean opacity with temperature inside a red supergiant (profile selected at $Y_{\rm c} = 0.5$) for the range of Z considered in our model grid. In stark contrast to the Z-dependence of the iron bump, the hydrogen bump gets stronger at lower Z. This can be understood by realizing that stars at lower Z have lost less mass during their evolution and are also more compact. This two-fold effect results in higher densities in their envelope layers and consequently a stronger H bump opacity at lower Z.

The reversal of the H bump opacity with the initial metallicity due to an indirect effect of mass loss means the radiative instability favours the maximum luminosity of red supergiants to grow at higher Z. This dependence on metallicity is a qualitatively different behavior compared to the previously discussed direct effect of mass loss and its dependence on Z.

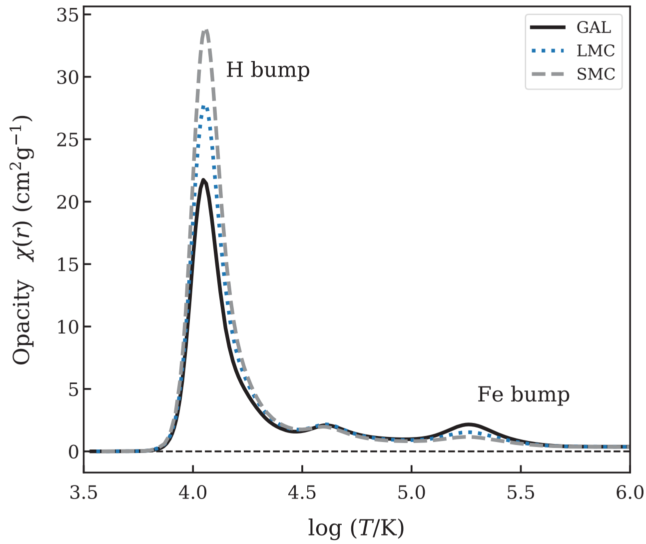

Figure 1. Rosseland mean opacity as a function of temperature showing the H and Fe opacity bumps at $\log(T_{\rm eff}) \approx 4$ and 5.3 respectively. The red supergiant profiles are taken halfway through core helium burning for Galactic (solid), LMC (dotted) and SMC (dashed) metallicity with $M_{\rm init} = 30 M_\odot$

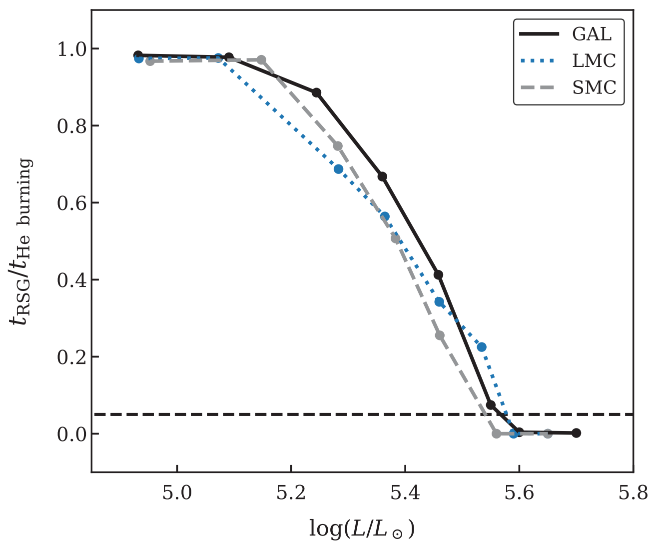

Figure 2. Distribution of fraction of He burning time spent below the threshold effective temperature $\log(T_{\rm eff}/{\rm K}) = 3.68$ as a function of the luminosity of the RSG. The solid, dotted and dashed lines correspond to Galactic, LMC and SMC-like metallicity respectively. The horizontal line marks the 5% limit that we assume to set the HD limit.

Any process that might destabilize and remove density inversions on top of inflated envelopes, be it turbulent convection or enhanced mass loss, will depend on the Eddington parameter in these zones given by

$$\Gamma(r) = \frac{g_{\rm rad}}{g_{\rm newt}} = \frac{\chi(r) l_{\rm rad}(r)}{4\pi G c m(r)} \qquad (3.1)$$

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which depends on the opacity. In Figure 2 we show the fraction of helium burning lifetime spent as RSG for models where the convective efficiencies in the H bump are scaled with the local Eddington parameter (for full grid see Sabhahit et al. (2021)). Models with sufficiently high over-shooting that spend a significant fraction of their post-MS with access to the H bump all have a very similar luminosity cutoff at $\log(L/L_{\odot}) \approx 5.5$ regardless of the initial Z. The effects of Z-dependent mass loss and the H bump radiative instability balances each other out and could potentially explain the Z-independence of the observed maximum luminosity of red supergiants.

4. Conclusions

In Sabhahit et al. (2021) we present a possible qualitative explanation for the observed Z-independence of the HD limit according to recent findings. Line-driven mass loss scales with the metal content: the lower the metallicity, the lower the mass loss rates. The direct effect of mass loss is thus to shift the luminosity boundary upwards at low Z.

On the other hand we have radiative instability in opacity bumps which could also set the HD limit. In contrast to pure helium stars and hot O stars whose envelope physics is dictated by the iron bump, the physics of red supergiant envelopes considered in this study is primarily dominated by the conditions in the H bump. In realistic stellar evolution models, we find the H bump to be stronger at lower Z due to higher densities - an indirect effect of mass loss. This can have a qualitatively different trend with Z on the maximum RSG luminosity compared to the direct of mass loss, and if balanced could potentially explain the Z-independence of the observed HD limit.

Finally, if future observational constraints further confirms the Z-independence of the limit or strongly favours a limit that varies with metallicity, it informs us about the physical processes inside the star and which effects dominate over the other.

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Discussion

Tomer Shenar: It is interesting to speculate whether the seeming Z-independence of the HD limit is caused by various effects that are cancelling each other out. What happens when the metallicity approaches zero

Gautham Sabhahit: With no metal lines the line driven mass loss would be negligible, but the star could still lose substantial amount of mass through continuum driven winds or other processes such as rotation and pulsations, which comes with its own uncertainties. Unless properly tested with all these relevant physics included, it would be hard to speculate what happens in these primordial conditions.