Winds of Stars and Exoplanets
Proceedings IAU Symposium No. 370, 2023
A. A. Vidotto, L. Fossati & J. S. Vink, eds.
doi:10.1017/S1743921322003623

Mass loss implementation and temperature evolution of very massive stars

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Abstract. Very massive stars (VMS) dominate the physics of young clusters due to their extreme stellar winds. The mass lost by these stars in their winds determine their evolution, chemical yields and their end fates. In this contribution we study the main-sequence evolution of VMS with a new mass-loss recipe that switches from optically-thin O star winds to optically-thick Wolf-Rayet type winds through the model independent transition mass loss.

Keywords. stars: mass loss, stars: winds, outflows, stars: evolution

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1. Introduction

The interest in very massive stars (VMS) up to 300 $M_\odot$ has grown substantially in the last few decades. VMS are defined as stellar objects with masses over 100 $M_\odot$ (Vink et al. 2015). They have strong emission line spectral features similar to an emission-line dominated Wolf-Rayet (WR) star of the nitrogen (N) type, but also with left-over hydrogen (H) in their spectra, and are given the WNh spectral type. These stars can be considered as a natural continuation of canonical O stars along the Main sequence (MS) and are likely still H-burning objects (e.g. Massey & Hunter 1998; de Koter et al. 1998).

VMS are often found in young, massive clusters such as the Arches and NGC3603 in our galaxy, and the vast 30 Dor region in the Large Magellanic cloud (LMC) with the central R136 cluster which hosts the most massive stars to date (Crowther et al. 2010). Due to their strong stellar winds these stars are responsible for enormous mechanical and chemical input to the surrounding medium and can significantly influence the evolution of the cluster. In high metallicity (Z) environments such as the Milky Way or the LMC, where winds are extremely strong, VMS may evaporate themselves, largely already on the MS (Vink 2018). If mass-loss rates are low, such as in the early universe or low-Z environments, VMS may produce pair-instability supernovae (PISNe) where the entire star is obliterated leaving no remnants behind, and one such PISN could potentially produce more metals than an entire initial mass function (IMF) below it (Langer 2012).

Due to their high luminosity-to-mass (L/M $\gtrsim 10^4$) ratio, VMS are very close to their so-called Eddington limit ($\Gamma \propto \kappa_{\rm F} L/M \rightarrow 1$). Their evolution is highly uncertain due to the unknown physics in close proximity to this limit of radiative pressure. Despite uncertainties in the mass loss of these stars, both theoretical (Vink et al. 2011) and empirical efforts (Gräfener et al. 2011; Bestenlehner et al. 2014) have hinted towards an enhanced mass loss in comparison to canonical O-type stars. In addition to increased mass loss, objects close to the Eddington limit may be subjected to substantial envelope *inflation*

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https://doi.org/10.1017/S1743921322003623 Published online by Cambridge University Press

Table 1. Properties of the transition stars in the Arches and the 30 Dor cluster. The luminosities, terminal velocities, effective temperatures and the surface H are empirically determined (Martins et al. 2008; Bestenlehner et al. 2014). The transition mass-loss rate is obtained from Eq. 3.1. For the transition mass and corresponding electron scattering Γ_e see Sec. 3.

	$L/L_\odot$	v_∞(km/s)	$T_{\rm eff}$(K)	X_s	$\dot{M}_{\rm trans}$	$M/M_\odot$	$\Gamma_{\rm e,trans}$
GAL	$10^{6.06}$	2000	33900	0.7	−5.16	76.9	0.39
LMC	$10^{6.31}$	2550	44400	0.62	−5.0	121.8	0.42

(Ishii et al. 1999; Gräfener et al. 2012) with models predicting very cool temperatures and large radii. While the physical existence of such inflated envelopes is debated, enhanced mass loss could potentially inhibit the formation of such inflated envelopes (Petrovic et al. 2006; Grassitelli et al. 2018).

In this contribution, we derive a new mass loss prescription for VMS using the transition mass-loss rate at two different metallicities and study the effects of enhanced mass-loss on the evolution of stars with initial masses upto 500 $M_\odot$

2. Methodology

The one-dimensional stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA version 12115) is used to compute our grid of stellar models. The models are evolved until the end of core H burning, where the models stop once the central hydrogen mass fraction (X_c) falls below 0.01. The initial mass ranges from 60 to 500 $M_\odot$. We consider two initial metallicities corresponding to the Galaxy ($Z = 0.02$) and the Large Magellanic Cloud ($Z = 0.008$), where the observed transition stars are available to obtain absolute rates.

Convective overshooting beyond the convective regions is treated using the exponential profile parameterized by $f_{\rm ov} = 0.03$. All models begin as solid-body rotators at the ZAMS with $\Omega/\Omega_{crit} = 0.2$. As discussed below, the choice of efficiencies of mixing processes that can influence the core size, such as overshooting and rotation-induced mixing, hardly influences the evolution of VMS.

Theoretical mass-loss prescriptions for OB stars as a function of stellar properties are available (Castor et al. 1975; Vink et al. 2001), and have been previously used to study the evolution of VMS. However these rates quickly start to under-predict the mass loss above the transition point. This has been shown both theoretically (Vink 2006; Vink et al. 2011) and empirically in the 30 Dor cluster (Bestenlehner et al. 2014). The challenge however is to determine the absolute rates of these objects and their mass-loss scaling with different stellar parameters. In this study we use the model-independent transition mass loss in the Arches and the 30 Dor region to calibrate the absolute rates of VMS and further scale these rates with a steeper dependence on the ratio L/M compared to canonical O star scaling.

3. Transition mass loss

Vink & Gräfener (2012) derive a model-independent way to characterize the physical transition from optically-thin winds of O stars to the optically-thick winds of WNh stars, regardless of the assumptions of clumping in the wind. They showed that at this transition the optical depth at the sonic point τ_s crossing unity coincides with the wind efficiency parameter $\eta = \dot{M}v_\infty/(L/c)$ crossing unity, under the assumption of very high Eddington parameter Γ. This condition $\eta = \tau_s = 1$ can be used to obtain a model-independent mass loss, called the *transition mass loss*, given the luminosity and the terminal velocity of the transition objects.

The $\eta = \tau_s = 1$ condition at the transition relies on the assumption that the ratio $(\Gamma - 1)/\Gamma$ is very close to unity or $\Gamma \gg 1$. Vink & Gräfener (2012) tested this assumption

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of high Γ using a hydro-dynamic model of WR22 from Gräfener & Hamann (2008), by numerically integrating inwards from infinity to the sonic radius to obtain τ_s. They derived a correction factor $f \approx 0.6$ for their transition condition: $\eta = f\tau_s$.

In the Arches cluster, we have a spectral morphological transition from O to the WNh sequence with the transition stars being classified as Of/WNh stars. Using the properties of the transition Of/WNh stars one can derive the transition mass-loss rate using the following formula

$$\dot{M}_{\rm trans} = f\frac{L_{\rm trans}}{v_\infty c} \tag{3.1}$$

Vink & Gräfener (2012) also found that the mass-loss rates of the transition objects in the Arches cluster agrees with the theoretical rates predicted from Vink et al. (2001) for Galactic metallicity. Using this assumption one can derive an 'average' transition mass as well as the electron scattering Eddington parameter at the transition $\Gamma_{\rm e,trans}$. One can perform a similar analysis for the 30 Dor objects in the LMC where we have empirical results of six transition stars (Bestenlehner et al. 2014). The transition properties of the two clusters are provided in Table 1.

We can thus use the transition mass loss as a kink or an anchor point connecting the *optically-thin regime* of canonical O stars below it and the much steeper scaling of *optically-thick regime* of WNh stars above it. In MESA, we implement a mass loss recipe that consists of an optically-thin scaling of $\dot{M} \sim L^{2.194} M^{-1.313}$ from Vink et al. (2001) till the transition point, which then smoothly switches to the optically-thick scaling of $\dot{M} \sim L^{4.77} M^{-3.99}$ derived in Vink et al. (2011). In Sabhahit et al. (2022), we go into more details of the effect of electron number density on the mass-loss rates and the consequent effects on the evolution of VMS.

As for the metallicity dependence of the winds, we implement a $\dot{M} - Z$ dependence that only reflects changes in surface iron (Fe) abundance as originally intended in Vink et al. (2001), with the following scaling $\dot{M} \sim Z^{0.85}$ in the optically-thin regime. The transition mass loss in two different Z environments allows us to derive a mass loss-metallicity scaling of $\dot{M} \sim Z^{0.76}$ at the transition point, which is then applied throughout the optically-thick regime. The terminal velocity v_∞ is also implemented to vary with the metallicity according to Leitherer et al. (1992), $v_\infty \sim Z^{0.13}$.

4. Implications for VMS temperatures and surface abundances

In Fig. 1 we plot a full grid of stellar tracks of VMS models with varying initial mass at Galactic metallicity. At the upper end of the initial mass spectrum ($\gtrsim 200\ M_\odot$) considered here, the VMS begin H-burning with luminosities in excess of $\log(L/L_\odot) = 6.5$. These VMS lie above the transition point and in the optically-thick regime of our mass loss recipe. Owing to the higher absolute mass loss these models quickly evaporate a large fraction of their initial mass, resulting in an overall drop in their luminosity. This is in stark contrast to the MS evolution of canonical massive stars where the luminosity increases as the overall mean molecular weight increases (μ effect) during H burning.

There are qualitative differences in the evolution of VMS model temperatures as well. VMS models with the new mass loss recipe evolve vertically at almost constant temperatures, which is in stark contrast to stars below the transition point where stars tend to expand to cooler temperatures and evolve horizontally during the MS. This reduction in luminosity suppresses both the effects of envelope inflation as well as enhanced mass loss (both being a function of L/M), thus maintaining a balance between the two effects for all initial masses. The drop in the luminosity owing to higher mass loss rates has a self-regulatory action in maintaining constant temperatures throughout the evolution.

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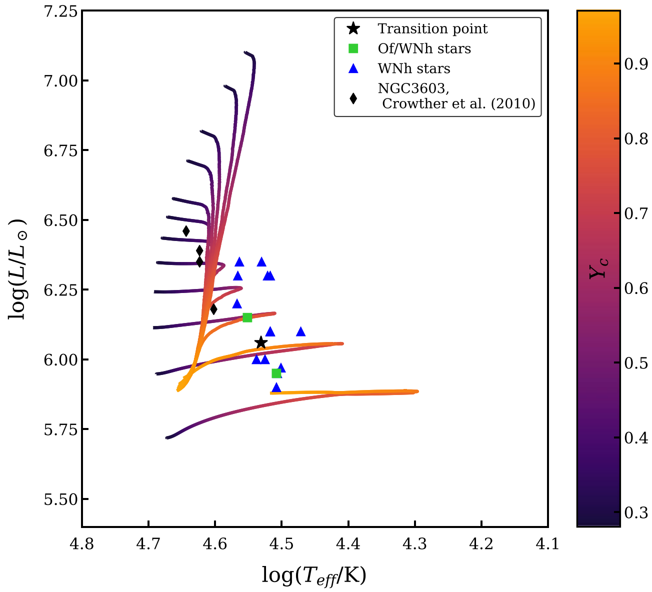

Figure 1. Stellar tracks of VMS models with initial mass ranging from 60 $M_{\odot}$ to 500 $M_{\odot}$. Empirical luminosities and temperatures of VMS in the Galaxy are also plotted (see text).

We over-plot the observed HRD locations of the transition Of/WNh stars as squares and WNh stars as triangles in the Arches cluster from Martins et al. (2008). The WN6h stars in the NGC3603 cluster is also plotted as diamonds from (Crowther et al. 2010). The star symbol marks the 'average' luminosity and the effective temperature of the transition stars obtained by averaging the surface properties of the two Of/WNh stars. The WNh stars in the Arches cluster occupy a narrow band of temperatures in the HRD with $\log(T_{\rm eff}) \approx 4.5 - 4.6$ above $\log(L/L_{\odot}) \approx 6.0$. The vertical alignment of the observed temperatures could just be due to the similar ages of the stars in a cluster. While it is possible to reproduce the observed temperatures with VMS models evolving horizontally in the HRD, their radii and temperatures are highly sensitive to the effect of inflation which grows with L/M. This causes VMS models to have varying temperatures with varying initial mass (for the same age) making it is highly unlikely for models with different initial masses to maintain such constant temperatures long enough to be observed. Vertical evolution would give a natural explanation of the observed constant temperatures of VMS over the entire mass range.

Another interesting property of VMS can be understood by studying the evolution of their surface abundances. The convective core size of a star is determined at the location where the temperature gradient required for radiation diffusion to transport the stellar luminosity outwards, $\nabla_{\rm rad} \sim \chi l/m$ equals the adiabatic temperature gradient $\nabla_{\rm ad}$. Owing to increasing l/m with initial mass, the convective core mass fraction increases with initial mass, reaching values greater than ≈ 0.9 at the beginning of MS for $M_{\rm init} \gtrsim 200\, M_{\odot}$.

A consequence of having an almost fully mixed star is the insensitivity of the evolution of VMS to processes that can affect the core size. Models with $M_{\rm init} \gtrsim 200\, M_{\odot}$ (see thick grey line in Fig. 2) remain fully mixed throughout the MS regardless of their rotational and overshooting inputs. The surface abundances closely maps the central abundances, and can be used as a clock to obtain constraints on the age of these objects (Higgins et al. 2022). The effects of varying overshooting and rotation on the core size becomes negligible and the evolution is completely dominated by mass loss.

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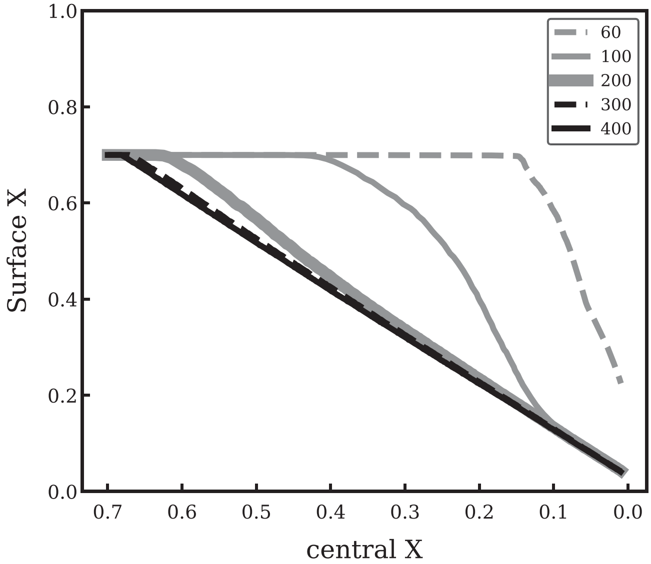

Figure 2. Evolution of surface and central hydrogen mass fraction for selected models in our grid (the initial masses of these models are provided in the legend).

In this study we used the model-independent transition mass-loss rate in two different metallicities to calibrate the absolute rates of VMS, and investigated the effects of a new mass loss recipe with a simple power law scaling on the evolution of stars above 60 $M_{\odot}$. The mass loss scaling instead could be more complicated than a simple power law and could vary with the surface electron density or the temperature. A promising step forward is to understand the mass-loss enhancement at the $\eta = \tau_{\mathrm{s}} = 1$, but now using stellar atmosphere codes such as PoWR that are capable of consistently solving the wind hydro-dynamics to determine wind parameters including mass loss.

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