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Very Massive Stars and the Eddington Limit

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Abstract. We use contemporary evolutionary models for Very Massive Stars (VMS) to assess whether the Eddington limit constrains the upper stellar mass limit. We also consider the interplay between mass and age for the wind properties and spectral morphology of VMS, with reference to the recently modified classification scheme for O2–3.5 If*/WN stars. Finally, the death of VMS in the local universe is considered in the context of pair instability supernovae.

1. Eddington limit

Empirical determinations for the upper stellar mass limit, $M_{\rm max}$, have led to the adoption of $M_{\rm max} \sim 150 M_\odot$ (e.g. Figer 2005; Oey & Clarke 2005). This limit closely coincides with the 'first approximation' for $M^{\rm Edd}_{\rm max} \sim 200 M_\odot$, i.e. the intersection between the Eddington limit and the $L \propto M^3$ mass-luminosity relation for main sequence stars (e.g. Maeder 2009, his Fig 3.6). Therefore, two obstacles need to be overcome for these findings to be reconciled with the claimed 320 $M_\odot$ initial mass for R136a1 by Crowther et al. (2010). Massey (2011) has provided convincing arguments regarding the empirical estimates of $M_{\rm max}$, so here we focus attention on $M^{\rm Edd}_{\rm max}$.

Main sequence models for very massive stars (VMS) have been calculated using the Geneva evolutionary code by R. Hirschi and N. Yusof (see Crowther et al. 2010) and the Bonn evolutionary code by K. Friedrich (see Gräfener et al. 2011). In Figure 1 we present the mass–luminosity relation for non-rotating, solar metallicity ZAMS, incorporating 9-85 $M_\odot$ models from Meynet & Maeder (2000). Although $x = 3$ represents a sensible average for $L \propto M^x$ across all stellar masses, $x \sim 2.5$ for 10–20 $M_\odot$ and flattens further at higher masses, reaching $x \sim 1.5$ close to 200 $M_\odot$.

The Eddington parameter, Γ_e, can be expressed as

$$\Gamma_e = g_e/g = 3 \times 10^{-5} q \frac{L/L_\odot}{M/M_\odot}$$

where $q = 0.86$ for main sequence hot stars. A decrease in the slope of the mass-luminosity relation at very high masses reduces Γ_e, and so raises $M^{\rm Edd}_{\rm max}$. Of course, Γ_e

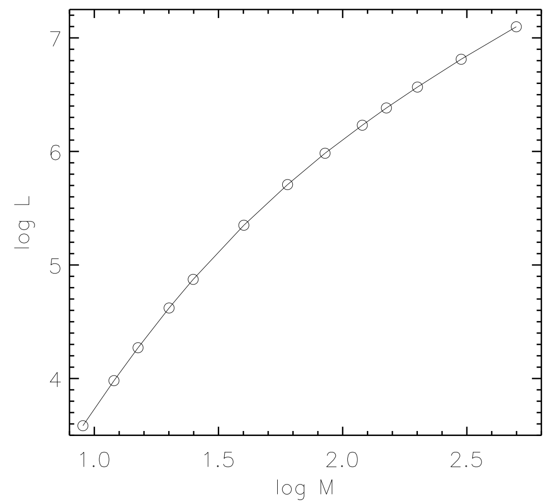

Figure 1. Mass-luminosity relation for non-rotating, solar metallicity ZAMS stars from Meynet & Maeder (2000, $\leq 85 M_\odot$) and Crowther et al. (2010, $\geq 120 M_\odot$).

increases once a star evolves away from the ZAMS (L/M increases), and since $\dot{M} \propto L(\Gamma_e/(1-\Gamma_e))^{2/3}$ for radiatively driven winds with a CAK power index of $\alpha \sim 0.6$ (Owocki 2003), stronger winds are anticipated both qualitatively (Smith & Conti 2008) and quantitatively (Gräfener & Hamann 2008) with age.

Figure 2 compares Γ_e for ZAMS spanning 10–500 $M_\odot$ at solar composition. This illustrates that the Eddington limit is not approached, so $M^{\rm Edd}_{\rm max} \gg 500 M_\odot$. In fact, $x \rightarrow 1$ as $M \rightarrow \infty$, so the Eddington limit might never be reached for ZAMS stars. Once on the main sequence, Γ_e, and in turn mass-loss rates, increase with both age and mass, so strong wind signatures may correspond either to a relatively evolved high mass star or an unevolved very high mass star. Table 1 compares the influence of mass and age upon spectral type for the case of the coeval cluster R136a whose age is ~1.5 Myr (Crowther et al. 2010).

Table 1. Influence of mass (vertical) and age (horizontal) upon spectral type for the young LMC star cluster R136a

Initial Mass ($M_\odot$)	Sp Type (ZAMS)	Sp Type (1.5 Myr)	Example
240	O2 If*?	WN5h	R136a2
140	O2 III?	O2 If*	R136a5
100	O2–3 V?	O3 III(f*)	R136a7
50	O3 Vz?	O3V	[HSH95] 50‡

‡: Hunter et al. (1995, HSH95)

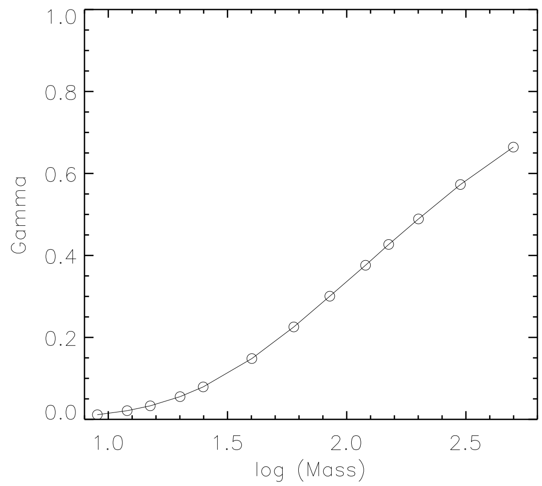

Figure 2. Eddington parameter, Γ_e, for non-rotating, solar metallicity ZAMS stars from Meynet & Maeder (2000, $\leq 85 M_{\odot}$) and Crowther et al. (2010, $\geq 120 M_{\odot}$).

2. Transition Of/WN stars

From the previous section, high Γ_e's develop either in young, very high mass stars or evolved lower mass stars. Spectroscopic signatures of strong winds in early type stars include He II λ4686 and/or Hα emission, corresponding to OBA supergiants or Wolf-Rayet stars in the case of very strong emission features. From Table 1, the current spectral type of R136a2 is WN5h, while its ZAMS spectral type may have resembled an O2 supergiant. Had we witnessed R136 perhaps 0.5 million years ago, it would have exhibited an intermediate spectral type. Indeed, a hybrid O3 If*/WN category – spectroscopically intermediate between early O stars and WN stars – was introduced by Walborn (1982).

Following the extension of the MK sequence to O2 (Walborn et al. 2002) and revisions to WN classifications, this has been refined recently by Crowther & Walborn (2011). Spectroscopically the morphology of Hβ is key to O2–3.5 If*, O2–3.5 If*/WN or WN subtypes, while a qualitative interpretation led Crowther & Walborn (2011) to conclude that most O2–3.5 If*/WN stars (e.g. Melnick 35) are very luminous, young stars with $150 \pm 30 M_{\odot}$. However, some Of/WN stars are substantially lower in luminosity/mass (e.g. Sk –67° 22, Melnick 51), with correspondingly larger ages, even though these may be spectroscopically indistinguishable from other examples, as illustrated in Fig. 3.

The incidence of O2–3.5 If*/WN stars in the LMC is significantly higher than in the Milky Way. Radiatively driven winds of Galactic stars would be expected to be modestly higher than LMC counterparts, so one would predict a slightly higher percentage of O2–3.5 If*/WN stars in the LMC with respect to the Milky Way. In fact, O2–3.5 If*/WN stars comprise 7% of the 106 WN-type stars in the LMC (Breysacher et al. 1999), versus only 2% of the highly incomplete 175 WN stars compiled by van der Hucht (2001, 2006). Since transition spectral types arise preferentially in very massive stars, one would expect them predominantly in regions of the highest star formation. In-

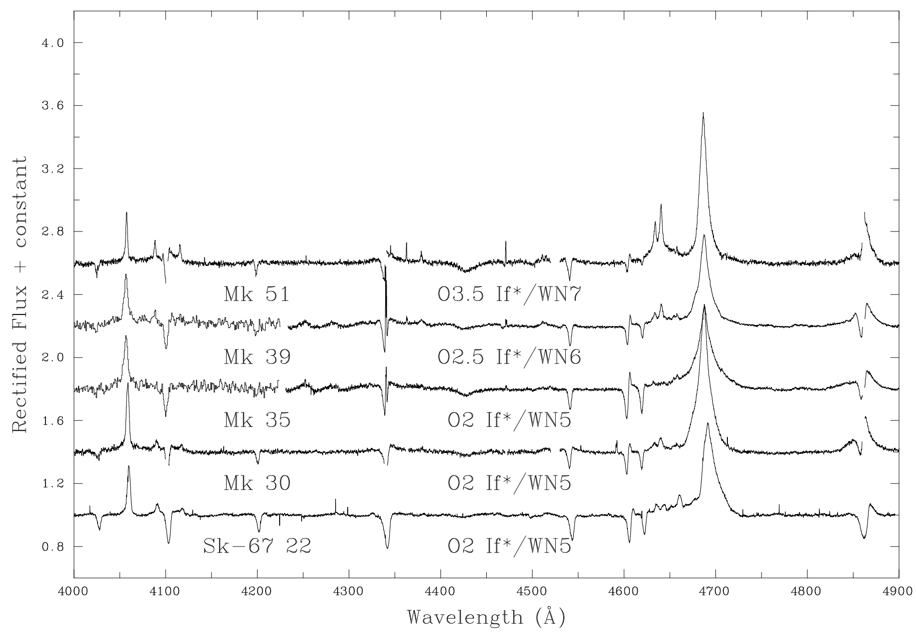

Figure 3. Spectrograms of transition Of/WN stars (Crowther & Walborn 2011)

deed, the 30 Dor region of the LMC dominates Of/WN statistics in the Local Group (Crowther & Walborn 2011).

3. Death of Very Massive Stars

A natural question relating to VMS is whether they would follow the usual path to core-collapse supernovae (CCSNe) or explode prematurely as pair-creation supernovae (PC-SNe)? Heger et al. (2003) concluded that metal-free, single massive stars with 140–260 $M_{\odot}$ would explode as PCSNe. However, unbiased transient surveys have recently identified exceptionally bright supernovae in the local universe, some of which have been attributed to PCSNe from initially $\sim 200 M_{\odot}$ stars with more modest metal-deficiencies (e.g. SN 2007bi Gal-Yam et al. 2009).

VMS models have been calculated throughout their post-main sequence evolution using Vink et al. (2001) mass-loss prescriptions for the main sequence and Nugis & Lamers (2000) for the post-main sequence Wolf-Rayet phase, the results of which are presented in Fig. 4. H-deficient CCSNe are predicted for 100–300 $M_{\odot}$ stars at solar and LMC metallicities, whereas CO core masses of 60–130 $M_{\odot}$ are obtained for rotating 150–200 $M_{\odot}$ stars at SMC metallicity. Therefore, VMS at low metallicity may indeed produce PCSNe. Indeed, Quimby et al. (2011) have identified a class of luminous H-deficient supernovae located in faint, metal-poor host galaxies. Quimby et al. attributed such bright SNe to a strong interaction between the CCSN of a very massive star and a H-free shell produced by violent pulsations, that was perhaps initiated by the pair instability.

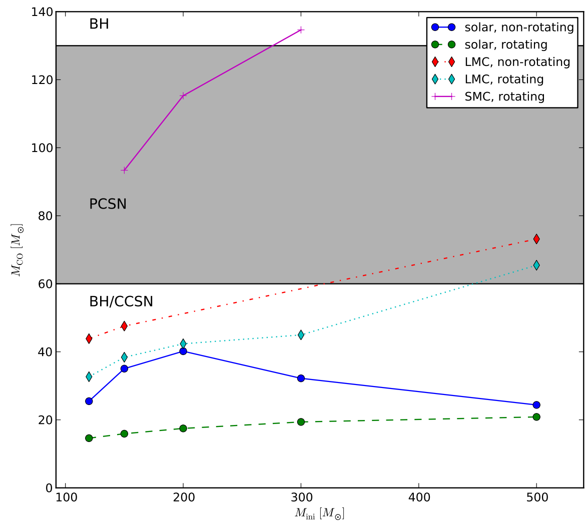

Figure 4. Final CO mass versus initial mass for VMS at SMC, LMC and solar metallicities, with the domain of PCSNe shown in grey, based upon mass-loss prescriptions of Vink et al. (2001) and Nugis & Lamers (2000) for, respectively, the H-rich and H-poor phases (from Yusof et al. in prep.).

However, these predictions are very sensitive to mass-loss prescriptions, especially for the post-main sequence phase. For the Wolf-Rayet phase separate expressions are adopted for WN and WC stars, in which mass-loss rates are expressed in terms of luminosity and composition (Nugis & Lamers 2000, eqns. 20–21). Such calibrations, based on results for Wolf-Rayet stars at solar composition, imply a factor of ∼30 increase in mass-loss rate from the H-rich (Vink et al. 2001) to the H-deficient phase of a 300 $M_\odot$ star at SMC metallicity. To illustrate the sensitivity, let us alternatively adopt equation 25 from Nugis & Lamers (2000), albeit modified to allow for the $\dot{M} \propto Z_{\rm Fe}^{0.7}$ dependence of mass-loss upon ambient (Fe-peak) metallicity, $Z_{\rm Fe}$ (Crowther et al. 2002; Vink & de Koter 2005; Crowther 2006), i.e.

$$\log M/(\dot{M_\odot}{\rm yr}^{-1}) = -5.7 + 0.88\log(M/M_\odot) + 0.7\log(Z_{\rm Fe}/Z_{Fe,\odot})$$

This would exceed the Vink et al. (2001) prediction by only a factor of 2 for the case of a SMC metallicity 300 $M_\odot$ star, leading to significantly higher CO masses than those presented in Fig. 4, raising the possibility of PCSNe from VMS progenitors at higher metallicity.

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Discussion

Krysztof Stanek *Is there any photometric variability information for your most massive stars?*:

Paul Crowther *Not that we know, although their location at the centres of very crowded clusters makes photometric studies challenging (R136a1 and R136a2 are separated by only 0.1 arcsec)*: