The mass-loss dominated lives of the most massive stars

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Abstract. Utrecht has a long tradition in both spectroscopy and mass-loss studies. Here we present a novel methodology to calibrate mass-loss rates on purely spectroscopic grounds. We utilize this to predict the final fates of massive stars, involving pair-instability and long gamma-ray bursts (GRBs) at low metallicity Z.

1. Introduction

Mass loss is an important ingredient in massive star evolution modelling. Nowhere is it more dominant than for the most massive stars, which are thought to evolve chemically homogeneously (Gräfener et al. 2011). Mass loss determines the final fate. This may involve normal supernovae (SNe) or pair-instability SNe, leaving either normal black holes or intermediate mass-black holes (IMBHs) behind (Belkus et al. 2007; Yungelson et al. 2008). The point is that very massive stars (VMS) up to 300 $M_\odot$ – and perhaps even as high as $\sim 1000 M_\odot$ through collisions in clusters – are now thought to exist in nature (Crowther et al. 2010; Bestenlehner et al. 2011).

In recent years a debate has arisen regarding the roles of stellar wind versus eruptive mass loss, as winds have been found to be clumped, which resulted in the reduction of empirical mass-loss rates. Stellar evolution modellers however generally employ theoretical mass-loss rates. These are already reduced by a moderate factor (of $\sim 2$-3) compared to non-corrected empirical rates. A key question is whether these reduced rates are correct or if they need to be reduced even more.

Whilst stationary winds in O and Wolf-Rayet (WR) stars are ubiquitous, it is not clear if objects like $\eta$ Car have experienced a special evolution, e.g. involving a merger, or if a majority of massive stars would encounter eruptive mass-loss phases. Alternatively, for the most massive main-sequence WNH stars there is strong evidence for a Eddington parameter $\Gamma$-dependent mass loss (Gräfener et al. 2011). In other words, for VMS the role of stationary mass loss has increased in recent years.

We recently introduced the transition mass-loss rate $M_{\text{trans}}$ between O and WR stars (Vink & Gräfener 2012). Its novelty is that it is model independent. All that is needed is the spectroscopic transition point in a data-set, and to determine the stellar luminosity. This is far less model-dependent than conventional mass-loss diagnostics. Our results suggest that the rates provided by Vink et al. (2000) are of the right order of magnitude in the $50 M_\odot$ range, but alternative mechanisms might be needed at lower Z, particularly relevant for the occurrence of GRBs.
2. The mass loss versus Eddington-Gamma dependence

Vink et al. (2011a) discovered a kink in the slope of the mass-loss vs. $\Gamma$ relation at the transition from optically thin O-type to optically thick WR-type winds. Figure 1 depicts mass-loss predictions for VMS as a function of the Eddington parameter $\Gamma$. For ordinary O stars with "low" $\Gamma$ the $M \propto \Gamma^x$ relationship is shallow, with $x \approx 2$. There is a steepening at higher $\Gamma$, where $x$ becomes $\approx 5$. Here the optical depths and wind efficiencies exceed unity. This result from Monte Carlo modelling, i.e. that the O to WR mass loss transition point coincides with $\eta \approx 1$, can also be found analytically.

2.1. The transition mass-loss rate

Lamers & Cassinelli (1999) provided momentum considerations for dust-driven winds that we apply to line-driven winds. The integral form of the momentum equation has four terms, but as hydrostatic equilibrium is a good approximation for the inner wind, and the gas pressure gradient is small beyond the sonic point, the 2nd and 3rd terms are neglected, leading to:

$$\int_{R_s}^{\infty} 4\pi r^2 \rho v \frac{dv}{dr} dr + \int_{R_s}^{\infty} \frac{GM}{r^2} (1 - \Gamma) \rho 4\pi r^2 dr = 0. \quad (1)$$

When we utilize the mass-continuity equation $\dot{M} = 4\pi r^2 \rho v$, we retrieve

$$\int_{R_s}^{\infty} \dot{M} \frac{dv}{dr} dr = \dot{M} v_\infty = 4\pi G M \int_{R_s}^{\infty} (\Gamma(r) - 1) \rho dr \quad (2)$$

where $r_s$ represents the sonic radius and $\Gamma(r) = \frac{\kappa_F L}{4\pi GM}$ is the Eddington factor with respect to the flux-mean opacity $\kappa_F$. Employing the wind optical depth $\tau = \int_{r_s}^{\infty} \kappa_F \rho dr$, we obtain
\[ \dot{M}_v \propto \frac{4\pi GM}{\kappa} (\Gamma - 1) \tau = \frac{L}{c \Gamma - 1} \tau. \]  

(3)

If we assume that \( \Gamma \) is larger than unity, the factor \( (\Gamma - 1)/\Gamma \) is close to one, which leads to \( \dot{M}_\infty = L/c\tau \). We can now derive the unique wind efficiency condition \( \eta = \frac{\dot{M}_\infty}{L/c} = \tau = 1 \) for the transition point from optically thin O-star winds to optically-thick WR winds, and we retrieve a model-independent \( \dot{M} \). In case we have an empirical data-set available that includes luminosity determinations we can provide the transition mass-loss rate \( \dot{M}_{\text{trans}} \), simply from the transition luminosity \( L_{\text{trans}} \) (and the terminal velocity \( v_\infty \)): \( \dot{M}_{\text{trans}} = \frac{L_{\text{trans}}}{v_\infty c} \). This transition point is obtainable just by spectroscopic means, and independent of any wind-clumping assumptions.

2.2. Do very massive stars make IMBHs or pair instability SNe?

To address these questions, we require accurate mass-loss rates for VMS. As Vink & Gräfener (2012) were able to calibrate the Vink et al. (2000) mass-loss prescriptions at the high-mass end, and given that these rates agree well with the Crowther et al. (2010) rates for the 30 Dor WNh core stars for moderate clumping factors \( D \sim 10 \), we employ the Vink et al. (2000) rates for now. When starting with 300\( M_\odot \), we find \( \dot{M} = 10^{-4.2} M_\odot \text{yr}^{-1} \). For a 2.5Myrs lifetime this leads to a total main-sequence mass lost of \( \approx 150 M_\odot \). Extra wind mass loss during the core helium phase will further evaporate these stars. There seems little space left for eruptive mass loss. Our results would imply that IMBHs and pair-instability SNe are unlikely, unless we move to lower \( Z \).

3. GRBs and the metallicity dependence of Wolf-Rayet stars

Mass loss at low \( Z \) has gained attention due to the issue of cosmic reionization by population iii stars. Also, massive stars are thought to be the progenitors of GRBs. Within the collapsar model, GRB progenitors require 2 properties: (i) rapidly rotating cores, and (ii) the absence of hydrogen envelopes. Therefore, GRB progenitors are thought to be rotating WR stars. A potential pitfall is that WR star have high mass loss which could remove all the angular momentum before core collapse. In the rapidly rotating stellar models of Yoon & Langer (2005), the objects evolve “quasi-homogeneously”. The objects are subjected to a strong magnetic coupling between the stellar core and envelope. If rapid rotation can be maintained as a result of lower main-sequence mass loss in lower \( Z \) galaxies, the objects may avoid spin-down during a RSG or LBV phase, and directly become rotating WR stars. If WR winds also depend on Fe driving (Vink & de Koter 2005), the objects could remain rapid rotators towards the end of their lives, enabling GRB formation, but exclusively at low \( Z \).

Recent GRB observations however suggest that GRBs are not restricted to low \( Z \). Indeed, there seems to be a need for a high \( Z \) GRB channel. We have recently identified a sub-group of rotating Galactic WR stars. This would allow for a potential solution to the problem (Vink et al. 2011b; Gräfener et al. 2012). Spectropolarimetry surveys show that the majority of WR stars have spherically symmetric winds indicative of slow rotation, but a small minority display signatures of a spinning stellar surface (see Fig. 2 for the example of WR 134). We recently found the spinning subgroup surrounded by ejecta nebulae – thought to be ejected during a recent RSG/LBV phase – suggesting that these objects are still young, and rotating.
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Figure 2. Galactic Wolf-Rayet star WR 134. (a) Position Angle (PA) of the polarisation. (b) Degree of linear polarisation. (c) Stokes I “intensity”.

If core-surface coupling were strong enough the cores would not rotate rapidly enough to make GRBs. However, if core-envelope coupling is less efficient stars may have sufficient angular momentum in the core to make a GRB. At high $Z$, the objects would in most cases still spin down due to mass loss, but with our post-RSG/LBV scenario one would not exclude the option of high $Z$ GRBs. Still, low $Z$ remains preferred due to weaker WR winds (Vink 2007).

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