Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Mass loss and fate of the most massive stars

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Abstract. The fate of massive stars up to $300 M_\odot$ is highly uncertain. Do these objects produce pair-instability explosions, or normal Type Ic supernovae? In order to address these questions, we need to know their mass-loss rates during their lives. Here we present mass-loss predictions for very massive stars (VMS) in the range of 60-$300 M_\odot$. We use a novel method that simultaneously predicts the wind terminal velocities v_∞ and mass-loss rate $\dot{M}$ as a function of the stellar parameters: (i) luminosity/mass Γ, (ii) metallicity Z, and (iii) effective temperature $T_{\rm eff}$. Using our results, we evaluate the likely outcomes for the most massive stars.

Keywords. stars: mass loss, stars: evolution, stars: Wolf-Rayet, supernovae: general

1. Introduction

Mass loss is the decisive parameter for predicting final stellar masses and the types of supernova (SN) explosion. Do the most massive stars disrupt as pair-instability SNe (PISNs), or do they produce normal SNe Ic? When does this occur in conjunction with a long gamma-ray burst (GRB)? Is low metallicity Z simply in *favour* due to lower mass-loss rates $\dot{M}$, or is it even a *stringent* requirement? Furthermore, the formation of intermediate mass-black holes (IMBHs) and the stellar black-hole mass distribution are determined by Z-dependent $\dot{M}$ (Heger *et al.* 2003; Eldridge & Vink 2006).

Another relevant issue concerns the stellar upper-mass limit. Until recently many researchers accepted a $150 M_\odot$ limit. Crowther *et al.* (2010) recently agued for much higher luminosities – with masses twice as high – for the WNh objects in dense clusters. A potential issue with the Crowther *et al.* luminosities is that these objects are clustered, involving a non-negligible chance of photon pollution from line-of-sight objects.

We have found a new WNh star VFTS 682 in 30 Dor (Evans *et al.* 2011; Bestenlehner *et al.* 2011). It is a near-identical twin of one of the 'Crowther' stars, R136a3. Surprisingly, VFTS 682 is in apparent isolation from the R136 cluster (see Bestenlehner *et al.* for a discussion on isolated formation or a "slow runaway" status). This enables a check on the reliability of the luminosities derived for the core stars. Our finding of $\log(L/L_\odot) = 6.5 \pm 0.2$ for VFTS 682 provides support for high luminosities and masses, as the chance of line-of-sight pollution is small for this isolated star. Mass-loss rates for VMS up to $300 M_\odot$ are needed to establish their fate. VMS are extremely close to the Eddington limit $\Gamma = g_{\rm rad}/g_{\rm grav} = \kappa L/(4\pi c G M)$.

2. Method: Monte Carlo mass-loss predictions

Stellar winds from massive stars are driven by radiation pressure on spectral lines (Castor *et al.* 1975, CAK), predominantly on Fe. The approach we use to compute $\dot{M}$ for VMS is similar to the Monte Carlo method used to predict $\dot{M}$ for normal OB stars (Vink *et al.* 2000). Until 2008 our methodology was semi-empirical, as we assumed a velocity law that reached a certain empirical v_∞. Müller & Vink (2008) suggested a new line-force

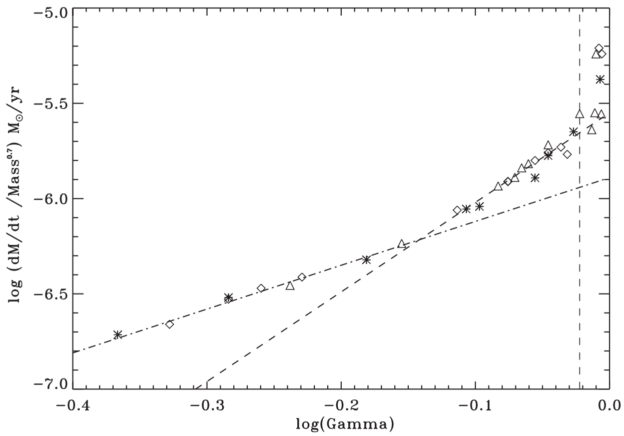

Figure 1. Mass-loss predictions versus the Eddington parameter Γ – divided by $M^{0.7}$. Symbols correspond to models of different mass ranges (Vink *et al.* 2011a).

parametrization that explicitly depends on radius (rather than the velocity gradient, as in CAK theory). We predicted v_∞ within ∼25% of the observations. In Muijres *et al.* (2012) we tested the Müller & Vink approach by comparison to hydrodynamical models. As both methods gave similar results, we use the Müller & Vink approach for VMS.

Nugis & Lamers (2002) and Gräfener & Hamann (2008) studied radiative driving due to Fe-peak opacities in deep photospheric layers of Wolf-Rayet (WR) winds. As Γ crosses unity in deep layers, the sonic point is located at high optical depth, leading to the initiation of optically-thick winds. In the Monte Carlo models, one traces the driving over the entire wind, and as the bulk of the energy is transferred in the supersonic portion of the wind, one is less susceptible to the details of the photospheric region. Our strategy allows us to explore the transition from optically thin O-star winds to optically thick WR winds.

3. $\dot{M} - \Gamma$ dependence - Do PISNs exist at $Z_\odot$?

In Figure 1 we show mass-loss predictions for VMS as a function of the Eddington parameter Γ (see Vink *et al.* 2011a for details). Most notable is the presence of a *kink* in the relation. For O-type stars with "low" Γ and optically-thin winds, the $\dot{M} \propto \Gamma^x$ relationship is shallow, with $x \simeq 2$. There is a steepening at higher Γ, where x becomes $\simeq 5$. Here the objects show optically thick WR-like winds, with optical depths and wind efficiencies above unity.

Gräfener *et al.* (2011) recently provided empirical evidence for our predicted steep exponent ($x \simeq 5$), but note that there are still issues with our v_∞ values for the high Γ range. For now we employ the Vink *et al.* (2000) mass-loss recipe for our assessment of the fate of the most massive stars. These mass-loss rates agree extremely well with the rates discussed by Crowther *et al.* (2010) for the 30 Dor R136 core stars. We have recently also calibrated the Vink *et al.* rates using an analytic method and applied it to the most massive stars in the Arches cluster (Vink & Gräfener 2012).

Using Vink *et al.* (2000) rates for a star starting with $300 M_\odot$ we find $\dot{M} = 10^{-4.2}$ $M_\odot \mathrm{yr}^{-1}$. For a lifetime of 2.5 Myrs, this leads to a total main-sequence mass lost of $\simeq 150 M_\odot$. Additional mass loss during the core helium WR phase should further "evaporate" the object. Our results indicate that there is little room for substantial additional

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mass loss in luminous blue variable (LBV) eruptions. Our results also imply that IMBHs and pair-instability explosions are unlikely. Unless we go to lower Z environments.

4. $\dot{M} - Z$ dependence - Are GRBs confined to low Z?

The issue of mass loss and evolution at low Z has gained attention due to the issue of the progenitors of long GRBs. Within Woosley's collapsar model, GRB progenitors require two key properties: (i) a rapidly rotating core, and (ii) the absence of a hydrogen envelope. Therefore, GRB progenitors are thought to be rotating WR stars. The potential problem with this is that WR star have high mass loss which should remove the angular momentum before the core collapses.

In the rapidly rotating stellar models of Yoon & Langer (2005), the objects evolve "quasi-homogeneously". The stars are subject to a strong magnetic coupling between the core and envelope. If the rapid rotation can be maintained due to low main-sequence mass loss in low Z galaxies, the objects may avoid slow-down in a red supergiant (RSG) or LBV phase, and directly become rapidly rotating WR stars. If the WR winds also depend on Fe driving (Vink & de Koter 2005), the WR stars can maintain rapid rotation towards the very end, making GRBs – but *only* at low Z.

GRB data presented at this meeting suggest that GRBs are not restricted to low Z, but there seems to be a need for a GRB channel at high Z. We have recently identified a sub-group of rotating Galactic WR stars – allowing for a potential solution to this problem (Vink *et al.* 2011b; Gräfener *et al.* 2012b). 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. We found this spinning sub-group to be surrounded by ejecta nebulae, which are thought to be ejected during a recent RSG/LBV phase, which suggests that these WR stars are still young and rotating.

If the core-surface coupling were strong enough, the cores would not be expected to rotate rapidly enough to make a GRB, but if the core-envelope coupling is less efficient, they may have the required angular momentum in their cores to make GRBs. In most high Z cases these stars would nonetheless still be expected to spin down due to mass loss, but within our post-RSG/LBV scenario one would not exclude the possibility of a high Z GRB. Yet, low Z environments are still preferred due to weaker WR winds.

5. $\dot{M} - T_{\rm eff}$ dependence - Do Luminous Blue Variables (LBVs) explode?

The stellar winds of O supergiants are fast ($\simeq$2000-4000 km/s) and transparent, whilst those emanating from lower $T_{\rm eff}$ B supergiants are much slower ($\simeq$100-1000 km/s). This is because O star winds are driven by high Fe ionization states, whilst those of B and later sub-types are driven by lower ones. This is wind bi-stability (BS).

LBVs increase their radii continuously on timescales of $\sim$10 yrs. These S Dor excursion across the HR diagram lead to winds with variable v_∞ and $\dot{M}$. If the LBV wind changes instantaneously at the BS-jump, we can explain the double-troughed Hα absorptions seen in LBV spectra (Groh & Vink 2011). Intriguingly such double-troughed Hα line profiles have also been seen in the luminous IIn SN 2005gj, which was for this reason suggested to have an LBV progenitor (Trundle *et al.* 2008). The same BS jump was also used to first suggest the LBV-SNe II link (Kotak & Vink 2006).

Even if $\dot{M}$ varies as a result of LBV radius changes, we still do not understand *why* LBVs change their radii (see Vink 2009 for a recent review). One possibility would be that the sub-photospheric outer envelopes of the stars become "inflated" as a result of the proximity to the Eddington limit (see Fig. 2). Ishii *et al.* (1999) first studied the

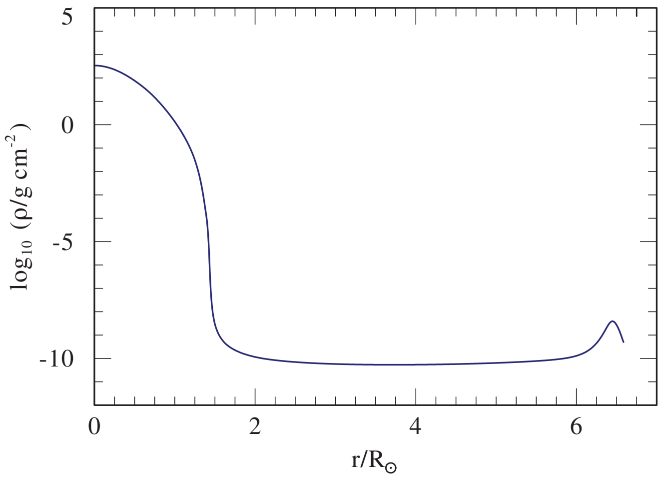

Figure 2. Density vs. radius for a $23 M_\odot$ helium model of Gräfener *et al.* (2012a) showing a density inversion. This leads to an inflation of the outer envelope.

outer envelope inflation from stellar evolution models, and in Gräfener *et al.* (2012a) we developed an analytic explanation for how such an envelope inflation would occur. We described the radial inflation as a function of a dimensionless parameter W, which largely depends on the topology of the Fe-opacity peak. For $W > 1$, we discovered an instability limit for which the stellar envelope becomes unbound. Within our framework, we are in principle able to explain LBV S Dor variations. Stellar temperatures could be strongly affected, and there could be important implications of the *radii* of WR and LBV progenitors prior to collapse, as SN with different sub-types II, SN Ibc, and GRBs.

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Discussion

Omukai: $300 M_\odot$ stars are unstable to pulsation by the epsilon mechanism. Did you include this effect in evaluating the mass-loss rate?

Vink: No, we didn't. The epsilon mechanism is thought to grow too slowly, and is usually not considered all that relevant.

Omukai: You said that the WR envelope has a density inversion during the inflation phase. Is it hydrodynamically stable?

Vink: The Gräfener *et al.* (2012) models are static, and until we have studied the hydrodynamic case we cannot be 100% sure. However, the suggested structure might not be all that unstable. Note that there is a lot of supporting radiation pressure!

Kulkarni: Angular momentum will only be efficiently removed from a mass-losing star if the core is coupled to the envelope. Could you comment on our current understanding of this coupling?

Vink: There is a debate regarding the magnetic coupling of the core and the envelope. Some massive star evolution modellers include magnetic fields, which results in a strong core-envelope coupling (e.g. Brott *et al.* 2011, *A&A* 530, 115), as this seems to be favoured when regarding the spins of neutron stars (Langer/Bonn argument). The Geneva models do not include magnetic fields, leading to less coupling.

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