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Pre-supernova mass loss predictions for massive stars

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Abstract. Massive stars and supernovae (SNe) have a huge impact on their environment. Despite their importance, a comprehensive knowledge of which massive stars produce which SNe is hitherto lacking. We use a Monte Carlo method to predict the mass-loss rates of massive stars in the Hertzsprung-Russell Diagram (HRD) covering all phases from the OB main sequence, the unstable Luminous Blue Variable (LBV) stage, to the final Wolf-Rayet (WR) phase. Although WR produce their own metals, a strong dependence of the mass-loss rate on the initial iron abundance is found at sub-solar metallicities (1/10 – 1/100 solar). This may present a viable mechanism to prevent the loss of angular momentum by stellar winds, which could inhibit GRBs occurring at solar metallicities – providing a significant boost to the collapsar model. Furthermore, we discuss recently reported quasi-sinusoidal modulations in the radio lightcurves of SNe 2001ig and 2003bg. We show that both the sinusoidal behaviour and the recurrence timescale of these modulations are consistent with the predicted mass-loss behaviour of LBVs. We discuss potential ramifications for the "Conti" scenario for massive star evolution.

1. Introduction

Massive stars have a huge influence on their environments via stellar winds and their final explosions. However, we currently do not know with any degree of certainty, which massive stars produce which type of supernova (SN). The evolution of a massive star ($M > 40\ M_\odot$) is generally believed to be *driven* by mass loss, as described in the "Conti" scenario: O → Luminous Blue Variable (LBV) → Wolf-Rayet (WR) star (Maeder, this meeting), where the WR stars include both nitrogen-rich (WN) and carbon-rich (WC) stars.

Mass loss determines the stellar mass before collapse and is thus relevant for the type of compact remnant that is left behind (i.e. neutron star or black hole). This process is expected to depend on the metal content (Z) of the host galaxy (e.g. Eldridge & Vink 2006). Furthermore, as WR stars are the likely progenitors of long-duration gamma-ray bursts (GRBs), the strength of WR winds as a function of Z is especially relevant for setting the threshold Z for forming GRBs.

Given the crucial role that mass-loss plays for massive star evolution, we have computed mass-loss rates using a Monte Carlo method, described in Abbott & Lucy

(1985), de Koter et al. (1997) and Vink et al. (1999). We discuss the predictions in Sects. 2-4 in order of decreasing temperature: WR stars → OB supergiants → LBVs. In Sects. 5 and 6, we link our mass-loss predictions with certain types of radio SNe. Conclusions and outlook are in Sect. 7.

2. Wolf-Rayet mass-loss rates as a function of metal content

In recent years, it has become clear that gamma-ray bursts (GRBs) are associated with the final explosion of a massive star, providing enormous impetus to the collapsar model (MacFadyen & Woosley 1999). The model works best if the progenitor fulfils two criteria: (i) the absence of a thick hydrogen envelope (so that the jet can emerge), and (ii) rapid rotation of the core (so that a disk can form). This may point towards a rapidly rotating WR star.

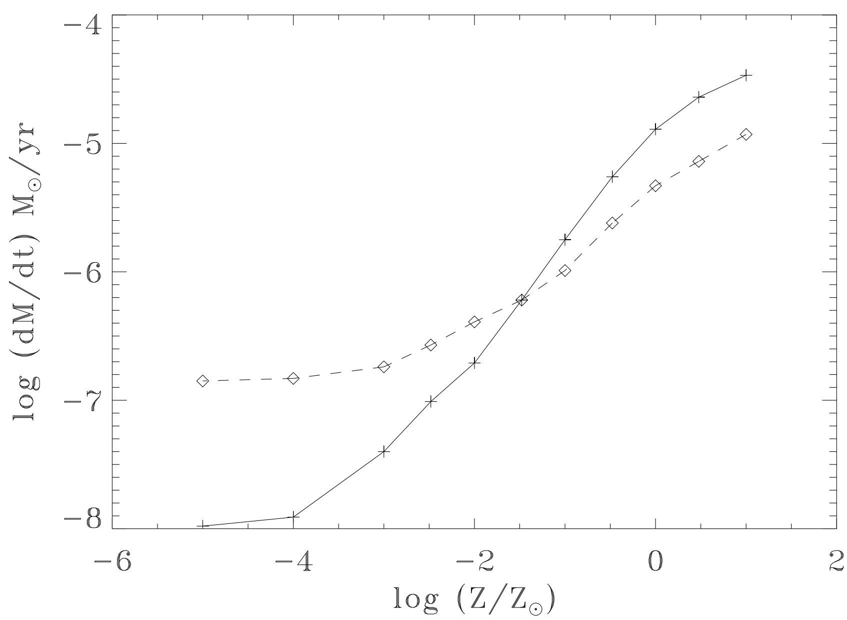

Figure 1. Mass loss versus initial Z for late-type WN stars (solid line) and WC stars (dashed line). Note that self-enrichment is accounted for, but does not enter in our expression of Z. See Vink & de Koter (2005) for details.

In the so-called "Conti" scenario (Conti 1976), WR stars are the result of mass-loss during earlier evolutionary phases, while in a complementary scenario, the removal of the hydrogen envelope may be due to a companion. Recently, an alternative scenario for producing a GRB progenitor has gained popularity (Yoon & Langer 2005; Woosley & Heger 2006): when a star rotates rapidly, it may mix "quasi homogeneously", and evolve along a track that more or less coincides with the zero age main sequence. A problem for producing a GRB within this scenario however, is that the WR stars in the Galaxy possess strong winds, which may remove the angular momentum (Langer 1998), making it challenging, if not impossible, to produce a GRB at Galactic Z.

This however might not be an issue if WR winds are weaker at low Z, so the question is: "are the winds of WR stars Z-dependent?" and if so, "how strong is this dependence?" The dense winds of WR stars are likely driven by radiation pressure (Nugis & Lamers 2002; Gräfener & Hamann 2005), just like their less extreme O star counterparts, which have been known to be driven by radiation pressure since the early 1970s. This in itself need not necessarily imply that WR winds depend on metal content. WR stars produce copious amounts of metals such as carbon (in WC stars). If, on the one hand, these self-enriched elements dominate the driving (by their sheer number of particles), one would expect WR winds to be independent of their initial Z and the requirements of the collapsar model may never be met. If, on the other hand, iron (Fe) is largely responsible for the driving (as in O stars; Vink et al. 2001), WR winds might indeed be less efficient in low Z environments.

To address the question regarding the Z dependence of WR winds, Vink & de Koter (2005) computed mass-loss rates for late-type WN and WC stars as a function of the initial metal content (representative of the host galaxy). The results are shown in Fig. 1. For a discussion of the flattening in the mass-loss-Z dependence for initial metallicities below log $(Z/Z_{\odot}) = -2$ and potential consequences for the first stars (Pop III), the reader is referred to Vink (2006), but for the Z range down to log $(Z/Z_{\odot}) = -2$, the mass loss is found to drop steeply, as $\dot{M} \propto Z^{0.85}$, for the WN phase - where WR stars spend most of their time. This inefficiency of WR mass loss at subsolar Z may prevent the loss of stellar angular momentum, providing a boost to the collapsar model.

3. Mass loss from OB stars: absolute rates and the bi-stability jump

We switch from a discussion of mass-loss versus Z to a discussion of mass loss versus $T_{\rm eff}$. This is best described in terms of the wind efficiency number $\eta = (\dot{M} v_{\infty})/(L_{*}/c)$, a measure for the momentum transfer from the photons to the ions in the wind. Here v_{∞} is the terminal velocity of the outflow and L_{*} the luminosity of the star. Vink et al. (2000) computed wind models as a function of effective temperature as shown in Fig. 2. The overall behaviour is one of decreasing η with decreasing $T_{\rm eff}$ due to a growing mismatch between the wavelengths of the maximum opacity (in the UV) and the flux (moving to longer wavelengths). The behaviour reverses at the "bistability jump" (BSJ; e.g. Lamers et al. 1995), where η increases by a factor of 2-3, as Fe IV recombines to Fe III (Vink et al. 1999).

Recent mass-loss studies (Trundle & Lennon 2005; Crowther et al. 2006) have reconfirmed discrepancies between empirical mass-loss rates and predictions for B supergiants (Vink et al. 2000). Discrepancies have also been reported for O stars (Fullerton et al. 2006), and it is as yet unclear whether the reported discrepancies for B supergiants could be due to model assumptions (e.g. the neglect of wind clumping) or the physical reality of the BSJ. The most accurate way to derive $\dot{M}$ is believed to be through radio observations. Intriguingly, Benaglia et al. (2007) present empirical radio mass-loss rates as a function of effective temperature that show a similar behaviour to the mass-loss efficiency

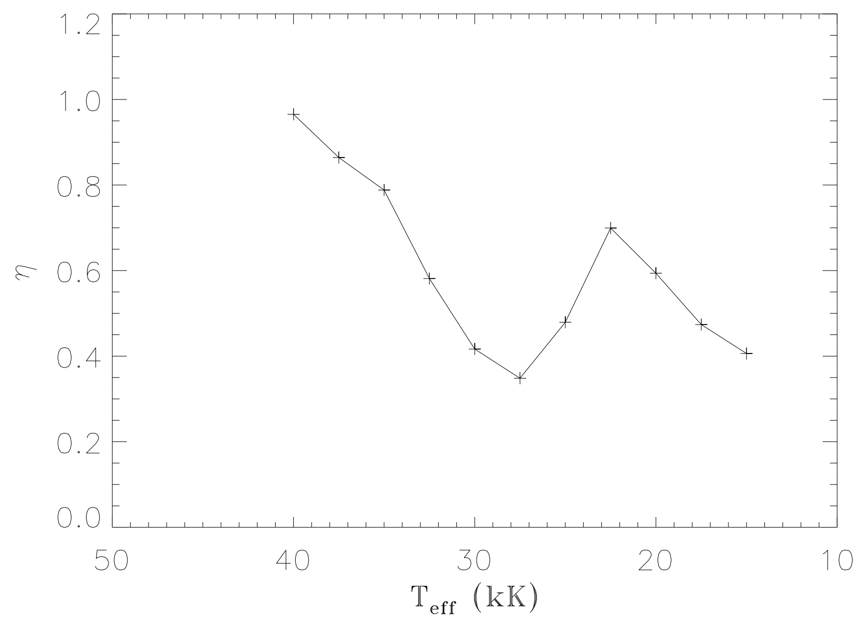

Figure 2. Wind efficiency $\eta = (\dot{M}v_\infty)/(L_*/c)$ as a function of effective temperature. These predictions are taken from Vink et al. (2000). Note the presence of the bistability jump around 25 kK, where η increases as Fe recombines to Fe III.

predicted by Vink et al. (2000). This may well be the first evidence of the presence of a mass-loss BSJ at the boundary between O and B supergiants. The relevance for stellar evolution is that when massive stars evolve to lower $T_{\rm eff}$ after the O star main sequence phase, they are expected to cross the BSJ. Interestingly, LBVs brighter than log $(L/L_\odot) = 5.8$ (see Fig. 3) are expected to encounter it continuously - on timescales of their photometric variability, which we discuss in the next section.

4. Mass loss from Luminous Blue Variables

LBVs are unstable massive stars in the upper part of the HRD (e.g. Humphreys & Davidson 1994). As can be seen in Fig. 3, the classical LBVs, like AG Car, are anticipated to cross the BSJ at $\sim 21\,000$ K. One of the defining characteristics for LBVs is their S Doradus (SD) variation of $\sim 1-2$ mag on timescales of years (short SD phases) to decades (long SD phases) (van Genderen 2001). Vink & de Koter (2002) computed LBV mass-loss rates as a function of $T_{\rm eff}$- shown in Fig. 4. Overplotted are the empirical mass-loss rates for AG Car (Stahl et al. 2001), which vary on the timescales of the photometric variability. Although the agreement is not perfect (see Vink & de Koter 2002, for a discussion), the amplitude of the predicted variability fits the observations well, and most importantly the overall behaviour appears to be very similar, and may indeed be explained in

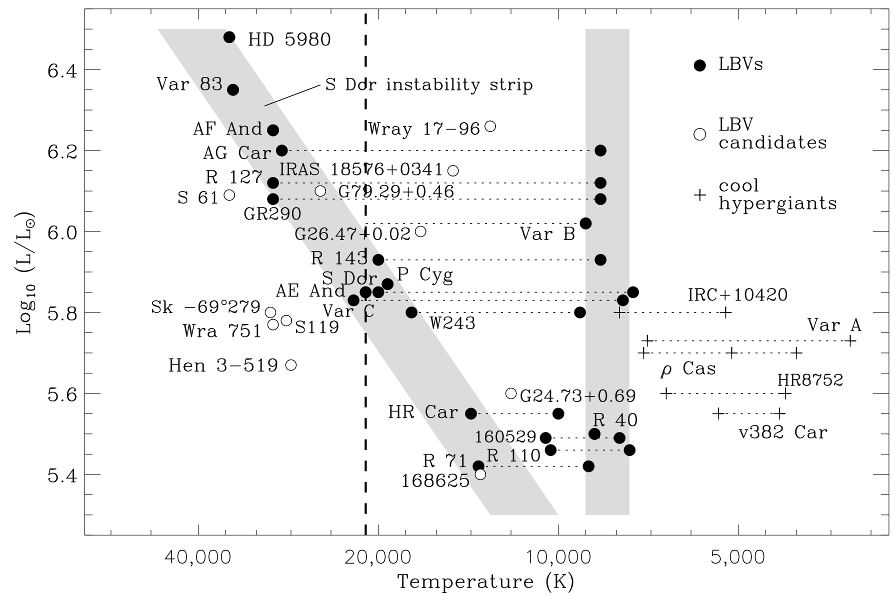

Figure 3. The LBVs in the HRD. The shaded areas represent the S Dor instability strip (diagonal) and the position of the LBVs during outburst (vertical). The dashed vertical line at 21 000 K indicates the bistability jump. Figure adapted from Smith et al. (2004).

terms of the physics of the BSJ. This bi-stable behaviour in an individual stellar wind (Pauldrach & Puls 1990) causes the star to flip back and forth between two states: that of a low mass loss, high-velocity wind, to a high mass-loss, low velocity wind. The wind density ($\propto \dot{M}/v_\infty$) would therefore be expected to change by a factor of $\sim$2 $\times$ $\sim$2, i.e. $\sim$4 on the timescale of the SD variations. In the absence of any other material around the star, this would result in a pattern of concentric shells of varying density.

5. Radio supernovae and progenitor mass loss

Radio SNe (RSNe) lightcurves and the model for SN interaction with the surrounding circumstellar material has been reviewed by Weiler et al. (1986), and is shown schematically in Fig. 5. The radio emission is due to non-thermal electrons, while the absorption may be due to both synchrotron self absorption as well as free-free absorption. Examples of the rise, peak, and power-law decline of radio lightcurves are shown in Fig. 6. (The episodic bumps at late time are discussed in Sect. 6.)

The model constrains the wind density and thus the ratio of $\dot{M}$ to the terminal wind velocity: $\rho \propto \dot{M}/v_\infty r^2$. Assuming v_∞, Weiler et al. (2002) list $\dot{M}$ values in the range 10^{-6}–10^{-4} $M_\odot \mathrm{yr}^{-1}$. Fortunately, these values agree with mass-loss predictions, but are broadly representative for massive stars over almost all post-main sequence evolutionary phases, making it hard to infer the

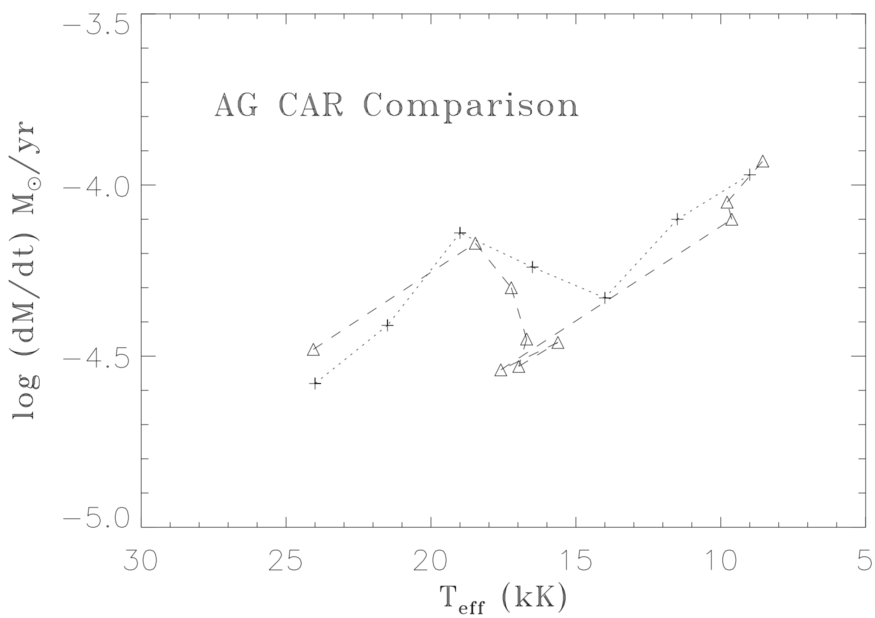

Figure 4. Predicted (dotted line) and empirical (dashed line) mass-loss rates versus $T_{\rm eff}$ for the LBV AG Car. Note that both the qualitative behaviour and the amplitude of the mass-loss variations are well reproduced. See Vink & de Koter (2002) for details.

progenitor from radio lightcurves alone, unless these lightcurves betray their progenitor in some other way.

6. Quasi-periodic oscillations in radio SNe lightcurves

A number of recent RSNe have shown sinusoidal modulations in their radio lightcurves, in particular SN 2001ig (Ryder et al. 2004) and SN 2003bg (Soderberg et al. 2006) are strikingly similar in terms of both amplitude and variability timescale (see Fig. 6). The recurrence timescale t of the bumps is $\sim$ 150 days. Using Eq. (13) from Weiler et al. (1986):

$$\Delta P \;=\; \frac{R_{\rm shell}}{v_{\rm wind}} \;=\; \frac{v_{\rm ejecta}\; t_{\rm i}}{v_{\rm wind}\; m} \left(\frac{t}{t_{\rm i}}\right)^{m} \qquad (1)$$

where m is the deceleration parameter (here m = 0.85) and $t_{\rm i}$ is the time of measurement of the ejecta velocity relative to the moment of the explosion. Assuming $v_{\rm wind}$ = 10–20 km sec^{-1}, typical wind velocities for red (super)giants, Ryder et al. (2004) found a period P between successive mass-loss phases that was too long for red (super)giant pulsations (100s of days), but too short for thermal pulses (10^2–10^3 years). They therefore invoked an edge-on, eccentric binary scenario involving a WR-star and a massive companion. One of the main differences between LBV and red giant winds is that LBV winds are about 10

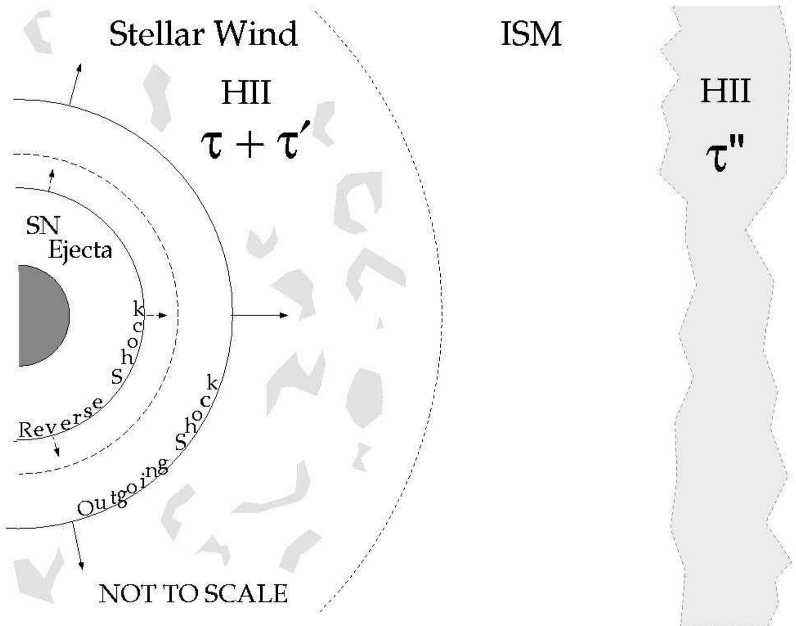

Figure 5. Model for SN ejecta interaction with the progenitor's wind. The radio emission arises at the interface between the outgoing shock and the most recent stellar wind. The various optical depth (τ, τ', τ'') contributions are respectively from a smooth wind, a clumped wind and a potential intervening H II region. Taken from Weiler et al. (2002).

times faster. If the progenitor of SN 2001ig were an LBV, the expected period between successive mass-loss episodes would be $\Delta P \sim 25\,\mathrm{yr}$ (for an assumed $v_{\rm wind} = 200\,\mathrm{km\,sec}^{-1}$), consistent with the long SD phase (Kotak & Vink 2006).

Soderberg et al. (2006) infer density enhancements of a factor of $\sim$2 during the deviations from pure power-law evolution. They consider a range of options that might account for the modulations, but they favour a single-star progenitor model of a WR star that underwent episodes of intensified mass loss. However, they do not specify the physical mechanism that gives rise to these periods of enhanced mass loss. Our SD mechanism for LBVs may alleviate this shortcoming.

7. Discussion: do LBVs explode?

Are LBVs viable SNe progenitors? It may be relevant that both SNe 2001ig and 2003bg are "transitional" objects. SN 2001ig was initially classified as type II (showing H lines) but metamorphosed into a type Ib/c object (no H lines, weak He lines) about 9 months later. This suggests that it has lost most of its H-rich envelope. SN 2003bg however was first classified as a type Ic, but within a month the spectrum evolved into a type II SN. This transitional behaviour hints at the fact that their progenitors are intermediate evolutionary objects:

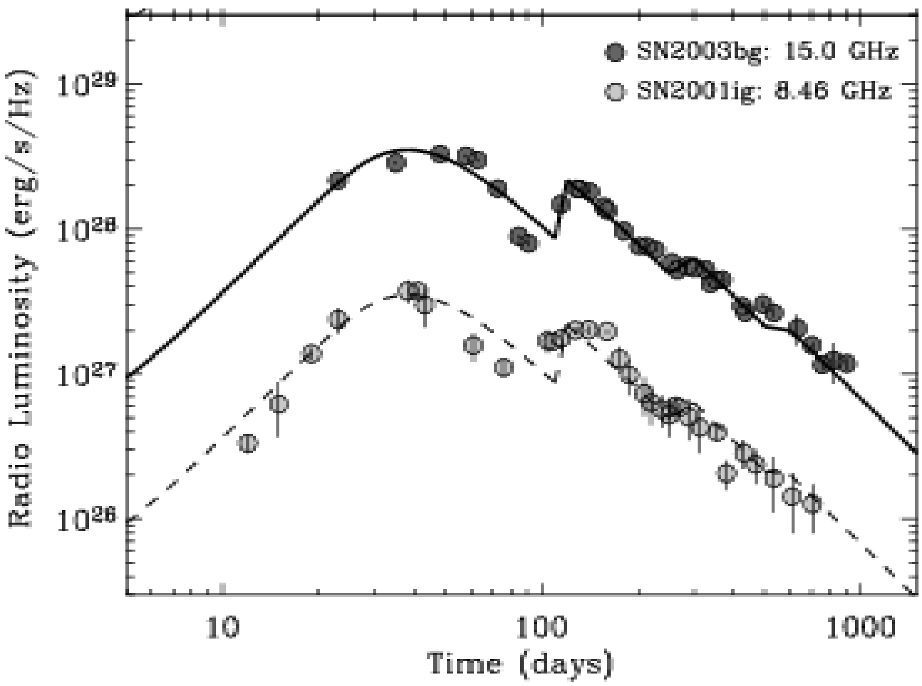

Figure 6. Radio luminosity versus time for two strikingly similar recent SNe: 2001ig and 2003bg. Note the quasi-sinusoidal modulations during the power-law decline phase. Taken from Soderberg et al. (2006).

H-rich compared to OB/red (super)giants, but H-poor compared to WR stars. LBVs are likely candidates.

During this meeting, there was discussion about clumping in O star winds. The value for the clumping factor in O star winds is very much an open issue. If these factors would be much larger than two, this would have severe implications for massive star evolution. One consequence might be that giant LBV eruptions (η Car type eruptions, not the typifying SD variations) dominate the integrated mass loss during evolution (Smith 2006). An alternative scenario could be that post-main sequence stars do not become WR stars, but explode early – during their LBV phase.

Here, we have presented indications that at least those SNe that show quasi-periodic modulations in their radio lightcurves might have LBV progenitors (Kotak & Vink 2006). It has also been speculated that LBVs may be the generic progenitors of type IIn SNe (**?**), however the type IIn phenomenon (arising from SN ejecta expanding into dense circumstellar matter) may be relevant to both core-collapse and thermonuclear SNe (Kotak et al. 2004), and although it may be reasonable to expect that some type IIn SNe have LBV progenitors, there remains a lot of work to be done to prove this. Nonetheless, it appears that the "standard scenario" for massive star evolution may need revision. Future mass-loss predictions will certainly play a major role in adjusting even our most basic knowledge of massive star evolution.

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