Eruptive Mass Loss in Very Massive Stars and Population III Stars

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I discuss the role played by short-duration eruptive mass loss in the evolution of very massive stars. Giant eruptions of Luminous Blue Variables (LBVs) like the 19th century event of η Carinae can remove large quantities of mass almost instantaneously, making them significant in stellar evolution. They can potentially remove much more mass from the star than line-driven winds, especially if stellar winds are highly clumped such that previous estimates of O star mass-loss rates need to be revised downward. When seen in other galaxies as “supernova impostors”, these LBV eruptions typically last for less than a decade, and they can remove of order 10 M⊙ as indicated by massive nebulae around LBVs. Such extreme mass-loss rates cannot be driven by radiation pressure on spectral lines, because the lines will completely saturate during the events. Instead, these outbursts must either be continuum-driven super-Eddington winds or outright hydrodynamic explosions, both of which are insensitive to metallicity. As such, this eruptive mode of mass loss could also play a pivotal role in the evolution and ultimate fate of massive metal-poor stars in the early universe. If they occur in these Population III stars, such eruptions would also profoundly affect the chemical yield and types of remnants from early supernovae and hypernovae thought to be the origin of long gamma ray bursts.

1. Introduction

Mass loss is a critical factor in the evolution of a massive star. In addition to the direct reduction of a star’s mass, it profoundly affects the size of its convective core, its core temperature, its angular momentum evolution, its luminosity as a function of time, and hence its evolutionary track on the HR diagram and its main-sequence (MS) lifetime (e.g., Chiosi & Maeder 1986). Wolf-Rayet (WR) stars are thought to be the descendants of massive stars as a consequence of mass loss in the preceding H-burning phases, during which the star sheds its H envelope (Abbott & Conti 1987; Crowther 2006). While the maximum initial mass of stars is thought to be ~150 M⊙ (Figer 2005; Kroupa 2005), WR stars do not have masses much in excess of 20 M⊙ (Crowther et al. 1995); thus, very massive stars have the immense burden of removing 30–130 M⊙ during their lifetime before the WR phase, unless they explode first. Stellar evolution calculations prescribe ˙M(t) based on semiempirical values, so we need to know when this mass loss occurs.

The main question I wish to address here is whether the majority of mass lost during the lifetime of the most massive stars occurs primarily via steady line-driven stellar winds, or instead through violent, short-duration eruptions or explosions. The two extremes are shown graphically in Figure 1. This question is critical for understanding how mass loss scales with metallicity, back to the time of the massive stars in the early Universe. In this contribution I would like to draw attention to the specific role of LBV eruptions, advocating for their importance. The essential points of the argument are the following:

- Recent studies of hot star winds indicate that mass-loss rates on the MS are probably much lower than previously thought due to the effects of clumping in the wind. If so,
then for the most massive stars, the revised mass-loss rates are inadequate to reduce the star’s mass enough to reach the WR phase, where the H-rich envelope has been removed and the He-rich core material is exposed. Something other than the O-star’s line-driven wind must account for this mass loss.

- Observations of nebulae around luminous blue variables (LBVs) and LBV candidates have revealed very high ejecta masses – of order 10 $M_\odot$. In some objects, there is evidence for multiple shell ejections on timescales of $10^3$ years. Cumulatively, these sequential eruptions could, in principle, remove a large fraction of the total mass of the star. Thus, a few short-duration outbursts like the 19th century eruption of $\eta$ Car could dominate mass lost during the lives of the most massive stars, and would be critical for the envelope shedding needed to form WR stars at any metallicity.

- The extreme mass-loss rates of these LBV bursts imply that line opacity is too saturated to drive them, so they must instead be either continuum-driven super-Eddington winds (see Owocki et al. 2004) or outright hydrodynamic explosions. Unlike steady winds driven by lines, the driving in these eruptions may be largely independent of metallicity, and might play a role in the mass loss of massive metal-poor stars (Population III stars).

These points have already been explained and justified in more detail by Smith & Owocki (2006), where more complete references can be found. That original paper was deliberately provocative, and some caveats had to be left out for the sake of brevity. Rather than repeat that discussion, I will briefly elaborate on a few of these issues, and will spend most of the time discussing alternatives and further implications.

### 2. The Problem: Line-Driven Winds Provide Insufficient Mass Loss

In order to shed a massive star’s envelope and reach the WR stage, models must prescribe semiempirical mass-loss rates, which can be scaled by a star’s metallicity (e.g., Chiosi & Maeder 1986; Maeder & Meynet 1994; Meynet et al. 1994; Langer et al. 1994; Langer 1997; Heger et al. 2003). Often-adopted “standard” mass-loss rates are given by de Jager et al. (1988), and Nieuwenhuijzen & de Jager (1990). In order for stellar evolution models to match observed properties at the end of H burning, such as WR masses and luminosities, and the relative numbers of WR and OB stars, these mass-loss rates need to be enhanced by factors of $\sim 2$ (Maeder & Meynet 1994; Meynet et al. 1994).

However, such enhanced mass-loss rates contradict observations. Recent studies suggest that mass-loss rates are in fact 3–10 or more times lower than the “standard” mass-loss rates, not higher. This is due to the influence of clumping in the winds (Fullerton et al. 2006; Bouret et al. 2005; Puls et al. 2006; Crowther et al. 2002; Hillier et al. 2003; Massa et al. 2003; Evans et al. 2004; Kudritzki & Urbaneja in these proceedings), such that mass-loss rates based on density-squared diagnostics like Hα and free-free radio continuum emission have led to overestimates if the wind is strongly clumped. The consequent reduced mass-loss rates mean that steady winds are simply inadequate for the envelope shedding needed to form a WR star. This is not such a problem for stars below $10^{5.8} L_\odot$, where the red supergiant (RSG) wind may be sufficient. However, above $10^{5.8} L_\odot$ (initial mass above 40–50 $M_\odot$) stars do not become RSGs (Humphreys & Davidson 1979), posing a severe problem if these stars depend upon line-driven winds for mass loss.

For example, consider the fate of a star with initial mass of 120 $M_\odot$. The most extreme O2 Ib supergiant HD93129A has a mass-loss rate derived assuming a homogeneous wind of roughly $2 \times 10^{-5} M_\odot$ yr$^{-1}$ (Repolust et al. 2004). If the true mass-loss rate is lower by a factor of 3–10 or more as indicated by clumping in the wind, then during a $\sim 2.5$ Myr MS lifetime (Maeder & Meynet 1994), the star will only shed about 5–20 $M_\odot$, leaving it with $M > 100 M_\odot$, and an additional 80 $M_\odot$ deficit to shake off before becoming a WR
Figure 1. These plots are schematic representations of a star’s mass as a function of time. Two extreme scenarios are shown: One has higher conventional O-star mass-loss rates assuming homogeneous winds on the main-sequence (MS) with no clumping. This is followed by a brief LBV wind phase and a longer WR wind phase before finally exploding as a supernova; this is the type of scenario usually adopted in stellar evolution calculations. The second has much reduced mass-loss rates on the main sequence (assuming clumping factors of 4–6), followed by an LBV phase that includes severe mass loss in several brief eruptions plus a steady wind in the time between them; this is the type of scenario discussed by Smith & Owocki (2006). Panel (a) shows the case for an initial stellar mass of 120 \( M_\odot \) (appropriate for a luminous LBV like AG Carinae), and Panel (b) shows an initial mass of 60 \( M_\odot \) (appropriate for a somewhat less luminous object like P Cygni, perhaps). The more numerous, more frequent, and less extreme eruptions of the 60 \( M_\odot \) scenario assume that the mass lost in an LBV burst may scale with proximity to the Eddington limit. Note that the clumping factors of 4–6 shown here are still fairly modest compared to some estimates of >10 for O-star winds.

star. After this, the stellar wind mass-loss rates are higher during post-MS phases, but they are still insufficient to form a WR star. They therefore cannot make up for the lower \( \dot{M} \) values on the MS. For a typical LBV lifetime of a few \( 10^4–10^5 \) yr (Bohannan 1997) and a typical \( \dot{M} \) of \( \sim 10^{-4} M_\odot \) yr\(^{-1} \) for most LBVs, the LBV phase will only shed a few
additional solar masses through its line-driven wind. Thus, some mechanism other than just a steady wind is needed to reduce the star's total mass by several dozen $M_\odot$.

3. Balancing the Budget: LBV Eruptions

The most likely mechanism to rectify this hefty mass deficit is giant eruptions of LBVs (e.g., Davidson 1989; Humphreys & Davidson 1994; Humphreys, Davidson, & Smith 1999; Smith & Owocki 2006), where the mass-loss rate and bolometric luminosity of the star increase substantially. While we do not yet fully understand what causes these giant LBV outbursts, we know empirically that they do indeed occur, and that they drive substantial mass off the star. Deduced masses of LBV and LBV-candidate nebulae from the literature are plotted in Figure 2 as a function of the central star's luminosity. We see that for stars with $\log(L/L_\odot)>6$, nebular masses of 10 $M_\odot$ are quite reasonable, perhaps suggesting that this is a typical mass ejected in a giant LBV eruption.

If such large masses are typical for LBV outbursts, then only a few such eruptions occurring sequentially during the LBV phase are needed to remove a large fraction of the star's total mass. This is shown schematically in Figure 1 for stars with initial masses of 120 and 60 $M_\odot$. Notice that in the 60 $M_\odot$ example, the LBV eruptions are more numerous and each one is less massive than in the 120 $M_\odot$ case; this is entirely hypothetical, but is based on the presumption that a more massive and more luminous star will have more violent mass ejections because of its closer proximity to the Eddington limit. For
example, we might expect that \( \eta \) Car currently has an Eddington parameter of \( \Gamma = 0.9 \) or higher, whereas a less luminous LBV like P Cygni probably has \( \Gamma = 0.5 \) or so. Further investigation of the amount of mass ejected in each burst, and their frequency and total number is probably the most important observational pursuit associated with LBVs and their role in stellar evolution.

Our best example of this phenomenon is the 19th century “Great Eruption” of \( \eta \) Carinae. The event was observed visually, the mass of the resulting nebula has been measured (12–20 \( M_\odot \) or more; Smith et al. 2003), and proper motion measurements of the expanding nebula indicate that it was ejected in the 19th century event (e.g., Morse et al. 2001). The other example for which this is true is the 1600 AD eruption of P Cygni, although its shell nebula has a much lower mass (Smith & Hartigan 2006). Both \( \eta \) Car and P Cyg are surrounded by multiple, nested shells indicating previous outbursts (e.g., Walborn 1976; Meaburn 2001). While the shell of P Cyg is less massive than \( \eta \) Car’s nebula, it is still evident that P Cyg shed more mass in such bursts than via its stellar wind in the time between them (Smith & Hartigan 2006). This difference between P Cyg and \( \eta \) Car hints that LBV outbursts do indeed become progressively more extreme near the Eddington limit. However, the Homunculus and the Little Homunculus around \( \eta \) Car also caution that any one star can eject very different amounts of mass in each of its subsequent eruptions, with a corresponding wide range of luminous and kinetic energy.

Although LBV eruptions are rare, a number of extragalactic \( \eta \) Car analogs or “supernova impostors” have been observed, such as SN1954J in NGC2403 and SN1961V in NGC1058 (Humphreys et al. 1999; Smith et al. 2001; Van Dyk et al. 2002, 2005), V1 in NGC2363 (Drissen et al. 1997), and several recent events seen as type IIn supernovae, like SN1997bs, SN2000ch, SN2002kg, and SN2003gm (Van Dyk et al. 2000, 2006; Wagner et al. 2004; Maund et al. 2006). Furthermore, massive circumstellar shells have also been inferred to exist around supernovae and gamma-ray bursters (GRBs). Some examples are the radio-bright SN1988Z with a nebula as massive as 15 \( M_\odot \) (Aretxaga et al. 1999; Van Dyk et al. 1993; Chugai & Danziger 1994), as well as similar dense shells around SN2001em (Chugai & Chevalier 2006), SN1994W (Chugai et al. 2004), SN1998S (Gerardy et al. 2002), SN2001ig (Ryder et al. 2004), GRB021004 (Mirabal et al. 2003), and GRB050505 (Berger et al. 2005).

These outbursts and the existence of massive circumstellar nebulae indicate that the 19th century eruption of \( \eta \) Car is not an isolated, freakish event, but instead may represent a common rite of passage in the late evolution of the most massive stars. A massive ejection event may even initiate the LBV phase, by lowering the star’s mass, raising its L/M ratio, and drawing it closer to instability associated with an opacity-modified Eddington limit (Appenzeller 1986; Davidson 1989; Lamers & Fitzpatrick 1988; Humphreys & Davidson 1994). Mass loss in these giant eruptions may play a role in massive star evolution analogous to thermal pulses of asymptotic giant branch stars. In any case, meager mass-loss rates through stellar winds, followed by huge bursts of mass loss in violent eruptions at the end of core-H burning (see Fig. 1) may significantly alter stellar evolution models.

### 4. Alternative Scenarios

The scenario where LBV eruptions dominate the mass loss of the most massive stars, as shown in Figure 1, would represent a dramatic change in our understanding of mass loss in stellar evolution. Therefore, it certainly deserves close scrutiny, and it is worth considering some possible alternatives or modifications.

First, however, I would like to emphasize that the scenario in which homogeneous line-
driven winds of O stars dominate the mass lost during the life of a star is almost certainly wrong. There are two independent reasons to think so.

This need for recognizing the role of LBV eruptions in mass loss is partly motivated by recent studies of the mass-loss rates of O stars, where clumping in the winds suggests rather drastic reductions in the MS mass-loss rates. To be fair, the required amount of reduction in mass-loss rates is not yet settled; some indications favor reduction of more than an order of magnitude, while other estimates are more moderate, indicating factors...
of only a few. While this is debated, it is worth remembering that even if the mass-loss rate reduction is only a factor of 3, it would still indicate that LBV eruptions may dominate the total mass lost during the lifetime of a very massive star. Note that the plots in Figure 2 adopt fairly modest mass-loss rate reduction factors of only 4–6.

However, clumping in O-star winds is only part of the story. The other part is the observational reality that LBV eruptions like η Car’s massive 19th century outburst do indeed occur, and we have evidence that they occur more than once, ejecting a mass of order 10 M⊙ each time. A star’s mass budget needs to allow for that. However, if we require several 10’s of solar masses in LBV eruptions, plus enhanced mass loss during a WNL phase (see below), we run into a serious problem — homogeneous winds simply do not allow enough room for additional mass loss through WNL phases and LBV eruptions! Thus, the mass-loss rates implied by the assumption of homogeneous winds are not viable. I would then suggest that the existence of WNL and LBV mass loss is an independent argument that O star winds must be clumped, reducing their mass-loss rates by at least a factor of 2–3.

Nevertheless, the provocative new scenario in Figure 1 may still seem a bit extreme, placing a huge and possibly unrealistic burden on LBV eruptions. The truth may lie somewhere in between, so let’s consider two likely alternatives.

### 4.1. A Long WNL Phase?

One alternative is that a very massive star spends a good fraction of its H-burning MS lifetime as a late-type WN star (WNL; see Crowther et al. 1995). Even if their winds are clumped, WNL stars have much higher mass-loss rates than their O star counterparts. Thus, if it is possible that massive stars spend something like a third or half of their MS lifetime as a WNL star, they can take a substantial chunk out of the star’s total mass. This could temper the burden placed upon LBVs. This scenario is sketched in Figure 3a. While Figure 3a seems reasonable (even likely) to me, there are a few caveats to keep in mind.

First, Figure 3a with its rather long WNL phase could only apply to the very most freakishly massive stars, with initial masses above roughly 90–100 M⊙. The justification for this comment is that spectral type O3 and even O2 stars still exist in clusters within star forming regions that are 2.5–3 Myr old (like Tr16 in the Carina Nebula). O3 stars probably have initial masses around 80–100 M⊙ or so, and MS lifetimes around 3 Myr. Therefore, these stars cannot spend a substantial fraction of their H-burning lifetime as a WNL star, because they evidently live for about 3 Myr without yet reaching the WNL phase. Only for the most massive stars, which are even more extremely rare, might a relatively long WNL phase be possible. This makes me wonder if we have yet another a dichotomy in stellar evolution, with very different evolutionary sequences above and below 100–120 M⊙ – much like the dichotomy above and below 45–50 M⊙. One could certainly make the case that the most luminous evolved stars that are sometimes called LBVs or LBV candidates – stars like η Car, the Pistol star, HD5980, and possibly LBV 1806-20 – have followed a different path than the “normal” LBVs like AG Car and R127.

Second, I would suggest that while WNL stars may make some contribution to the mass loss at the highest luminosities, their influence must be limited. They cannot provide the majority of mass lost by these stars, so the LBV eruption mass loss must still dominate. The reasoning behind this comment has to do with the available mass budget of η Carinae; namely, that η Car is probably a post-WNL star, but it still has retained most of its original mass.

Let’s remember that η Car is the most luminous and most evolved member of a rich
Figure 4. Same as Figures 1 and 3, but for a star with an initial mass at the upper mass limit of 150 M☉, perhaps appropriate for η Carinae. Here I show what the mass evolution might look like for a relatively short (small contribution) and a relatively long (dominant contribution) WNL phase, as well as the simpler extremes with a strong MS wind, as well as LBV eruptions with no WNL phase in gray. The dot shows the likely currently-observed locus of η Carinae (note that I am being quite generous here with the correction for η Car’s companion star). Considering that we know η Car has already suffered 2–3 major LBV eruptions, which scenario is most consistent with its present mass?

region containing over 65 O-type stars, as well as 3 WNL stars (see Smith 2006). It is fair to assume that the current LBV phase of η Car is not only a post-MS phase, but probably also a post-WNL phase, since its ejecta are more nitrogen rich than the WNL stars in Carina. It is also safe to assume that η Car has advanced further in its evolution sooner than the WNL stars of the same age in this region simply because it is more luminous and started with a higher initial mass. Now, η Car is seen today surviving as a very massive star of around 100 M☉ or more, and we measure a total of something like 20-35 M☉ in its circumstellar material ejected in only the last few thousand years (the Homunculus, plus more extended outer material; see Smith et al. 2003, 2005). That means η Car began its LBV phase – and ended its MS and/or WNL phase – with more than 120 M☉ still bound to the star!† If there really is an upper limit of about 150 M☉ to the mass of stars, then this rules out the possibility that winds during the MS or WNL phases could dominate the mass-lost by the star in its lifetime. Consequently, it also requires that the MS and WNL winds were indeed highly clumped. If folks don’t like relying on just η Car because it is an abomination, there’s the Pistol star, which is also a post-MS object and has a present-day mass that probably exceeds 100 M☉.

This argument is made graphically in Figure 4, where options of “long” and “short” WNL phases are shown. Keeping three facts in mind — 1) that we see more than 20 M☉ of nebular material from recent LBV eruptions around η Car, 2) that η Car has a present

† Parameters could be chosen selectively to push this as low as perhaps 100–105 M☉, but not lower).
day mass around 100 \( M_\odot \) if it is not violating the classical Eddington limit (I am being generous with the companion star’s mass in Figure 4), and 3) that there is a likely upper mass limit for stars of around 150 \( M_\odot \) — where would you place \( \eta \) Carinae on each track in Figure 4? What does that signify for the relative importance of the WNL phase?

4.2. An Early Death at the End of the LBV Phase?

The main motivation for such huge amounts of mass loss in continuum-driven LBV eruptions is the assumption that even the most massive stars eventually reach the WR phase, requiring that their mass be reduced down to about 20 \( M_\odot \) before that point (see Smith & Owocki 2006). If we can relax this constraint and say that the most massive stars above 100 \( M_\odot \) perhaps do not make it to the WR phase, then we can alleviate the burden of removing so much mass through LBV explosions. This would be saying that the most massive stars might undergo core collapse at the end of the LBV phase, instead of entering the WR phase (Figure 3b).

That is easy to say and it would seem to fix the uncomfortable problem of depending on LBVs for such drastic mass shedding. However, we should be mindful that this alternative would require an even more radical paradigm shift in our understanding of stellar evolution than Figure 1a. Namely, Figure 3b would require that not only are LBVs in a core He burning phase†, but that LBVs even reach advanced stages like core O and Si burning. Current understanding implies that LBVs have not yet reached He burning.

On the other hand, perhaps an early supernova explosion during the LBV phase is not crazy after all, since we really don’t know what is going on deep inside the star. In fact, there are several reasons why an early explosion like in Figure 3b might be attractive:

- As noted earlier in §3, several observations of supernovae (especially Type IIn supernovae) and GRBs reveal that they have dense, massive circumstellar shells close to the star. In their talks at this meeting, H.-W. Chen and D. Fox noted additional examples of GRBs with dense (\( \sim 10^6 \text{ cm}^{-3} \)) circumstellar shells seen in absorption spectra of afterglows. In some cases these closely resemble the absorption features in the shell around \( \eta \) Car (T. Gull, these proceedings). Where did these compact and dense circumstellar shells come from if the WR phase has a sustained fast wind for a few \( 10^5 \) years? The answer may be that these shells did in fact originate in LBV-like outbursts that occurred within about 1000 years of the final death of the star. That would be astonishing and very important if true.

- So far, I don’t know any example of a bona-fide WR star that is surrounded by an extremely massive (like \( \sim 50 \, M_\odot \)) group of nested shells left over from a previous LBV phase. Perhaps such objects would be rare anyway and don’t last long in an observable phase like this, but it would be reassuring to see at least one example. If the most massive stars explode at the end of the LBV phase, then we wouldn’t necessarily expect such massive shells around any WR star.

- Oxygen burning is unstable, and as noted by A. Heger in his talk, can lead to short pulsational bursts that may supply sufficient mechanical energy to power an eruption like \( \eta \) Car’s 19th century event with \( \sim 10^{50} \) ergs. The problem with this scenario, though, is that the duration of O burning is extremely short and could not account for the observational fact that \( \eta \) Car-like eruptions tend to recur on timescales of \( \sim 10^3 \) years. These O-burning blasts could only account for a last hurrah right before the star’s final demise...but the possibility is interesting anyway.

In any case, an explosion at the end of the LBV phase when the star is still very massive would almost certainly form a black hole, and this should happen in roughly 3 Myr. Are

† In fact, they must have reached it before the LBV phase, because the LBV phase is so short.
there any examples of massive black holes in massive star clusters? If so, where are the expanding supernova remnants from these events? If this scenario were true, of course, it would mean that η Carinae and stars like it in other galaxies may explode as hypernovae at any moment. This would be good for my chances of getting future observing proposals accepted, but I assure the reader that this is not why I am mentioning the possibility.

4.3. Binaries…?

In addition to these two alternatives listed above, the potential role of close binaries – in particular, Roche Lobe Overflow (RLOF) – has been a glaring omission so far. In a wide variety of different scenarios depending on initial conditions, close binary evolution can modify a star’s mass (see, for example, Vanbeveren et al. 1998). Given the fact that most stars are binaries, this should be considered as well, but I don’t wish to get into this complex topic here. I would like to note, however, that like the continuum-driven mass loss in LBV eruptions, mass loss/transfer through RLOF will be relatively insensitive to metallicity compared to line-driven winds. Therefore, some of the comments in the next section apply to binary alternatives as well.

5. Potential Implications for the First Stars and their Environments

The first stars, which should have been metal free, are generally thought to have been predominantly massive, exhibiting a flatter initial mass function than stars at the present epoch (e.g., Bromm & Larson 2004; Bromm in these proceedings). With no metals, these stars should not have been able to launch line-driven winds, and thus, they are expected to have suffered no mass loss during their lifetimes. The lack of mass loss profoundly affects the star’s evolution and the type of supernova it eventually produces (Heger et al. 2003), as well as the yield of chemical elements from the first supernovae and hypernovae that seeded the early interstellar medium of galaxies.

This view rests upon the assumption that mass loss in massive stars at the present time is dominated by line-driven winds, for which $\dot{M}$ can be scaled smoothly with metallicity — but this assumption may be problematic in view of recent observational constraints. As discussed above, massive shells around LBVs and the so-called “supernova impostors” in other galaxies indicate that short-duration eruptions contribute substantially – and may even dominate – the mass loss of very massive stars, while steady, line-driven winds on the MS contribute little to the total mass lost during their lifetime. Unlike line-driven winds, the driving mechanism for these outbursts is probably insensitive to metallicity, as explained in more detail by Smith & Owocki (2006).

Since the trigger of LBV eruptions is still unidentified, one of course cannot yet claim confidently that these eruptions will in fact occur in the first stars. However, the possibility that they offer a way for low-metallicity stars to shed large amounts of mass compels us to consider their potential influence for stellar evolution of the first stars and their surroundings. Some potential consequences are listed here:

- If the first stars were able to shed large amounts mass through continuum-driven blasts at the end of MS evolution, then it could affect the type of explosion and the type of remnant the star leaves behind. Thus, the expected relative numbers of pair instability explosions compared to supernovae that produce black holes or neutron stars as their remnants will change. Very massive stars that lose enough mass may fall below the threshold for pair-instability supernovae, allowing much of their core metals to remain trapped inside a black hole or neutron star. This change, in turn, will seriously alter expectations for the chemical yield returned to the ISM by early supernovae, and would
affect the initial mass function (IMF) inferred from studies of very metal poor stars (e.g., J. Tumlinson, these proceedings).

- The early ISM of galaxies was very different than it is today. In the early universe, elements heavier than He recycled back into the ISM all came from massive stars. This is partly because of the IMF skewed to higher masses, but mostly because at early times, intermediate mass stars had not yet evolved off the main sequence to return C and O to the ISM as an AGB star. If the first stars were able to shed large amounts mass before exploding as supernovae, the ISM would have been profoundly affected. Namely, the pollution of the early ISM could have a substantial contribution of nitrogen-rich CNO ashes, since these massive stars were likely mixed and self-enriched due to rotation. In other words, the early ISM may have been similar to the N-rich material in circumstellar LBV shells seen today. This could significantly affect the dust content of the early ISM as well, especially for the generation of stars immediately following the first stars.

- Continuum-driven blasts at the end of MS evolution might enable the first stars to reach and pass through a WR phase. In that case, the self-enrichment of CNO products in WR atmospheres would likely allow them to have line-driven winds, providing even further mass loss (Vink & de Koter 2005; Eldridge & Vink 2006). In addition to giving us further complications in determining the end product of stellar evolution for Population III stars (pair instability, BH, NS), the existence of a WR phase in the first stars would affect the mechanical energy of the surrounding ISM and would contribute additional N and C, not to mention affecting the immediate circumstellar environment into which a GRB shock expands.

In short, if mass loss of massive stars at the present epoch is dominated by mechanisms that are insensitive to metallicity, then we must question the prevalent notion that the first stars did not lose substantial mass prior to their final supernova event. If these outbursts can occur at low metallicity, it would profoundly alter our understanding of the evolution of the first stars and their role in early galaxies.

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REFERENCES

Abbott, D.C., & Conti, P.S. 1987, ARAA, 25, 113
Appenzeller, I. 1986, IAU Symp. 116, 139
Aretxaga, I., et al. 1999, MNRAS, 309, 343
Berger et al. 2005, astro-ph/0511498
Bohannan, B. 1997, in ASP Conf. Ser. 120, 3
Bouret, J.C., Lanz, T., & Hillier, D.J. 2005, A&A, 438, 301
Bromm, V., & Larson, R.B. 2004, ARAA, 42, 79
Chiosi, C., & Maeder, A. 1986, ARAA, 24, 329
Chugai, N.N., & Chevalier, R.A. 2006, ApJ, 641, 1051
Chugai, N.N., & Danziger, I.J. 1994, MNRAS, 268, 173
Chugai, N.N., et al. 2004, MNRAS, 352, 1213
Crowther, P.A. 2006, ARAA, in press
Crowther, P.A., et al. 2002, ApJ, 579, 774
Crowther, P.A., et al. 1995, A&A, 293, 427
Davidson, K. 1989, in IAU Coll. 113, 101
Drissen, L., Roy, J.R., & Robert, C. 1997, ApJ, 474, L35
Eldridge, J.J., & Vink, J.S. 2006, A&A, 452, 295
Evans, C.J., et al. 2004, ApJ, 610, 1021
Figer, D.F. 2005, Nature, 434, 192
Fullerton, A.W., Massa, D.L., & Prinja, R.K. 2006, ApJ, 637, 1025
Gerardy, C.L., et al. 2002, ApJ, 575, 1007
Heger, A., et al. 2003, ApJ, 591, 288
Hillier, D.J., Lanz, T., Heap, S.R., et al. 2003, ApJ, 588, 1039
Humphreys, R.M., & Davidson, K. 1979, ApJ, 232, 409
Humphreys, R.M., & Davidson, K. 1994, PASP, 106, 1025
Humphreys, R.M., Davidson, K., & Smith, N. 1999, PASP, 111, 1124
de Jager, C., et al. 1988, A&AS, 72, 259
Kroupa, P. 2005, Nature, 434, 148
Lamers, H.J.G.L.M., & Fitzpatrick, E. 1988, ApJ, 324, 279
Langer, N. 1997, A&A, 329, 551
Langer, N., et al. 1994, A&A, 290, 819
Maeder, A., & Meynet, G. 1994, A&A, 287, 803
Massa, D., et al. 2003, ApJ, 586, 996
Maund, J.R., et al. 2006, MNRAS, 369, 390
Meaburn, J. 2001, in ASP Conf. Ser. 233, 253
Meynet, G., et al. 1994, A&AS, 103, 97
Mirabal, N., et al. 2003, ApJ, 595, 935
Morse, J.A., et al. 2001, ApJ, 548, L207
Nieuwenhuijzen, H., & de Jager, C. 1990, A&A, 231, 134
Owocki, S.P., Gayley, K.G., & Shaviv, N.J. 2004, ApJ, 616, 525
Puls, J., et al. 2006, A&A, 454, 625
Repolust, T., Puls, J., & Herrero, A. 2004, A&A, 415, 349
Ryder, S.D., et al. 2004, MNRAS, 349, 1093
Smith, N. 2006, MNRAS, 367, 763
Smith, N., & Hartigan, P. 2006, ApJ, 638, 1045
Smith, N., & Owocki, S.P. 2006, ApJ, 645, L45
Smith, N., et al. 2003, AJ, 125, 1458
Smith, N., Humphreys, R.M., & Davidson, K. 2001, PASP, 113, 692
Smith, N., Morse, J.A., & Bally, J. 2005, AJ, 130, 1778
Smith, N., Vink, J., & de Koter, A. 2004, ApJ, 615, 475
Vanbeveren, D., van Rensbergen, W., & de Loore, C. 1998, The Brightest Binaries (Boston: Kluwer)
Van Dyk, S.D., et al. 1993, ApJ, 419, L69
Van Dyk, S.D., et al. 2000, PASP, 112, 1532
Van Dyk, S.D., Filippenko, A.V., & Li, W. 2002, PASP, 114, 700
Van Dyk, S.D., et al. 2005, PASP, 117, 553
Van Dyk, S.D., et al. 2006, PASP, in press, astro-ph/0603025
Vink, J.S., & de Koter, A. 2005, A&A, 442, 587
Wagner, R.M., et al. 2004, PASP, 116, 326
Walborn, N.R. 1976, ApJ, 204, L17