Mass Loss: Its Effect on the Evolution and Fate of High-Mass Stars

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Abstract
Our understanding of massive star evolution is in flux, due to recent upheavals in our view of mass loss, and observations of a high binary fraction among O-type stars. Mass-loss rates for standard metallicity-dependent line-driven winds of hot stars are now thought to be lower by a factor of 2-3 compared to rates adopted in modern stellar evolution models, due to the influence of clumping on observed diagnostics. Weaker line-driven winds shift the burden of H-envelope removal elsewhere, so that the dominant modes of mass loss are the winds, pulsations, and eruptions of evolved supergiants, as well as binary mass transfer. Studies of stripped-envelope supernovae, in particular, require binary mass transfer. Dramatic examples of eruptive mass loss are seen in Type IIn supernovae, which have massive shells ejected just a few years before core collapse. These are a prelude to core collapse, and may signify severe instabilities in the latest nuclear burning phases. The shifting emphasis from steady winds to episodic mass loss is a major change for low-metallicity regions, since eruptions and binary mass transfer are less sensitive to metallicity. We encounter the predicament that the most important modes of mass loss are also the most uncertain, undermining the predictive power of single-star evolution models beyond core H burning. Moreover, the influence of winds and rotation in models has been evaluated by testing single-star models against observed statistics that, as it turns out, are heavily influenced by binary evolution. Altogether, this alters our view about the most basic outcomes of massive-star mass loss — are Wolf-Rayet stars and Type Ibc supernovae the products of single-star winds, or are they mostly the result of binary evolution and eruptive mass loss? This is not fully settled, but mounting evidence points toward the latter. This paradigm shift has far-reaching impact on other areas of astronomy, since it changes predictions for ionizing radiation and wind feedback from stellar populations, it may alter conclusions about star formation rates and initial mass functions in external galaxies, it affects the origin of various compact stellar remnants, and it determines how we use supernovae as probes of stellar evolution across cosmic time.
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## 1 INTRODUCTION

Because of the scaling of luminosity with initial mass, relatively rare stars born with masses above \( \sim 10-20 \, M_\odot \) vastly outshine the much larger number of lower-mass stars. The radiative
output of massive stars is so intense that photon momentum can drive strong winds, and the
energy transport through the stellar interior may jeopardize the stability of the star itself.
Mass loss from massive stars has a deterministic influence on the structure and evolution
of those stars, which in turn have tremendous impact on other areas of astronomy.

Massive stars are the cosmic engines that provide most of the luminosity in star-forming
galaxies. Since massive stars have short lifetimes, their ultraviolet (UV) radiation (repro-
cessed in various forms) is the most observable tracer of star formation and is used to calcu-
late the star formation rates (Kennicutt 1998, Kennicutt & Evans 2012). Feedback in the
form of UV radiation, stellar winds, and supernovae (SNe) stirs interstellar gas, driving tur-
bulence and perhaps triggering new generations of stars by sweeping gas into dense filaments
(Elmegreen & Lada 1977). Through this feedback, massive stars have a profound impact
on the evolution of disk galaxies (van der Kruit & Freeman 2011). Massive star feedback
may also terminate star formation locally, blowing giant bubbles (Cox 2005) and leaking
hot processed gas into the Galactic Halo (Putman et al. 2012). Elemental yields from nu-
clear burning in the cores of massive stars and explosive nucleosynthesis in SNe provide the
elements in the periodic table that pollute the interstellar medium (ISM), driving galactic
cosmic evolution and the metallicity (Z) evolution of the Universe. Through their violent
deaths as SNe, massive stars provide brilliant displays that permit us to dissect individual
stellar interiors at distances of many Mpc while the star’s inner layers are peeled away for
us to see (Filippenko 1997). They leave behind exotic corpses such as black holes, neutron
stars, pulsars, magnetars, and all the bizarre high-energy phenomena that occur when com-
 pact objects remain bound in a binary system (e.g., Remillard & McClintock 2006). Shock
fronts in their beautifully complex SN remnants echo through the ISM for thousands of
years after the bright SN display has faded (Reynolds 2008).

Mass loss affects a star’s luminosity, burning lifetime, apparent temperature, the hard-
ness of its emitted radiation field, its He core mass, and it will profoundly impact the
end fate of a star. As a consequence, changes in estimates of mass-loss rates can alter
expectations for their collective ionizing radiation, UV luminosity, winds, and SNe. Thus,
understanding massive stars and their mass loss also remains important as we push ever
farther to the distant reaches of the Universe. Inferences about the initial mass function
(IMF; Bastian et al. 2010) and variation of the star-formation rate through cosmic time
(Hopkins & Beacom 2006, Madau et al. 1998) hinge upon converting reprocessed mas-
 sive star UV luminosity to a collective star-formation rate. Gamma ray bursts (GRBs;
Gehrels et al. 2009, Woosley & Bloom 2006) and SNe also provide a probe of very distant
populations and stellar evolution in early environments, but this requires us to under-
stand the connection between stars of various types, their mass loss, and the eventu-
type of SN seen. The first stars in Z-poor environments are expected to be very massive
(Bromm & Larson 2004), and hence, the scaling of mass loss with Z affects abundances of
the lowest Z stars (Beers & Christlieb 2002, Bromm & Yoshida 2011) polluted by a small
number of early SNe. Since dense stellar winds can absorb portions of the Lyman continuum
emitted by a hot star’s photosphere (Najarro et al. 1996), estimates of mass-loss rates and
their scaling with metallicity can profoundly impact topics as remote as reionization of the
universe and the interpretation of spectra from galaxies at the highest redshifts currently
being detected (Fan et al. 2006, Loeb & Barkana 2001, Morales & Wyithe 2010).

Although convenient recepies and simple scaling relations to account for the collective
effects of mass loss and feedback will always be available, researchers working in these
other branches of astronomy should not believe that such recepies are reliable to better
than order-of-magnitude levels. Even in the very local universe where we have excellent

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multiwavelength observations, there is still tremendous uncertainty in derived mass-loss rates for massive stars, and so there is large uncertainty in its influence on evolution. This is exacerbated by the predicament that these uncertainties are largest for the most massive and most luminous stars, but these stars also tend to be the most influential. Extrapolating to the early Universe is still quite risky, and should always raise eyebrows. The aim of this review article is to provide a broad overview of the current understanding of mass loss and its influence on the evolution of massive stars, and to raise a flag of caution about the uncertainties involved.

1.1 The Importance of Mass Loss in Massive-Star Evolution

For low- and intermediate-mass stars ($M_{ZAMS} < 8 M_\odot$), wind mass loss is relatively unimportant for evolution until the final stages as the asymptotic giant branch (AGB) star transitions to a protoplanetary nebula. For massive stars, however, mass loss cannot be ignored. For most of their lives — even on the main sequence — massive stars above $\sim 20 M_\odot$ shed mass in fast winds that affect their subsequent evolution (i.e. $\int \dot{M} dt$ can be a significant fraction of the stellar mass), and in post-main sequence phases the mass loss becomes critical in determining the type of resulting SN explosion.

Thus, mass loss is inexorably linked to evolution for massive stars. This article will not provide a detailed review of our understanding of stellar evolution from a theoretical perspective, since this has already been done in a number of excellent reviews. Although somewhat dated, Chiosi & Maeder (1986) provide a good description of how models that incorporate mass loss compare to stellar evolution models without mass loss. Maeder & Meynet (2000) provide a review of how the inclusion of rotation can influence single-star stellar evolution models, while Langer (2012) has reviewed more recent advances as well as important aspects of how close binarity may dramatically change the evolutionary paths of stars. Finally, Woosley et al. (2002) discuss stellar evolution models with particular emphasis on the late pre-SN burning phases and their connection to core collapse.

Instead, this review will concentrate mostly on observational estimates of mass-loss and their impact on stellar evolution, because this is where the largest uncertainty currently resides. Stellar evolution calculations must adopt prescriptions for mass-loss rates as input to their code, but these assumed rates determine the outcome of evolution. Depending on precarious assumptions about wind strength, a red supergiant (RSG) can be made to evolve to the blue on the Hertzsprung-Russell (HR) Diagram, or not. A massive star can be driven to the luminous blue variable (LBV) phase, or it can avoid it altogether. Moreover, the mass-loss rates typically used in stellar evolution models are time-averaged, even though eruptive and explosive mass loss events are observed. Hence, there is great uncertainty in the predictions of all evolutionary models. Tracks on the HR diagram are not plotted with error bars that reflect these uncertain assumptions.

Due to the need for time-averaged prescriptions in stellar evolution calculations, the steady line-driven winds of hot stars have consumed the majority of effort in understanding mass loss in the massive star community for the past three decades, both theoretically and observationally. There have been great leaps in quantitative non-LTE modeling of spectra influenced by winds. A previous review by Kudritzki & Puls (2000) (KP00 hereafter) dealt with line-driven winds of hot stars, focussing on the theory of the driving mechanism as well as common scaling relations used to convert observables to rates. A more recent review by Puls et al. (2008) also concentrated on the relatively steady line-driven winds of hot stars, providing a thorough discussion of wind theory and its connection to a wide array
observational diagnostics. Those reviews did not focus on more extreme winds of evolved massive stars or mass loss in binaries, and they did not discuss highly time-dependent mass loss associated with transient events (eruptions, explosions, mergers). This review will therefore emphasize these latter topics, but it will discuss more recent developments, in particular the reduction in mass-loss rates and the consequent paradigm shift in stellar evolution.

1.2 Historical Perspective and Paradigm Shift

Our present understanding of mass loss has undergone dramatic changes, due in large part to major shifts in our quantitative estimates of what mass-loss rates actually are. The historical path to our current understanding has had some interesting swings.

Very early observations of transient events like Tycho’s SN, P Cygni’s 1600 AD eruption, and many nova eruptions, as well as the broad emission lines in Wolf-Rayet (WR) stars (Wolf & Rayet 1867) and the broad blueshifted absorption seen in spectra of many objects indicated the presence of outflowing material. However, these were seen as rare stars or brief eruptive events, and the connection to the lives of normal stars was unclear. Later, estimates for the solar wind (Parker 1958) powered by hot gas pressure had such low mass-loss rates that winds would not matter much in stellar evolution. There were some important early indications and expectations of mass loss from hot stars (Sobolev 1960), but the mass-loss rates were very uncertain. Therefore, the dominant paradigm (e.g., Paczynski 1966, 1967, 1971) was that, as in low-mass stars, binary Roche-Lobe Overflow (RLOF) played a major role in making massive stripped-envelope stars like the He-rich WR stars.

The birth of UV astronomy triggered a revolution in our understanding of massive stars by providing the decisive evidence that all luminous hot stars have strong winds, indicated by deep P Cyg absorption in their UV resonance lines (Morton 1967). This led to a new paradigm wherein line-driven winds dominate the stripping of the H envelope, rather than binaries, leading to WR stars and Type Ibc SN progenitors via single-star evolution (i.e., the so-called “Conti scenario”; Conti 1976). As with UV observations, the development of IR detectors led to a similar recognition of the importance of dust-driven winds in red supergiants (Gehrz & Woolf 1971). With the assumption that mass loss in steady winds dominates mass loss, theorists could adopt simple prescriptions for that mass loss and calculate single-star evolutionary tracks on the HR Diagram (see reviews by Chiosi & Maeder 1988, Maeder & Meynet 2000). These single-star models were able to provide a plausible explanation for observed distributions of stars, including the relative amounts of time spent in different evolutionary phases as O-type stars, WR stars, and RSGs. Massey (2003) has reviewed how these single-star models have been compared to observations and how observed statistics have been used to test and refine the single-star models. This single-star paradigm then permitted one to extend even further, to compute models for the collective radiative output of entire stellar populations as a function of age (e.g., codes like STARBURST99; Leitherer et al. 1999).

In the last decade this paradigm has shifted yet again because of two important realizations: 1) due to the effects of clumping (see below), empirical mass-loss rates for line-driven winds are lower than previously thought, and 2) other unsteady modes of mass loss are more important than previously recognized, due to increased estimates for mass ejected in episodic mass loss events (Smith & Owocki 2006) and the very high binary fraction among massive stars (Sana et al. 2012). These changes to our view of mass loss are discussed in detail below. This may alter a huge number of predictions for the evolutionary tracks of
2 THE DIMINISHED ROLE OF STEADY LINE-DRIVEN WINDS

Massive stars spend the majority of their lives as hot stars (mostly as OB types, and more briefly as WR stars), and during these phases the dominant mode of mass loss is through line-driven winds. Again, see KP0 and Puls et al. (2008) for reviews concerning steady, line-driven winds from hot stars. Here we focus on the treatment of winds in evolution, as well as important updates.

2.1 The Standard View

In the wind of a hot star, momentum is transferred from the outwardly propagating radiation to the gas through absorption and scattering by UV metal lines (Castor et al. 1973, Lucy & Solomon 1971). Thus, the rate at which mass is lifted from the star by this...
mechanism depends on the UV luminosity of the star, the temperature (and ionization), and the metallicity, $Z$ (Mokiem et al. 2007, Puls et al. 2008). Most stellar evolution models therefore adopt simple prescriptions for the mass-loss rates that scale smoothly with the stellar luminosity, temperature, and metallicity. For the generation of models calculated throughout the 1990s, the most commonly adopted mass-loss rates were those of de Jager et al. (1988) and Nieuwenhuijzen & de Jager (1990) for O-type stars and RSGs, and Nugis & Lamers (2000) for WR stars. A representative example of the application of this technique to infer the evolution and fate of massive stars as a function of metallicity is discussed by Heger et al. (2003), where $Z$-dependent mass loss ($\propto \sqrt{Z}$) is adopted (many other stellar evolution models are reviewed by Langer 2012). Hence, it is expected that the total mass lost by a star will increase smoothly with luminosity and $Z$, yielding trends with $M_{ZAMS}$ and $Z$ such as that shown in Figure 1 (Heger et al. 2003). This basic picture has been widely regarded as the “standard view” of single-star evolution at high initial mass, although details of the implementation differ from one model to the next.

### 2.2 Observational Diagnostics and Clumping

The mass-loss rate, $\dot{M} = 4\pi r^2 \rho(r) v_\infty$, depends on the average mass density $\rho(r)$ at a particular radius where the wind has reached its terminal velocity $v_\infty$. Connecting these ideal values to observations is non-trivial and requires detailed models including realistic opacities, since the radius where the emissivity or absorption originates is wavelength dependent. The wind terminal speed can be deduced from resolved profiles of P Cygni absorption in UV resonance lines. There are several diagnostics of the wind density, the most common being the strength of wind free-free emission in the IR or radio (Wright & Barlow 1975), H$\alpha$ or other recombination emission lines, and the strength of blueshifted P Cygni absorption features in unsaturated UV resonance lines (see Puls et al. 2008).

Radio/IR free-free continuum excess and emission lines like H$\alpha$, He i, and He ii are recombination processes, so their emissivity varies as $\rho^2$, whereas P Cyg absorption varies linearly with $\rho$. The quadratic density dependence of recombination emissivity raises a problem — if small-scale inhomogeneities (i.e. “clumps”) permeate the wind, then recombination emission arising in dense clumps will be stronger than emission from the same amount of mass distributed uniformly throughout the wind (in other words, $\langle \rho^2 \rangle > \langle \rho \rangle^2$).

It is now well-established that winds are in fact clumpy (see below), so when mass-loss rates are derived from H$\alpha$ or free-free excess using the assumption of a homogeneous wind, the mass-loss rates are overestimated. This is the case for the frequently used “standard” mass-loss rates of de Jager et al. (1988) and Nieuwenhuijzen & de Jager (1990), which assumed a smooth wind. The factor by which mass-loss rates are overestimated is $\sqrt{f_{cl}}$, where it is standard practice to define the “clumping factor” as $f_{cl} = \langle \rho^2 \rangle / \langle \rho \rangle^2$. (This assumes that the gas is optically thin.) Constraining the value of $f_{cl}$ observationally is paramount for understanding stellar evolution.

Significant wind clumping is expected on theoretical grounds (Dessart & Owocki 2003, Feldmeier 1993, Owocki & Rybicki 1984, Owocki & Puls 1999, Owocki et al. 1988, Sundqvist & Owocki 2013), due mostly to the line-driven instability (this arises because the force of line driving is velocity dependent; gas parcels which absorb line photons are accelerated, and are therefore Doppler shifted out of the line to absorb adjacent photons). Clumps are expected on a size scale comparable to the Sobolov length, given by the thermal velocity divided by the radial velocity gradient in the wind ($dv/dr$), which means that clumping should exist on a size scale smaller than the stellar radius. Clumping may also be induced at the base of the wind.
A comparison of the mass-loss rates derived from diagnostics that are linearly proportional to wind density, like UV P Cyg absorption, and those which are proportional to $\rho^2$, like free-free and Hα emission. This is from Fullerton et al. (2006), reproduced with permission. Although there is still discussion about the P v lines used for this study and if they may overestimate the reductions in $\dot{M}$ that are applied, this nevertheless forced an important discussion in massive star research by highlighting the potential influence of clumping.

because of sub-surface convection driven by the Fe opacity bump (Cantiello et al. 2009). In fact, it has long been known that hot-star winds are probably clumpy on small scales (Drew et al. 1994; Hillier 1991; Moffat & Robert 1994) and inhomogeneous on larger scales; large scales include such complexities as the time-variable discrete absorption components (Cranmer & Owocki 1996; Fullerton et al. 1997; Howarth et al. 1993; Massa et al. 1995), or axisymmetric winds due to rapid rotation (Owocki et al. 1996), and a wide array of magnetically induced inhomogeneities (Townsend et al. 2005; ud-Doula & Owocki 2002). However, it was only recently that the severity of the problem for the global mass-loss rate was quantified.

One can check the influence of clumping on $\rho^2$ diagnostics (and thereby measure $f_{cl}$) by studying the same winds using diagnostics that are linearly proportional to density, like P Cyg absorption in UV resonance lines and the strengths of electron-scattering wings. Using UV resonance absorption lines in O-type stars, Fullerton et al. (2006) have proposed a reduction by a factor of 10 or more from traditional mass-loss rates ($f_{cl}$ values of 100 or more), while Bouret et al. (2003) require reductions by factors of $\sim$3. For the Milky Way, LMC, and SMC, various studies using modern non-LTE analysis find $f_{cl} \approx 10$ (Crowther et al. 2002; Evans et al. 2004; Figer et al. 2002; Hillier et al. 2003; Massa et al. 2003; Puls et al. 2003), corresponding to $\dot{M}$ reductions by a factor of $\sim$3 with typical uncertainties of $\sim$30%. Based on unifying Hα measurements with the theoretical mind momentum
relation, both Repolust et al. (2004) and Markova et al. (2004) found $f_{cl}=5$, or a mass-loss
reduction by 2.3. Puls et al. (2006, 2008) and others have discussed that the larger mass-loss rate reduction
of 10 found by Fullerton et al. (2006) may be an overestimate because of how ionization can
affect the optically thin $P\nu$ lines that the large clumping factor is based upon, as well as
possible mediating effects of porosity in the wind. These topics are not completely set-
tled, but nevertheless, most observational studies agree that for mid/early O-type stars,
clumping is significant enough to warrant mass-loss rates reduced by a factor of 2 to 3
relative to the standard rates from Hα and radio flux that assume homogeneous winds
(de Jager et al. 1988, Nieuwenhuijzen & de Jager 1990). Reductions by factors of 2-4 are
confirmed by X-ray observations (Cohen et al. 2010, 2011, Kramer et al. 2003). Thus, re-
ductions in mass-loss rates for normal O-type stars by a factor of 3 (±30%) is a good
guide.

2.3 Recent Developments and Modifications

In current generations of stellar evolution models (see the recent review by Langer 2012),
the most commonly used prescription for the mass-loss rates of hot stars with line-driven
winds is from Vink et al. (2001). These are theoretical mass-loss rates based on the expected
radiative acceleration of a wind, calculated by loss of photon energy using a Monte-Carlo
method. These $\dot{M}$ values are comparable to the values of the old “standard” rates derived
observationally from $\rho^2$ diagnostics assuming homogeneous winds. The prescriptions for
O-star mass-loss rates taken directly from de Jager et al. (1988) and Vink et al. (2001) are
compared in Figure 3 (this figure also includes $\dot{M}$ for other types of stars discussed in this
review). For comparison, Figure 3 also plots the de Jager et al. (1988) rates divided by
factors of 3 (the favored reduction) and 10 (possibly an overestimate) to account for the
way clumping affects the observationally derived rates. These $\dot{M}$ prescriptions are for O-
type MS stars over a range of luminosities (using different $M_{ZAMS}$ and $T_{eff}$ values from
stellar evolution models) at $Z_\odot$. All these values of $\dot{M}$ increase with both increasing $L$
and decreasing $T_{eff}$, so $\dot{M}$ will climb by a factor of 3–4 as an O-type star evolves along the MS,
giving rise to observed properties Of and WNH stars. The most luminous WNH stars are
generally assumed to be in the late phases of core H burning, rather than He burning like
traditional WR stars, but some other WN stars with H in their spectra are indeed thought
to be transition objects and possibly related to LBVs. Binary evolution may of course play
a role in creating some of these WN stars with H, and the connections between terminology
and evolutionary state are often complicated.

An important point to recognize is that the theoretical Vink et al. (2001) prescription
for $\dot{M}$ is almost the same as the empirical de Jager et al. (1988) prescription (in fact, for
much of the range of O-star luminosities, the Vink et al. mass-loss rates are higher). This
is for physical parameters from model ZAMS stars from Ekström et al. (2012); note that
the Vink et al. recipe depends on $L$, $T_{eff}$, $M$, and $v_\infty$, whereas the de Jager prescription
uses only $L$ and $T_{eff}$. The two prescriptions therefore change differently as a star evolves.
In any case, it appears that stellar evolution calculations are still using mass-loss rates

1Note that long ago, small scale clumping with $f_{cl}$ values of 4-20 (a reduction in mass-loss rates by
factors of 2-4) was required to fit both the emission cores ($\propto \rho^2$) and electron-scattering wings ($\propto \rho$) in
WR stars (Hiller 1993; Moffat & Robert 1993). Line wings of O-type stars are too weak for this analysis.
In addition, polarization variations in WR+O eclipsing binaries (St. Louis et al. 1993) implied $f_{cl} \approx 10$.
2The interested reader can consult the proceedings volume of a recent conference on this topic for more
detailed information (Hamann et al. 2008).
A number of different prescriptions for wind mass loss used in models, as well as typical observed ranges of mass-loss rates for a number of different types of stars. For O-type stars, the theoretical rates from the prescription of Vink et al. (2001) are shown, along with “standard” observational rates using the prescription from de Jager et al. (1988), as well as these same prescriptions divided by factors of 3 and 10 for comparison. The green line labeled “weak-wind problem” refers to lower mass-loss rates for late O-type and early B-type MS stars (see text). Rates for WN and WC stars are from Crowther (2007). RSG mass-loss prescriptions are from de Jager et al. (1988) and van Loon et al. (2005), as indicated. For YHGs, see de Jager (1998). For $\dot{M}$ corresponding to normal winds of LBVs, values were compiled from a number of studies (Groh et al. 2007, Hillier et al. 2001, Smith et al. 2004, Vink & de Koter 2002). For LBV eruptions, the “rates” shown are calculated from total masses observed in LBV CSM shells (Smith & Owocki 2004) divided by a nominal eruption duration of 10 yr (see Figure 5). For “binary RLOF”, an order-of-magnitude value for the strongest mass-transfer rates expected in brief RLOF phases is noted, although the mass-transfer or mass-loss rate can be much less for slow mass transfer, or possibly more for dynamical common-envelope ejection events; see references in the text, especially the review by Langer (2012).
that are too high by a factor of ∼3 during the MS lifetimes of massive stars.\footnote{The Vink et al. (2001) mass-loss rates are indeed a factor of ∼2 lower than rates used in some massive star evolution models. In particular, older models by Meynet et al. (1994) adopted mass-loss rates that were artificially a factor of 2 higher than the de Jager et al. (1988) mass-loss rates, because this enhanced mass loss did a better job of accounting for the observed statistics of WR stars. Moreover, these models with enhanced mass-loss rates are still often employed in stellar population synthesis models.} It is likely that adopting the reduced mass-loss rates will have a profound impact on the outcome of single-star evolution calculations, but a meaningful comparison with observed properties of stars cannot be attempted until this is updated.

Modifications to standard mass-loss rates have also occurred at the high and low ends of the luminosity range. As the most massive O-type stars (spectral types of O3 and O2) evolve toward the terminal-age MS, their luminosities go up and they move close to Γ = 1, where Γ = κL/4πGMc is the Eddington ratio. High Γ values in hot stars can substantially affect the winds and increase mass-loss rates (Grafener et al. 2011, Vink et al. 2011). Thus, it may be possible for stars with initial masses of 80–100 \( M_\odot \) or more to lose mass so fast in a WNH phase that they avoid the LBV phase altogether, although this effect has not yet been included in stellar evolution calculations. For these very massive stars it is likely that steady winds could have a more significant impact on evolution than for the majority of SN progenitors with lower initial masses.

While the most massive H-burning stars may have winds that are stronger than the standard Vink et al. (2001) prescriptions, it has been found that later O-type and early B-type stars have surprisingly weak winds for their luminosity compared to theoretical expectations. Below \( \log(L/L_\odot) = 5.2 \) (spectral types of O7 and later), observed wind momenta and mass-loss rates are much lower than theoretical predictions (see Figure 3). This is known as the “weak-wind problem” for O dwarfs (Muijres et al. 2012, Puls et al. 2008), and may indicate inefficient line driving in hot dwarfs. Analysis of the bow shock around the O9.5 V runaway star \( \zeta \) Oph suggests that the weak-wind problem may not be as bad as indicated by UV absorption (factor of 100 lower), but that the mass-loss rates are still a factor of 6–7 lower (Gvaramadze et al. 2012). Similarly, Huenemoerder et al. (2012) find from considering X-ray diagnostics that the \( \dot{M} \) reduction may not be as severe as suggested from UV diagnostics, although their favored rate of \( \dot{M} = 2 \times 10^{-9} M_\odot \text{ yr}^{-1} \) for the O9.5 V star \( \mu \) Col lies on the green line for weak winds in Figure 3. Note that similar considerations of UV diagnostics were noted earlier as well (Cohen et al. 1997, 2008, Drew et al. 1994).

### 2.4 Wolf-Rayet Winds

The strong winds of WR stars yield spectacular spectra with extremely strong and broad emission lines, as well as strong excess in the IR and radio from free-free emission. Crowther (2007) has recently reviewed the properties of WR stars, and typical mass-loss rates for WN and WC stars are plotted in Figure 3. Much of the discussion of clumping and mass-loss rates of WR stars echoes that of O-type stars, except for the fact that the effects of clumping were already known more than a decade ago based on the relative strengths of electron-scattering wings and emission-line cores, as noted earlier (Hillier 1991). The mass-loss rates of WR stars, like O-type stars, are line-driven winds and are \( Z \) dependent. Vink & de Koter (2002) find that Fe dominates the driving in WN stars and that they have a metallicity dependence similar to O-type stars, whereas WC stars have a somewhat shallower dependence on \( Z \) because intermediate-mass elements from self-enrichment contribute more to the driving as \( Z \) drops.
2.5 Implications of lower O-star mass-loss rates

It would appear that the net result of decades of detailed study of line-driven winds is that, at least concerning stellar evolution, they don’t matter as much as was previously believed (except perhaps for the most massive stars where proximity to the Eddington limit enhances the winds; see above). It is still commonly stated in the literature that a massive star of $M_{\text{ZAMS}} = 60 M_\odot$ will shed half its mass on the main sequence, but if clumping requires us to reduce mass-loss rates by a factor of 3, then such statements are no longer true. For example, a 60 $M_\odot$ star will begin the main sequence with $\log(L/L_\odot)=5.7$ and $\log(T_{\text{eff}})=4.7$ according to standard evolutionary models, and $\dot{M}=10^{-5.86} M_\odot$ according to the de Jager et al. (1988) prescription. The mass-loss rate will climb throughout the MS because the luminosity goes up, and so the average $\dot{M}$ is about a factor of 2 higher. However, with $\dot{M}$ reduced by a factor of 3 as a standard clumping correction, a 60 $M_\odot$ star would ultimately lose only a few $M_\odot$ during the entire 3.5 Myr MS evolution. This raises the important question of where WR stars come from in light of lower mass-loss rates. No H-free WR stars are known with masses above roughly 20-25 $M_\odot$ (see Crowther 2007, Smith & Conti 2008), so the lion’s share of mass loss is yet to come. Stars with $M_{\text{ZAMS}} = 60 M_\odot$ don’t become RSGs, and the observed $\dot{M}$ values of steady winds of post-MS stars at these luminosities (i.e. blue supergiants and quiescent LBVs; see Figure 3) are not high enough when combined with the short duration of these post-MS phases envisioned in single-star evolution models. There are only a few options (Smith & Owocki 2006): (1) eruptive LBV mass loss makes up the difference, or (2) single stars with $M_{\text{ZAMS}} = 60 M_\odot$ don’t fully shed their H envelopes before core-collapse, and binaries are instead responsible for most of the observed WR stars that may come from these initial masses. For stars of lower initial mass $M_{\text{ZAMS}} = 40-60 M_\odot$, the problem is worse. Below $M_{\text{ZAMS}} \simeq 35 M_\odot$, single stars should go through a RSG phase and this may help shed the H envelope to make WR stars. RSG mass-loss rates are highly uncertain as well, however (see below).

At higher initial masses above 80-100 $M_\odot$, stars pass through a WNH phase with very strong winds enhanced by high $\Gamma$ values (see above). Although the mass loss here may be strong enough to evaporate the H envelope, stars of such high initial mass would yield He cores that are more massive than any observed H-poor WR stars. Since the most massive stars are rare, it is uncertain if this is a show stopper. As discussed later, however, it seems easy for known binaries to account for WR stars, and indeed binary evolution (mass accretion, mergers) may factor prominently in producing some N-rich WR stars that may still be H burning.

Even with $\dot{M}$ values reduced by a factor of 3, however, line-driven winds operating over the entire MS lifetime of O-type stars may still be quite important in angular momentum loss and the rotational evolution of massive stars, especially with the possible aid of magnetic fields. This important aspect of rotational evolution is discussed by Langer (2012).

2.6 Metallicity Dependence and Implications for Feedback

While the winds of OB-type main-sequence (MS) stars may be less important for a star’s evolution than previously thought, having relatively precise (better than factor of ~2) estimates of $\dot{M}$ is still desirable to assess the role of wind feedback in clustered star-forming regions, starbursts, and disk galaxy evolution. This is because massive stars spend most of their lifetimes as H-burning O-type stars, and the youngest ages are when the natal ISM of the star-forming environment is still close to the star and susceptible to the direct impact of
radiation pressure and winds. Although binary RLOF, eruptive LBV mass loss, and RSG winds remove more mass from a typical O-type star than line-driven winds, this mass loss is generally slow and/or cold, it usually happens on a very short timescale, and it usually occurs late in a star’s life, so that the energy and momentum injection into the surrounding ISM integrated over the lifetime of the star is far less. The eventual SNe tend to explode in a large cavity, and may be less influential as well. Thus, for assessing local mechanical feedback from massive stars, line-driven winds are still an important consideration.

The good news is that, modulo the uncertainty in $\dot{M}$ caused by clumping, the simple $Z$-dependent scaling of line-driven winds (e.g., Mokiem et al. 2007, Vink et al. 2001) is probably reliable enough to estimate the global contribution of feedback of MS O-type stars from solar to mildly sub-solar metallicities. At a given temperature and luminosity, one expects mass loss to scale as $\dot{M} \propto Z^m$. Theoretically, Vink et al. (2001) predict $m=0.69 \pm 0.10$ for O-type stars, whereas observations suggest $m=0.83 \pm 0.16$ (Mokiem et al. 2007). These are in reasonable agreement, although note that both are steeper than the $Z^{0.5}$ scaling given by KP00 and adopted by Heger et al. (2003) (Figure 1) due to the $Z$ dependence of wind speed (Vink et al. 2001). These relations have only been tested to roughly 1/5 $Z_\odot$, so extrapolating to hyper-metal-poor environments is still uncertain.

It should be noted that lower mass-loss rates are also important for assessing the collective radiative feedback from a cluster or starburst, because lower values of $\dot{M}$ allow more UV radiation to escape the wind. Moreover, the lower mass-loss rates that result from clumping may indirectly but substantially influence the global feedback of SNe from a stellar population, since weaker winds during H-burning could modify the burning lifetime, core size, and end state of the star, and hence, the characteristic of the resulting SN explosion.

3 DENSE WINDS FROM COOL SUPERGIANTS

Winds of cool supergiants have received less attention from the massive-star community than hot-star winds, even though RSG winds are much stronger (Figure 3) and far more important for the evolution of 8–35 $M_\odot$ stars (i.e., the vast majority of SN progenitors). Willson (2000) has reviewed mass loss from cool stars, although that paper focussed on lower-masses ($M_{ZAMS} = 1 – 9 M_\odot$). The basic physical picture of the mechanism by which more massive RSG stars lose mass is similar; pulsations lift gas to a few $R_\star$, where the equilibrium temperature becomes low enough (1000–1500 K) for substantial dust condensation to occur. Radiation pressure on newly formed dust (coupled to the gas by collisions in these dense winds) then takes over and pushes the wind to escape the star’s gravity.

Willson (2000) also reviewed observational diagnostics of mass-loss rates in these cool stars. For lower mass-loss rates in cool supergiants with coronal winds, UV spectra and radio emission can be used to investigate the mass-loss rate and other wind properties (see also Bennett 2010). For stronger winds, the primary methods used to measure the mass loss are with thermal-IR excess from hot dust and molecular emission. For extreme mass-loss rates, one can also use masers (Habing 1996), and spatially resolved circumstellar material using a variety of techniques like IR interferometry (Monnier et al. 2004).

The most common prescriptions for RSG mass loss in modern stellar evolution codes are from the same sources as the old rates for hot stars (de Jager et al. 1988, Nieuwenhuijzen & de Jager 1990), and they come with comparably large uncertainty. This uncertainty must be kept in mind when evaluating the predictions of single-star evolution models that pass through the RSG phase. Some models adopt the significantly higher empirical RSG mass-loss prescription of van Loon et al. (2003), which is intended for dust-enshrouded RSGs. Both these rela-
tions are shown in Figure 3. Depending on which RSG mass-loss recipe is chosen for a model, RSGs can stay in the red (lower $\dot{M}$) or be driven to hotter temperatures on the HR Diagram. This general behavior has been known for a long time, discussed in detail with regard to models for the blue progenitor of SN 1987A (Arnett et al. 1989). However, after Smartt (2009) discussed that the most massive RSGs apparently do not explode as Type II-P SNe, new evolutionary tracks that included blueward evolution for RSGs with initial masses above $\sim 20 M_\odot$ became more common (Ekström et al. 2012). Thus, the model outcome of the RSG phase is sensitively dependent on an uncertain input mass-loss prescription. Unfortunately, there is, as yet, no well-established quantitative theoretical prediction for the mass-loss rates of RSG winds or the detailed physics driving them (including pulsations), as there is for hot stars. RSG mass loss is time dependent, and there appears to be a wide dispersion even for a given luminosity and temperature (Willson 2000). Moreover, the mass loss may not obey any single prescription throughout the whole RSG evolution of an individual star, and in fact there is suggestive evidence of this.

Observations of massive clusters with numerous RSGs have shed some important light on this topic. These provide excellent probes of massive-star evolution in general — and RSGs in particular — because massive clusters sample a relatively coeval group of stars, whereas different clusters sample different ages and initial masses of stars that have reached the RSG phase (see Davies et al. 2012 and references therein). An example from the cluster RSGC1 is shown in Figure 4 (Davies et al. 2008). This compares the locations of several RSGs in the HR Diagram to a 12 Myr isochrone (Maeder & Meynet 2000), indicating that these

Figure 4:

An HR diagram of the cluster RSGC1, with RSGs and a YSG. Sources that are circled include maser emission (as noted) from dense envelopes, indicating especially strong mass loss. Adapted from Davies et al. (2008) with permission.
RSGs probably all have initial masses close to 18 \( M_\odot \). It is interesting that the RSGs with the strongest mass loss indicators (traced by \( H_2 \)O, SiO, and OH maser emission; encircled in Figure 4) are found only at the top of the RSG branch. This seems to indicate that the highest mass-loss rates that lead to self obscuration and maser emission (the sources for which the van Loon et al. mass-loss rates are appropriate) may be concentrated toward the very end of the RSG phase when turbulence and pulsations are most vigorous. Moreover, this cluster also includes a yellow hypergiant (YHG) at a luminosity comparable to the most luminous RSGs with masers. This provides compelling evidence that around 18 \( M_\odot \) or above, enhanced RSG mass loss can indeed drive these stars toward warmer temperatures at the ends of their lives. This, in turn, has implications for connections between progenitor stars and the types of SNe that they make, as well as their circumstellar environments into which the SNe explode.

Some of the most luminous RSGs tend to have extremely high mass-loss rates that cause self-obscuration by dust and strong maser emission. The best studied Galactic object in this category is VY Canis Majoris, which has an extended dust-scattering nebula seen in \( HST \) images (Smith et al. 2001). In the case of VY CMa, the density of its nebula drops off sharply at \( \sim 8000 \) AU from the star, indicating that its high average mass-loss rate of \( \sim 10^{-3} \) \( M_\odot \) yr\(^{-1} \) has been limited to the previous \( 10^3 \) yr or so (Decin et al. 2006, Smith et al. 2001, 2009). The nebula around VY CMa is quite similar to that around the yellow hypergiant IRC+10420, which is regarded as the prototypical post-RSG because of its maser shell surviving around such a warm star, and its observed fast blueward evolution (Humphreys et al. 1997). Cases like this provide additional evidence that strong mass-loss among more luminous RSGs will drive them on blueward evolutionary tracks. Some models predict that this very strong mass-loss phase is short-lived, and enhanced before core collapse caused by increasingly violent pulsations during C burning due to a high \( L/M \) ratio (Arnett & Meakin 2011, Yoon & Cantiello 2010).

### 4 SUPER-EDDINGTON WINDS, ERUPTIVE MASS LOSS, AND TRANSIENTS

Stellar evolution models demonstrate the critical impact of mass loss on stellar evolution, and we see results of mass loss in the existence of WR stars and the diversity of SN types. The uncertainty gets large as we move toward post-MS phases, as we have seen in the case of RSG mass-loss rates, and the probably dominant role of binaries (next section). The uncertainty is worst at the highest stellar luminosities, where mass-loss is strongest, and where systems observed in detail are few. Proximity to the Eddington limit can enhance the strength of a steady wind, or worse, it can make the star unstable, potentially leading to violent eruptive or explosive mass loss associated with transient events that can dramatically change the star in a short time. For extreme cases in very massive stars, a single eruptive event can remove more mass in a few years than is shed during its MS evolution. It is therefore sobering to recognize that none of these effects are included in current generations of stellar evolution models.

In section 2.3 we briefly mentioned the role of the Eddington ratio, \( \Gamma \), in enhancing the relatively steady mass-loss rates of very luminous H-burning stars, like the WNH stars. Here we focus on the more extreme cases where the high \( \Gamma \) leads to instability in the star and highly time-dependent mass loss, or where advanced nuclear burning stages may play a role (Arnett & Meakin 2011). When this variability is observed, the stars are designated as LBVs, or LBV candidates if they are suspected to be dormant versions of the same stars.
4.1 LBVs: History and Phenomenology

The most dramatic instability arising in post-MS evolution is the class of objects known
as luminous blue variables (LBVs). These were recognized early as the brightest blue ir-
regular variables in nearby galaxies (Hubble & Sandage 1953, Tammann & Sandage 1968),
and these classic examples were referred to as the “Hubble-Sandage variables”. Famous
Galactic objects like P Cygni and η Carinae had spectacular outbursts in the 17th and 19th
centuries, respectively, but their connection to other eruptive massive stars was unclear.
Conti (1984) recognized that many different classes of hot, irregular variable stars in the
Milky Way and Magellanic Clouds were probably related to the Hubble-Sandage variables
and to η Car and P Cygni, so he grouped them together as “LBVs”. The LBVs are a rather
diverse class, consisting of a wide range of irregular variable phenomena (Clark et al. 2005,
Humphreys & Davidson 1994, Smith et al. 2004, 2011a, Van Dyk & Matheson 2012, van Genderen 2001).

Their initial masses are uncertain, but comparing their luminosities to single-star evolution
tracks suggests initial masses greater than 25 $M_{\odot}$ (Smith et al. 2004). LBVs are defined
by their irregular eruptive variability. There are, however, stars that spectroscopically re-
semble LBVs in their quiescent state, but which have not (yet) been observed to show the
signature variability of LBVs; these are often called LBV candidates, and they are usually
of spectral type Ofpe/WN9 or early B supergiants. It is not known if LBVs pass through
long dormant periods, and if they do, the duty cycle is unknown. As noted below, the
detection of a dense circumstellar shell is often taken to indicate a prior giant outburst.

**S Doradus phases.** S Dor outbursts are seen as a visual brightening that occurs when
the peak of the star’s energy distribution shifts from the UV to visual wavelengths. The
increase in visual brightness (i.e. 1–2 mag, typically) corresponds roughly to the bol-
ometric correction, so that hotter stars exhibit larger amplitudes. In their quiescent states,
LBVs have apparent temperatures that increase with increasing luminosity: they often
appear as Ofpe/WN9 stars at high luminosity, or early/mid B supergiants at the lower
luminosity end (Humphreys & Davidson 1994, Smith et al. 2004). Visual maximum occurs
at a constant temperature of ~8000 K, causing the star to resemble a late F super-
giant. S Dor events were originally proposed to occur at constant bolometric lumin-
osity (Humphreys & Davidson 1994), but quantitative studies do reveal varitions in $L_{\text{Bol}}$
(Groh et al. 2009). The traditional explanation for the apparent temperature change was
that the star dramatically increases its mass-loss rate, driving the wind to very high optical
depth and causing a pseudo photosphere (Davidson 1987, Humphreys & Davidson 1994).
However, quantitative spectroscopy revealed that the measured mass-loss rates in outburst
do not increase enough to cause a pseudo photosphere (de Koter et al. 1999), and that the
increasing photospheric radius is therefore more akin to a pulsation. A possible cause of this
inflation of the star’s outer layers may be near-Eddington luminosities in the sub-surface
Fe opacity bump (Gräfener et al. 2012, Guzik & Lovekin 2012). S Dor eruptions of LBVs
are therefore not major mass-loss events. However, the average mass-loss rate in a wind
throughout the LBV phase (quiescent or not) is about an order of magnitude higher than
for O-type stars of comparable luminosity (Figure 3).

**LBV Giant eruptions.** The most pronounced variability attributed to LBVs is their so-
called “giant eruptions”, in which stars are observed to increase their bolometric luminosity
for months to years, accompanied by extreme mass loss (Humphreys, Davidson, & Smith 1999).
The best studied example is the Galactic object η Carinae, providing us with its historically
observed light curve (Smith & Frew 2011), as well as its complex ejecta that contain 10-20
$M_{\odot}$ and ~$10^{50}$ ergs of kinetic energy (Smith 2006, Smith et al. 2003). Light echoes from
the Great Eruption of η Carinae have just recently been discovered (Rest et al. 2012), and their continued study with spectroscopy may modify long-held ideas about LBVs. A less well-documented case is P Cygni’s 1600 AD eruption, for which a much smaller ejecta mass of 0.1 $M_\odot$ has been measured (Smith & Hartigan 2006). P Cyg’s nebula has an expansion speed of \(~140\) km s\(^{-1}\) (Barlow et al. 1994, Smith & Hartigan 2006), with an implied total kinetic energy of a few \(10^{46}\) ergs. P Cyg and η Car are the only two cases of observed LBV giant eruptions where the ejected mass has actually been measured, because they have spatially resolved shell nebulae ejected in the events. With decade-long durations, the implied mass-loss rates are at least 0.01 $M_\odot$ yr\(^{-1}\) and 1 $M_\odot$ yr\(^{-1}\) for P Cyg and η Car, respectively. These rates are too high to be driven by traditional stellar winds because the material is opaque (Owocki et al. 2004, Smith & Owocki 2006). Dust formation in LBV eruptions also points toward eruptive mass loss (Kochanek 2011).

**Extragalactic SN Impostors.** LBV giant eruptions are rare, so our only other observed examples are a few dozen found in nearby galaxies (Smith et al. 2011a, Van Dyk & Matheson 2012). Due to their serendipitous discovery in SN searches, they are sometimes called “SN impostors”. Other names include “Type V” SNe, “η Car analogs”, and various permutations of “intermediate luminosity transients”. These have peak absolute magnitudes of $-11$ to $-15$ mag (Smith et al. 2011a, Van Dyk & Matheson 2012). Typical expansion speeds observed in outburst spectra are 100-1000 km s\(^{-1}\) (Smith et al. 2011a), although lower speeds can be seen along the line of sight if the ejection speed is latitude dependent (Smith 2006). A realization in the past decade is that there is wide diversity among the SN impostors and their progenitors; some events that resemble LBV eruptions may actually arise in lower-mass progenitor stars (Prieto et al. 2008a, Thompson et al. 2009). A review of the lower-mass analogs of LBV giant eruptions is beyond the scope of this article, but the fact that lower-mass stars may experience similar transient events casts doubt on the long-held belief that these eruptions result from high luminosities near the Eddington limit (see below).

**LBV winds.** Most LBVs exhibit strong emission lines in their visual-wavelength spectra, similar to WR stars but with narrower widths and stronger H lines. Wind speeds are typically 100-600 km s\(^{-1}\), reflecting the lower escape speed of BSG stars as compared to 1000-2000 km s\(^{-1}\) in more compact O and WR stars. The wind mass-loss rates implied by quantitative models of the spectra typically range from $10^{-5}$ to $10^{-4} M_\odot$ yr\(^{-1}\) (de Koter et al. 1996, Groh et al. 2009, Smith et al. 2004, Vink & de Koter 2002), or even $10^{-3} M_\odot$ yr\(^{-1}\) in the extreme case of η Car (Hillier et al. 2001). These LBV wind mass-loss rates are indicated in Figure 3. LBV winds are strong enough to play an important role in the evolution of the star if the LBV phase lasts more than $10^5$ yr, and eruptions further enhance the mass loss. Other stars that exhibit similar spectra but are not necessarily LBVs include WNH stars, Ofpe/WN9 stars, and B[e] supergiants, which overlap on the HR Diagram.

**Circumstellar shells.** Many LBVs have spatially resolved circumstellar shells that are fossils of previous eruptions. Stars that resemble LBVs spectroscopically and have massive shells, but have not been observed to exhibit LBV variability, are called LBV candidates, as noted earlier. LBV circumstellar shells are extremely important, as they provide the only reliable way to estimate the amount of mass ejected in an LBV giant eruption. A large number of LBVs and candidates in the Milky Way and Magellanic Clouds are surrounded by massive shell nebulae (Clark et al. 2007, Gvaramadze et al. 2010, Smith & Owocki 2006, Wachter et al. 2011). Thus, eruptive LBV mass loss is inferred to be important in the late evolution of massive stars. Masses of LBV nebulae occupy a very large range from $\sim 20 M_\odot$ at the upper end down to 0.1 $M_\odot$, although even smaller masses become difficult to detect.
Figure 5:
Masses of circumstellar shells around LBVs and LBV-like stars, as a function of luminosity, from Smith & Owocki (2006). The left side of the plot (grey box) corresponds to stars below log(\(L/L_\odot\))=5.8, so these LBVs could be post-RSGs and the nebular mass could have been ejected in the RSG phase and swept up into a shell. Objects on the right must have ejected their massive shells in giant LBV eruptions. There may be many lower-mass shells that are hard to detect around the very bright central stars.

Around bright central stars. In some cases a very large range in mass is seen in multiple shells around the same star, as for \(\eta\) Car (Smith 2005), so there is no clear one-to-one correlation of shell mass and stellar luminosity, although there may be such a relation for the most massive shell a star can eject. Masses for a collection of LBV shells are shown in Figure 5 compiled by Smith & Owocki (2006). To compare with steady winds, LBV giant eruption mass-loss “rates” in Figure 3 are shown by dividing LBV shell masses by the \(\sim 10^2\) yr duration in the eruptions of \(\eta\) Car and P Cyg, although the true instantaneous \(\dot{M}\) may be higher. Dynamical ages of the shells around LBVs/candidates range from \(10^2\) yr to several thousand years. It is, however, difficult to use this age as an indication of the duration of the LBV phase, since expanding shells can decelerate. The duration of the LBV phase may be further complicated, since it may vary with initial mass and may depend on details of binary evolution.

4.2 Physics of Eruptive Mass Loss

Although the violent variability of LBVs has been known for a century or more, the search for a physical theory of LBV eruptions is still in early stages. Most work so far has concentrated on how to lift material off the star, or on tighter observational constraints on the mass, speed, and energy of outbursts. In terms of driving the mass loss, two broad classes of
models have developed: super-Eddington winds and explosions. Both may operate at some level, but neither of these addresses the deeper question of what initiates LBV eruptions in the first place. Ideas for the underlying trigger are still speculative.

4.2.1 Super-Eddington Winds Traditionally, LBV giant eruptions have been discussed as super-Eddington (SE) winds driven by a sudden unexplained increase in the star’s bolometric luminosity. Humphreys & Davidson 1994, Humphreys, Davidson, & Smith 1999, Owocki et al. 2004, Shaviv 2000, Smith & Owocki 2006. This is motivated mostly by the fact that \( \eta \) Car’s Great Eruption had an observed luminosity that indicated \( \Gamma \approx 5 \) for about a decade or more, and that extragalactic SN impostors show similar high luminosities. With \( \Gamma \) values substantially above unity, one naturally expects strong mass loss, but the detailed physical picture of such winds is not obvious. SE winds are expected to be very dense but porous, allowing the star’s atmosphere to remain in steady state while exceeding the classical Eddington limit (Owocki et al. 2004, Shaviv 2000). An important point is that the mass loss is so strong that the high density in the wind causes UV absorption lines to be saturated. Therefore, SE winds are driven by photon momentum transferred to gas through electron scattering opacity and not line opacity (Owocki et al. 2004). This makes SE wind mass loss essentially independent of metallicity, which may allow this mode of mass loss to operate in Pop III stars (Smith & Owocki 2006).

Numerical simulations of continuum-driven SE winds show complex structure with both infall and outflow (van Marle et al. 2008, 2009), confirming expectations that these winds should be highly inhomogeneous (Owocki et al. 2004, Shaviv 2000). SE winds may also account for the bipolar shape of nebulae around LBVs like \( \eta \) Car if the star is a rapid rotator, since equatorial gravity darkening will lead to a higher \( \dot{M} \) and faster speed in the polar wind (Dwarkadas & Owocki 2002, Owocki et al. 1996).

Open questions surrounding SE winds are whether the mechanism can supply the mass loss in the most extreme observed cases, and what initiates the SE phase. Current estimates of the mass lost in \( \eta \) Car’s 19th century eruption are of order 15 \( M_\odot \) or more (Smith & Ferland 2007, Smith et al. 2003). SE winds can in principle cause that much mass loss averaged over 20 years (Owocki et al. 2004), but those same models predict relatively slow outflow speeds. This makes it hard to explain the nebula around \( \eta \) Car, with most of the mass moving at speeds of 500-600 km s\(^{-1}\). Moreover, \( \eta \) Car also shows a smaller mass of extremely fast material moving at 5000 km s\(^{-1}\) or more (Smith 2008), which is hard for a SE wind model to achieve while driving such a large amount of mass. SE winds are still viable for most LBVs, which are less extreme than \( \eta \) Car’s 19th century eruption. As for the extra radiative energy output that initiates the SE wind, this is not known. Lastly, SE winds are assumed to be launched from the surface of the star, but it is also not yet clear if the star’s interior can remain stable at \( \Gamma = 5 \) for more than a decade.

4.2.2 Explosions There is growing observational evidence that some giant LBV eruptions may be non-terminal hydrodynamic explosions. Part of the motivation for this is based on detailed study of \( \eta \) Carinae, which has shown several signs that the 1840s eruption had a shock-powered component to it. This includes estimates of the ratio of total ejecta kinetic energy to the integrated radiated energy of \( E_k/E_{rad} > 3 \), which is hard for a radiation-driven wind to achieve (although perhaps not impossible with extreme photon-tiring; Owocki et al. 2004). The very thin walls of the nebula indicate a small range of expansion speed (Smith 2006), which is easiest to achieve from compression in a shock. Lastly, observations show extremely high-speed ejecta moving at 5000 km s\(^{-1}\), which seems
impossible to achieve without a strong blast wave (Smith 2008). A number of extragalactic LBV-like eruptions show spectra that closely resemble shock-powered Type II SNe and also show evidence for extremely fast ejecta that may signify a shock-powered event, such as the precursor outbursts of SN2009ip (Foley et al. 2011, Smith et al. 2010a).

One normally expects sudden, hydrodynamic events to be brief (i.e., a dynamical time), which at first may seem incompatible with the decade-long Great Eruption of η Car. However, an explosion followed by CSM interaction can generate a high sustained luminosity, as in core-collapse SNe II. Smith (2013a) showed that a shock-powered event with CSM interaction could account for the 1845-1860 light curve of η Car, using a SN II-type model but with lower explosion energy. The resulting slower shock speed from a sub-energetic explosion (10^{50} instead of 10^{51} ergs) produces a lower CSM interaction luminosity compared to a core-collapse SN II, and takes much longer to expand through the CSM. The duration of the event is determined by the outer extent of the dense CSM — in principle, a CSM-interaction powered LBV eruption might continue for several decades, or it could last only 100 days (Falk & Arnett 1977), depending on the extent of the dense pre-explosion wind. Since shock/CSM interaction is such an efficient way to convert explosion kinetic energy into luminosity, it is plausible that many of the SN impostors with narrow emission lines may be powered in this way. The shock model would help explain the wide observed diversity of SN impostors (Smith et al. 2011a, Van Dyk & Matheson 2012). The catch is that even this model requires something else to create the dense CSM into which the shock expands, which may be where super-Eddington winds or binary interaction play an important role.

4.2.3 Eruption Triggers The reason for the onset of an LBV eruption and its power source remain unanswered for either mechanism. In the SE wind model, even if the wind can be driven at the rates required, we have no underlying physical explanation for why the star’s bolometric luminosity suddenly increases by factors of 5-10, and we don’t know how the star’s envelope would process that high energy flux. In the explosion model, the underlying trigger for an explosive event is unknown. In either case, something must inject a large amount of extra energy (10^{48} – 10^{50} ergs) into the star’s interior in a highly time-dependent way. There have been a number of physical mechanisms discussed in connection with LBVs, recently reviewed in detail by Smith et al. (2011a). In brief, there is no clearly favored explanation, but some ideas appear to be ruled out based on the required energy and mass budgets. These can be thought of in two broad categories: instability and energy deposition.

Envelope Instability. LBVs are massive stars that are in close proximity to the Eddington limit. Consequently, their loosely bound envelopes may be susceptible to strange-mode instabilities (Glatzel & Kiriakidis 1993, Glatzel et al. 1999), runaway mass loss (a.k.a. the “Geyser” model: Humphreys & Davidson 1994, Maeder 1992), or the critical rotation limit (a.k.a. the “Ω limit”; Langer 1998, 2012). While these may help explain some of the irregular variability seen in S Dor outbursts of LBVs, they are unsatisfactory explanations for giant LBV eruptions. This is because the total mass ejected can be much more than the small mass in the outer H envelope where the relevant instabilities reside, and LBV eruptions can have substantially more kinetic energy than the total thermal energy in the star’s envelope.

Energy deposition. A large amount of extra energy can be deposited deep in a massive star’s envelope by a number of suggested mechanisms, including unsteady burning (Smith & Arnett 2014), the pulsational pair instability (Woosley et al. 2002, 2007), other explosive shell burning instabilities (Dessart et al. 2010, Smith & Arnett 2014), wave-driven
mass loss ([Meakin & Arnett 2007, Quataert & Shiode 2012, Shiode & Quataert 2013], and
stellar collisions or mergers in a binary system [Podsiadlowski et al. 2010, Smith 2011,
Smith & Arnett 2014]). While any of these provides a plausible result, the main criti-
cism for explaining LBV eruptions is that the mechanisms which are related to late nuclear
burning instabilities are expected to occur only in the few years preceding core collapse.
However, many LBVs with massive shells appear to have survived for $10^2-10^4$ yr after a
giant eruption. Such an objection turns into an advantage, however, in the case of violent
pre-SN eruptions needed for SNe IIn (see below).

Research on LBV eruptions and pre-SN eruptions is actively ongoing, and it is a major
unsolved problem in astrophysics. Observations demonstrate that these events do occur,
and the mass budget involved can dominate or significantly contribute to the total mass
lost by a massive star.

4.3 The Role of LBV Mass Loss in Stellar Evolution

If this section were to review the influence of LBV eruptions when they are included in
stellar evolution models, it would be a very short section. Without exception, no current
stellar evolution models account for LBV giant eruptions. This is because we don’t know
how to include them properly. Observationally, we don’t have reliable estimates of the
typical mass ejected as a function of the star’s initial mass, how many repeating eruptions
occur for a given star, or the duty cycle of eruptions. Theoretically, we don’t know the
underlying physical mechanism(s), when they occur during the evolution of a star, or how
they should vary with $M_{ZAMS}$.

The traditional view of LBVs, which emerged in the 1980s and 1990s, is that they cor-
respond to a very brief transitional phase of evolution, when the massive star moves from
core H burning to core He burning ([Humphreys & Davidson 1994]). A typical monotonic
evolutionary scheme is:

100 $M_{\odot}$: O star $\rightarrow$ Of/WNH $\rightarrow$ LBV $\rightarrow$ WN $\rightarrow$ WC $\rightarrow$ SN Ibc

In this scenario, the strong mass-loss experienced by LBVs is important for removing what
is left of the star’s H envelope after the MS, leaving a WR star following the LBV phase. The
motivation for a very brief phase comes from the fact that LBVs are extremely rare: the du-
ration of the LBV phase is thought to be only a few $10^4$ yr ([Humphreys & Davidson 1994]).

However, a number of inconsistencies have arisen with this standard view. The very
short inferred LBV lifetime depends on the assumption that the observed LBVs occupy the
whole transitional phase. In fact, there is a much larger number of blue supergiant stars
that are not seen in eruption — these are the LBV candidates. Examining populations in
nearby galaxies, Massey et al. (2007) find that there are more than an order of magnitude
more spectroscopically similar LBV candidates than there are LBVs confirmed by their
variability. If LBV candidates are included, then the average LBV phase rises from a few
$10^4$ yr to several $10^5$ yr. This is comparable to the whole He burning lifetime of very massive
stars, making it impossible for LBVs to be mere transitional objects. Massey (2006) has
pointed to the case of P Cygni as a salient example: its 1600 A.D. giant LBV eruption was
observed and so we call it an LBV, but it has shown no eruptive LBV-like behavior since
then. If the observational record had started in 1700, then we would have no idea that P
Cygni was an LBV.

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4Soker and collaborators have discussed a model to power the luminosity in LBV eruptions using
accretion onto a companion star ([Kashi & Soker 2003]), but this invokes an eruption to provide the mass
that is then accreted; it does not explain what initiates the mass loss from the primary in the first place.
Another major issue is that we have growing evidence that LBVs or something like them (massive H-rich stars with high mass loss, N enrichment, slow 100-500 km s$^{-1}$ winds, massive shells) are exploding as core-collapse SNe while still in an LBV-like phase (see below). This could not be true if LBVs are only in a brief transition to the WR phase, which should last another 0.5-1 Myr.

A prolonged LBV phase, and indeed any very massive stars above $M_{\text{ZAMS}} = 40 \, M_\odot$ making it to core collapse with H envelopes still intact at $Z_\odot$, is in direct conflict with the single-star evolution models. The evolutionary state and basic nature of LBVs is therefore still quite uncertain. This is problematic for our understanding of massive star evolution, in which mass-loss is a key ingredient, since LBVs have the highest known mass-loss rates of any stars (Figure 3).

4.4 Low Metallicity

While we don’t yet know the root cause of LBV eruptions, we do know that the huge observed mass-loss rates demand that the mechanism imparting momentum to the ejecta is not a $Z$-dependent wind, because the outflowing material is very optically thick and lines are saturated. LBV eruptions must be either continuum-driven SE winds or hydrodynamic events (violent pulsations, explosions), and both of these are relatively insensitive to $Z$. Since this mode of eruptive mass loss may actually dominate the total mass shed by a massive star at $Z_\odot$, there is not yet any reason to think it won’t also work in the early universe. This may be important for Pop III stars, since they are argued to have been preferentially very massive. There may, of course, be some unrecognized way that metallicity creeps into the problem (i.e. Fe opacity bumps, some $Z$ dependence of explosive burning, etc.), but this has not yet been investigated. LBVs have been identified in nearby low-Z dwarf galaxies [Izotov & Thuan 2009, Izotov et al. 2011], in addition to the very nearby case of HD 5980 in the SMC, and the LBV-like eruptions that precede SNe IIn (see below) often occur in dwarf galaxies. Thus, there is empirical evidence that low metallicity does not inhibit eruptive mass loss.

5 BINARY MASS TRANSFER, MERGERS, AND MASS LOSS

At massive-star conferences, a common refrain heard upon completion of a talk about single-star evolutionary models is: “What about binaries?” This is often followed by an uncomfortable silence, shrugging of shoulders, nervous laughter by the speaker, or intervention by the session chair to move to a serious question.

Actually, this is a serious problem. Exclusion of complicated binary effects and a focus on single-star evolution models is valid, in principle, because indeed we must start by having a foundation in understanding single stars. However, comparing single-star models to the observed statistical properties of stars – and then using these diagnostics to inform the validity of assumptions in those single-star models – can lead to serious errors if binaries make a significant contribution to observed distributions. The most critical influence of binaries on the observed distribution of massive stars comes through the process of mass loss and mass transfer via RLOF, which exceeds the influence of stellar winds and rotation for most (and possibly all) initial masses.
5.1 Massive Stars are Mostly in Binaries

Based on work in the past decade, we now have secure evidence that the binary fraction is not only high among massive stars, but that the large majority of massive stars (roughly 2/3-3/4) reside in binary systems that have orbital periods short enough that the stars will interact and exchange mass (or merge) during their life (Mason et al. 2009, Sana & Evans 2011, Sana et al. 2012). There have been several monitoring campaigns to measure the observed spectroscopic binary fraction among massive stars in clusters using radial velocities, which typically find an observed binary fraction of 20-60% (Chini et al. 2012, De Becker et al. 2006, Garcia & Mermilliod 2001, Gies 1987, Kiminki & Kobulnicky 2012, Kiminki et al. 2012, Mahy et al. 2009, Sana et al. 2008, 2009, 2012). However, these observed binary fractions are only a lower limit, because they must be corrected for the spectroscopic binary systems that are missed because of low inclination, periods that are too long compared to the observational cadence or have high eccentricity, or low-mass companions that are more difficult to detect. Some fraction of these have orbital separation small enough that the stars will actually interact and exchange mass, typically determined by the maximum radius of a RSG (roughly 5 AU) or LBVs in outburst (a few AU) depending on the initial masses of the stars (Kiminki & Kobulnicky 2012).

Recent estimates including the results from several young clusters suggest that, when corrected for observational bias, the fraction of massive stars in binary systems whose orbital period is so short that the stars must exchange mass or merge is something like 3/4 (Kiminki & Kobulnicky 2012, Kobulnicky & Fryer 2007, Sana et al. 2012). Of the total population of massive stars, Sana et al. (2012) estimate that ~1/4 will merge, ~1/3 will have their H envelopes stripped before death, and ~14% will be spun up by accretion, whereas only about 1/4 of massive stars are actually effectively single (including stars in wide binaries). This means that binary RLOF is not just a factor that we should perhaps consider, but that it must dominate the observed effects of mass loss and mixing seen in massive stars. It is also likely that the vast majority of the most rapidly rotating stars, including potentially all Be stars, result from interaction with a companion star (de Mink et al. 2013) rather than single stars born with a very high rotation rate. This, in turn, suggests that influence of rotation and rotational mixing in current single-star models may be overestimated (de Mink et al. 2013, Vanbeveren 2009).

5.2 Physics of Mass Loss in Binaries

From the ZAMS until the H envelope is substantially stripped or removed completely, a massive star will tend to have its radius increase due to interior evolution. This begins on the MS as stars steadily become more luminous and slightly cooler, and the radius then expands more severely in post-MS phases. In a binary system, significant mass transfer begins when the primary star expands to a size where its photosphere crosses the inner Lagrange point (L1).

The onset of RLOF therefore depends sensitively on the initial orbital separation; it may occur while the primary is still on the main sequence (orbital periods of a few days) or when it expands to a much larger size in post-MS supergiant phases (orbital periods of 10s of days or longer). RLOF on the MS is referred to as Case A, whereas Case B is for RLOF during H shell burning and Case C for core He burning (Langer 2012, Petrovic et al. 2003, Podsialkowski et al. 1992). Mass transfer becomes increasingly unstable and rapid from Case A to C, in some cases involving dynamical events, common envelopes, or inspiral and
mergers. The mass transfer rate also depends sensitively on the mass ratio \( q = M_2/M_1 \) (\( q \leq 1 \)), with increasing rates for lower values of \( q \). For Case A, the orbit widens and the mass transfer rate drops as \( q \) approaches unity.

Mass-transfer rates (and hence, mass-loss rates from the primary) can be very high, and can far exceed any mass-loss rate for a line-driven wind (see Figure 3). The detailed physics of mass transfer in RLOF is quite complicated and time-dependent. There is much remaining uncertainty about the proper treatment of contact systems, as well as their mass and angular momentum loss. A common prescription for the strongest phases of RLOF mass transfer is to assume that the mass transfer is limited by the thermal timescale of a massive star with a radiative envelope:

\[
\dot{M} = \frac{(M_0 - M_{WR})}{\tau_{KH}}
\]

where \( \tau_{KH} \) is the thermal (Kelvin-Helmholtz) timescale of the envelope, \( M_0 \) is the initial mass, and \( M_{WR} \) is the mass of the resulting WR star. Mass-transfer rates can therefore be the highest for more massive and more luminous stars, which have short thermal timescales. Resulting mass transfer rates can be extremely high; during fast Case A or Case B and C phases, mass-loss rates can be of order \( 10^{-3} \, M_\odot \, \text{yr}^{-1} \) or higher (Langer 2012, Taam & Sandquist 2000), although there is a wide range (only order of magnitude values are represented in Figure 3). With thermal timescales of order \( 10^4 \) yr, binary RLOF is therefore capable of quickly removing almost the entire H envelope of a massive star and leaving behind a WR star (Petrovic et al. 2005). When RLOF ends, the star’s radius will shrink and there will be a small residual H layer on the star.

The physics and observed phenomenology of the RLOF phase and common envelopes can be very complicated (Taam & Sandquist 2000), and could probably fill several review articles. The main uncertainties are in the degree to which mass transfer is conservative (Cantiello et al. 2007, de Mink et al. 2007), the related question of how the mass gainer responds to the added angular momentum that may lead to critical rotation (de Mink et al. 2013), and the consequent orbital evolution. The most important point for our purpose here is to concentrate on the net result: large amounts of mass are “instantly” (relative to nuclear burning timescales) stripped from one star, and much or all of this is accreted by the other. The envelope stripping of the primary is similarly efficient to the also “instantaneous” removal of \( \sim 10 \, M_\odot \) in giant eruptions of LBVs (see above). Indeed, their mass-loss rates are suspiciously similar in Figure 3 and it remains possible that some LBV giant eruptions are extreme mass transfer or merger events (many LBVs or LBV candidates have only a single massive CSM shell). Podsiadlowski et al. (2010) have discussed extreme cases where mixing of fresh fuel into deeper layers during a binary merger might lead to explosive burning and removal of the H envelope, reminiscent of some ideas for explosive LBV giant eruptions.

There are few observational constraints on mass loss and mass transfer rates in binaries undergoing RLOF. Since the most active phases are very brief (\( \sim 10^4 \) yr; less than 1% of a massive star’s life), systems undergoing strong RLOF at any given time are rare. (The longer-lasting systems in slow Case A RLOF are more common, but have lower mass-transfer rates; see de Mink et al. 2007.) One well-studied example of a short-period system caught in the phase of fast Cas A mass transfer is the 11-day eclipsing binary RY Scuti. It has component masses of roughly 8 and 30 \( M_\odot \), with a mass-gainer surrounded by an opaque disk (Grundstrom et al. 2007) and a spatially resolved toroidal nebula (Smith et al. 2011c). A noteworthy object for wider orbital separations (probably Case C) is the famous YHG

\[5\]“Conservative” mass transfer means that no significant mass is lost from the binary system in RLOF.
star HR 5171A, which Chesneau et al. (2014) recently resolved as a mass transfer binary using interferometry. This system hints that some of the YHGs may actually be wide binary systems, where RLOF truncates further redward evolution of the primary, rather than being products of single-star RSG mass loss. Since the companion was not discovered until it was resolved with interferometry, this also demonstrates that these binaries may be easily hidden. Interestingly, Prieto et al. (2008b) report the discovery of a rare extragalactic YSG eclipsing binary, which may provide a similar indication. Aside from these rare cases, much of our empirical understanding of RLOF therefore comes from studying the more common post-RLOF binaries (WR+OB systems). Their inferred histories depend on a number of assumptions, however (Hellings 1984).

5.3 Binary Evolution Models and Population Synthesis

The idea that binary RLOF strips a star’s H envelope to dominate the production of WR stars and SNe Ibc is an old one (Paczynski 1967). As noted in the introduction, this view fell out of favor due to the estimated strength of radiatively driven winds, but is now experiencing a resurgence due to lower wind mass-loss rates and very high observed binary fractions. As such, it is now clear that the complexity of RLOF and its many varying parameters are a necessary evil to consider. Some advocates for the importance of binaries may point out that this was true all along (e.g., Vanbeveren et al. 1998).

Before and after binary stars interact, they behave largely as single stars, and so binary stellar evolution models come with all the assumptions and uncertainties that go into single-star models, like the treatment of convection, assumptions about convective overshoot, the importance of rotational mixing and angular momentum diffusion, and of course wind mass loss (Maeder & Meynet 2000, Woosley et al. 2002). Binary evolution introduces additional parameters (Langer 2012). The total mass lost or transferred in RLOF, its transfer rate, the amount of angular momentum lost/transfered, and time dependence of these are influenced by several intial conditions: 1) the primary/secondary initial mass ratio \( q \), 2) the primary star’s initial mass, 3) the initial orbital separation, 4) the orbit eccentricity, and 5) the relative wind mass-loss rates of both stars. It may also matter if a system has additional multiplicity, but this is usually ignored. Calculating grids of detailed binary stellar evolution that explore this parameter space and also provide a detailed treatment of rotation and mixing in the stars would require a large fraction of the computing power on Earth. Therefore, present state-of-the-art binary models and population synthesis must make simplifying assumptions (Langer 2012). Binary population synthesis models have demonstrated that RLOF can naturally account for many of the observed statistical distributions of stellar types, as well as the relative rates of various types of SNe (Dessart et al. 2011, Eldridge & Stanway 2009, Eldridge et al. 2008, Petrovic et al. 2003, Podsia[ldowski et al. 1992, Sana et al. 2012, Vanbeveren et al. 1998, 2007, Yoon et al. 2010). Earlier studies made inferences about what the interacting binary fraction would need to be in order to account for observations. If new estimates of the very high binary fraction are correct, it now seems unavoidable that binary evolution will dominate the observed populations of WR stars and SNe Ibc (sections 6.1 and 6.2).

The fact that binary population synthesis can naturally explain the observed statistical properties of massive stars (like the observed ratio of WR to OB stars, relative numbers of various SN types, etc.) means that single-star models (which represent a minority of stars) should not do so. The point is that by including efficient rotational mixing and stellar winds that are too strong, single-star models mimic outcomes that are in fact dominated
to a large extent by binary RLOF. This raises concerns about the correctness of physical ingredients adopted in these single-star models, including the treatment of rotation and turbulent convection in addition to the overestimated mass-loss rates.

5.4 Low Metallicity

The physics of RLOF is governed by the gravitational interaction of two stars, and is insensitive to the metallicity of the gas being transferred. The insensitivity to $Z$ for the extreme mass loss induced by RLOF is therefore similar, in principle, to the continuum-driven winds and explosions of LBVs (Smith & Owocki 2006). This should have strong implications for populations of evolved stars and SNe at low $Z$, although this aspect has not been much explored in the literature.

Observations do indicate evolution with metallicity, such as the WC/WN ratio (Massey 2003) and the relative rates of Type Ib to Type II SNe (Boissier & Prantzos 2009, Prantzos & Bissier 2003, Prieto et al. 2008a). However, we should be cautious that even binary RLOF may have some dependence on metallicity, since metallicity affects the opacity in the star’s envelope, and hence, the hydrostatic stellar radius. With lower opacity, low-$Z$ stars are more compact (Heger et al. 2003, Maeder & Meynet 2000). The onset of RLOF depends on the primary star’s radius, so a low-$Z$ stellar population might be less affected by RLOF on average than at $Z_\odot$. It might be easy to mistakenly attribute such apparent $Z$ dependence entirely to line-driven winds, so the $Z$ dependence (or not) of RLOF therefore deserves additional study. Of course, extrapolating RLOF to low $Z$ also requires detailed knowledge of binary star formation physics and the resulting period distribution as a function of $Z$, which are not readily available but may be quite important. This impacts a number of issues in astrophysics, but most obvious is the progenitors of GRBs.

Nevertheless, even if we were to adopt zero $Z$ dependence for RLOF, observed trends with $Z$ of WC/WN stars and SNe Ib/c/H do not contradict the dominant role of binary RLOF. An important point for interpreting WR subtypes and SN progenitors is that even when stripping of the H envelope is done by RLOF, the subsequent evolution from WN to WC (and SN Types IIb to Ib to Ic) is still determined largely by $Z$-dependent line-driven winds. This is discussed next.

6 END RESULTS OF MASS LOSS AND IMPLICATIONS

6.1 Outcomes I: WR stars as the product of mass loss

One of the most fundamental tenets of massive star evolution is that strong mass loss through winds will strip off a star’s H envelope and leave a bare He core that we observe as a luminous WR star. (For the purpose of discussion here, we exclude WNH stars.) The agent that dominates that stripping of the H envelope and how it varies with metallicity is a long-standing unsolved issue. Does every massive O-type star evolve to become a WR star, or only those in interacting binaries or in certain initial mass ranges? The answer to this question has important implications for relative nuclear burning timescales in various phases, SN progenitors, and many other issues.

In a single-star framework, only the most massive stars are luminous enough to have radiation-driven winds that can remove the massive H envelope, so one expects a $Z$-dependent minimum initial mass that can yield a H-poor WR star, $M_{WR}(Z)$. Standard single-star models predict $M_{WR} \approx 35M_\odot$ at $Z_\odot$ (Georgy et al. 2012, Heger et al. 2003), in-
creasing to about 45 and 70 $M_\odot$ at $Z_{LMC}$ and $Z_{SMC}$, respectively (Heger et al. 2003). $M_{WR}$ can be lowered by adopting substantially enhanced mass-loss rates in models (Ekström et al. 2012, Meynet et al. 1994), or by including the effects of relatively rapid rotation (Georgy et al. 2012).

At first glance, models and observations would seem to be reasonably well aligned (Massey 2003): $M_{WR}$ is inferred to be about 25 $M_\odot$ at $Z_\odot$ (Crowther 2007), increasing to about 30 and 70 $M_\odot$ at $Z_{LMC}$ and $Z_{SMC}$, respectively (Massey et al. 2000). However, theoretical expectations for $M_{WR}$ are based on models that incorporate mass-loss rates that are known to be a factor of $\sim 3$ too high. (They also do not include the weak-wind problem discussed earlier, which is important in this mass range, and which affects a large fraction of SN progenitors.) With the $Z^{0.69}$ scaling of mass-loss in line-driven winds (Vink et al. 2001), this means that the appropriate mass-loss rates for $Z_\odot$ are actually similar to those currently adopted in SMC models. Grids of models with appropriate mass-loss rates have not been published, but we can infer that the net effect will be to move the predicted $M_{WR}$ upward significantly in single-star models for each $Z$ range, to a point that probably cannot be reconciled with observed $M_{WR}$.

In a binary evolution paradigm, on the other hand, He stars stripped of their H envelope can occur over a wider range of initial mass (Claeys et al. 2011, Vanbeveren et al. 2007). In that case, the dominant factors controlling observationally inferred values of $M_{WR}$ are detectability and classification, as well as the wind strength that removes whatever residual H layer may be left at the end of RLOF. Even if the H envelope is removed (by any mechanism), classifying an object as a “WR star” observationally requires a strong wind to produce strong emission lines, which will favor sources of higher $L$ and $Z$. It may be hard to detect exposed He cores resulting from binary RLOF in $M_{ZAMS} = 10-25 M_\odot$, and their low luminosity and weak emission lines would prevent them from being classified as WR stars. Their brighter, cooler companion star may be overluminous because it has just accreted its companion’s H envelope. Such stripped-envelope stars should be the most common SN Ibc progenitors (see below).

Two other key considerations are the observed WC/WN ratio that increases with $Z$ (Massey 2003), as well as the fact that even early-type WR stars in the SMC tend to have some small amount of H present in their atmospheres (Foellmi et al. 2003); both of these are generally attributed to the important role of $Z$-dependent, line-driven winds. Again, it is important to recognize the influence of the stellar wind after the H envelope is stripped in binary RLOF. No matter what mechanism removes the H envelope (binary RLOF, LBV eruptions, RSG winds, or hot-star winds), the subsequent evolution will be dominated by a line-driven wind (Claeys et al. 2011, Vanbeveren et al. 2007). Binary RLOF leaves a thin H layer, and stars at lower $Z$ or lower $L$ will have a harder time removing it. Similarly, the evolution from a WN to a WC star (if this progression is monotonic) will be harder at lower $Z$ or lower $L$, even if the H envelope was stripped by binary interaction. Therefore, comparing models to the observed WC/WN ratio and showing that it increases with $Z$, for example, is not indicative of the importance of line-driven winds in any earlier phases of evolution, since any scenario should predict an increasing WC/WN ratio with $Z$.

Altogether, it is difficult to rule out the hypothesis that binary RLOF is the dominant agent responsible for producing most or all WR stars, and it remains unclear under what ranges of $L$ and $Z$ (if any) a single-star can become a WR star via its own wind mass loss.

Vanbeveren et al. (2007) has criticized the application of these rotating models to observed trends, pointing out that the initial 300 km s$^{-1}$ rotation speeds in models are not representative of most massive stars. Correcting observed rotation speeds for a distribution of inclination angles, he argues that most O-type stars rotate more slowly at 100-120 km s$^{-1}$. 

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**Mass Loss** 27
Unfortunately, finding examples of apparently single WR stars does not provide a conclusive answer, since a companion star may have exploded already. Moreover, the possible importance of RSG mass loss in producing WR stars is still not well understood. It is suspicious that most H-poor WR stars have luminosities of \( \log(L/L_\odot) = 5.5 \) to 5.8 (Crowther 2007, Hamann et al. 2006), which also corresponds to the strongest RSG mass loss (Fig. 3). The creation of WR stars is, of course, also closely related to the end fate in a SN and the rates of various SN subtypes that are seen, as discussed next.

6.2 Outcomes II: The main supernova subtypes

Core-collapse SNe exhibit a wide diversity of properties, summarized briefly in the accompanying sidebar. Different SN types are the direct product of different amounts of mass loss from massive stars, and they provide key constraints that inform our understanding of stellar evolution. Here we discuss the main types of SNe II and Ib with “normal” SN atmospheres. Types Ibn and Ibn with narrow emission lines from dense CSM that indicate eruptive pre-SN mass-loss are discussed separately in the next section. Table 1 includes a map of SN type to progenitor star properties, based on current prevailing ideas.

For understanding the main population of SNe, the relative rates of various subtypes are critical, since they must match the relative fractions of different progenitor stars for a given initial mass function (IMF). Volume-limited rates of the various core-collapse SN sub-types (excluding SNe Ia) measured in a controlled sample are now available (Smith et al. 2011); these come from the Lick Observatory SN Search, which targeted mainly large galaxies representative of \( \sim Z_\odot \) (Li et al. 2011). The most common core-collapse SNe are Type II-P (48.2\%\pm6\%), marking the explosions of relatively low-mass RSGs. Types II-L and II contribute 6.4\%\pm3\% and 9\%\pm3\%, respectively. The remainder (36.5\%\pm6\%) are “stripped envelope” SNe of Types IIb (10.6\%\pm3.6\%) and Ib (26\%\pm5\%; including a few peculiar cases like SNe Ic-BL and Ibn that are rare at \( Z_\odot \)).

The observed fraction of stripped-envelope SNe is a key constraint on mass loss for the majority of massive stars. Smith et al. (2011) pointed out that the observed fraction of stripped-envelope SNe (IIb+Ib+Ic) of 36.5\% is far too high to be reconciled with predictions of single-star evolution. If SN Ib progenitors are assumed to be WR stars, then the observed fraction of SNe Ib (not including SNe IIb) would require \( M_{WR} = 22 M_\odot \) (Smith et al. 2011b). While this is not much lower than the lowest-mass WR stars observed in the Milky Way (Crowther 2007), it is much lower than can be explained by standard single-star evolution models — especially if we recognize that “standard” single-star models all adopt mass-loss rates that are too high. The observed SN statistics strongly favor the interpretation that most stripped-envelope SNe (including SNe IIb) come from lower-mass stars (10-25 \( M_\odot \)) that lose their H envelope in binaries. Again, \( \sim\)36\% is the observed SN IIb+Ib+Ic fraction; compare this to 33\%, which is the fraction of massive stars that Sana et al. (2012) expect to have their H envelopes stripped in a binary system, given the observed binary fraction of O-type stars. One infers that binary RLOF can account for the observed statistics. (Recall that \( \sim80\% \) of SNe come from initial masses <25 \( M_\odot \), assuming a Salpeter IMF where every star with initial mass above 8.5 \( M_\odot \) explodes as a SN.) Preference for the binary channel agrees with relatively low ejecta masses and H/He mass fractions inferred from detailed radiative transfer models of stripped-envelope SNe (Dessart et al. 2011, Hachinger et al. 2012, Yoon et al. 2010), which seem to rule out the idea that SNe Ib and II can come from progenitors much more massive than progenitors of SNe II-P, on average.
A dominant binary channel for stripped-envelope SNe is also consistent with available direct detections and upper limits of SN progenitors. Smartt (2009) summarized progress up until 2008, but there have been several important additions since then. Observations to date are consistent with stars that have initial masses of roughly 8-20 $M_{\odot}$ dying as SNe II-P, but this does not necessarily mean that all stars in this mass range die that way. Stars in the same mass range could die as stripped-envelope SNe if they are in a binary system. In fact, there are currently 3 direct progenitor detections for SNe Iib (SN 1993J, 2011dh, and 2013df) that are thought to be YSGs in binary systems with inferred initial masses of 13-17 $M_{\odot}$ (Maund & Smartt 2009, Van Dyk et al. 2013a,b). Two other SNe Iib, SN 2001ig and SN 2008ax also show possible indications of a companion star (Crockett et al. 2008, Ryder et al. 2006). Moreover, there are as yet no detections of progenitors of SNe Ibc. This seems unlikely if luminous WR stars are their progenitors (Smartt 2009), but the hot temperatures of WR stars make it hard to definitively rule them out.

What about stripped-envelope SN fractions at lower Z? The SN Ibc/II ratio decreases at lower metallicity (Boissier & Prantzos 2009, Prantzos & Bressan 2003, Prieto et al. 2008a), as noted earlier. However, Smith et al. (2011b) pointed out that the relevant ratio really is ($Ib + Ibc$)/($II-P + II-L + IIn$), since SNe Iib are almost identical to SNe Ibc but for $<0.01 M_{\odot}$ of H in their outermost layer (Dessart et al. 2011, Hachinger et al. 2012). The recent study by Arcavi et al. (2010) finds that compared to giant galaxies at high Z, there is a much larger fraction of SNe Iib and a lower fraction of normal SNe Ibc in lower-Z dwarf galaxies. The lower fraction of SNe Ibc is expected in single-star models, but the higher fraction of SNe Iib is not. Since the removal of the H envelope itself would be greatly hindered, we would expect a much larger fraction of SNe II-P and II-L at lower Z, not SNe Iib. This result is, however, expected in binary evolution, since low-Z line-driven winds have a harder time removing the residual H layer that remains after RLOF (Claeys et al. 2011). Interestingly, Arcavi et al. (2010) also find a larger relative fraction of SN Ic-BL in low-Z dwarf galaxies; this is not yet explained, partly because we don’t have a good understanding of what physical mechanism makes some SNe Ic have such broad lines. It follows the trend that GRBs and their associated SNe Ic-BL seem to prefer low Z (Modjaz et al. 2008).

Altogether, current evidence strongly suggests that it is no longer true that single WR stars are the preferred progenitors of most stripped-envelope SNe. Massive WR stars might yield some of the SNe Ibc, of course, especially in the smaller category of SNe Ic and GRBs that may favor high-mass progenitors, but many SNe Ibc must come from lower initial masses where the H envelope is stripped in a binary.

Using radio and X-ray observations, one can probe the density in the wind of the SN progenitor directly. Assuming wind speeds of $\sim$1000 km s$^{-1}$, observations suggest a very wide range of mass-loss rates for SN Ibc progenitors, from $10^{-7} M_{\odot}$ yr$^{-1}$ up to values near the line-driving limit, with an average around $10^{-5} M_{\odot}$ yr$^{-1}$ (Welhows et al. 2012). The examples near the lower end of this range are inconsistent with WR winds, while those near the upper end of the range are (see Figure 3). This is further evidence that SNe Ibc may arise from a large range of initial mass, including relatively low-luminosity stars with weak winds.

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7The upper bound of this range is uncertain, and higher than found by Smartt (2009) if one accounts for progenitor reddening (Walmswell & Eldridge 2012).

8Many studies group SNe Iib and II-L together into a transitional class between SNe II-P and Ib in a single-star framework (e.g., Figure 3). However, it is important to note that SNe Iib and II-L are actually quite different, and they are not part of the same continuum in decreasing H envelope mass. SNe Iib really are almost identical to SNe Ib, whereas SNe II-L have more in common with normal SNe IIn and SNe II-P.

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that must have lost their envelopes in binary RLOF. Interestingly, the SN Ibc near the top of this range tend to show density modulation in their winds, which may indicate slow and dense outflows from RLOF or interacting winds in binaries (Podsiadlowski et al. 1992), pre-SN eruptive mass loss (Smith & Arnett 2014), or S Doradus (LBV-like) variability (Kotak & Vink 2006). This pre-SN variability is not yet understood, while much more extreme cases of eruptive pre-SN mass loss are also seen, discussed next.

6.3 Outcomes III: Enhanced pre-SN mass loss and luminous SNe

One of the more exciting new developments in massive star and SN research in the past decade is the recognition that a subset of massive stars undergo violent eruptive mass loss immediately preceding core collapse, and that this may yield some of the most luminous SNe in the universe.

A SN blast wave expands outward into the CSM and the ensuing collision, referred to as “CSM interaction”, is commonly observed in the form of X-ray or radio emission (Chevalier & Fransson 1994) for normal winds (Figure 3). In 8-9% of core-collapse SNe (Smith et al. 2011b), however, the CSM is so dense that the shock interaction gives rise to strong narrow emission lines in the visual-wavelength SN spectrum. When the CSM is very dense, it can substantially decelerate the fast SN ejecta and convert a large fraction of the kinetic energy (10-50% or more) into radiation. When these strong narrow emission lines are observed, we refer to the SN as Type IIn (narrow H lines) or Ibn (narrow He lines). In general, $\dot{M}$ values of at least $10^{-3}$ to $10^{-2} M_\odot$ yr$^{-1}$ are required for the narrow emission lines to compete with the luminosity of the normal SN photosphere. There is a huge diversity among SNe with strong CSM interaction, which can be understood in a few different regimes:

- Super-luminous SNe (SLSNe) with Type IIn spectra represent the most extreme cases of eruptive pre-SN mass loss, with luminosities ~10 times higher than a normal bright SN Ia. Smith & McCray (2007) proposed that these extremely high luminosities could be achieved with normal energy core-collapse SNe (a few $10^{51}$ ergs) if the fast SN ejecta crash into a very massive 10-20 $M_\odot$ CSM shell. This large mass comes from the basic physical requirement that the CSM must have enough inertia to substantially decelerate the fast SN ejecta and convert its expansion kinetic energy into thermal energy that can be radiated away. Diverse SLSN light curve shapes are possible, depending on the distribution of the mass and explosion properties (Chatzopoulos & Wheeler 2013, Chevalier & Irwin 2011, Moriya et al. 2013, van Marle et al. 2010). SN 2006gy was the first observed event that instigated these ideas of massive CSM shell collisions (Ofek et al. 2007, Smith & McCray 2007, Smith et al. 2007, 2010a, Woosley et al. 2007), but a number of very luminous SNe IIn have been studied in detail since then, including objects like SN 2006tf (Smith et al. 2008), SN 2003ma (Rest et al. 2011), and SN 2008tz (Drake et al. 2013).

- SNe IIn with moderate luminosity represent less extreme cases than SLSNe, but they still require strong CSM interaction that indicates eruptive or episodic pre-SN mass-loss events. Instead of pre-SN ejections of 10-20 $M_\odot$, more typical luminosities require less massive shells of order 0.1-1 $M_\odot$. The lower luminosity could result from lower explosion energy (see SNe IIn-P below), but for normal SNe IIn it is

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9 Note that slower outflows would reduce the value of $\dot{M}$ inferred from radio observations.
more likely attributed to lower density CSM, or asymmetric CSM that only intercepts a portion of the explosion solid angle. Some well studied SNe IIn like SN1998S (Leonard et al. 2000) and SN 2009ip (Levesque et al. 2013, Smith et al. 2014) are consistent with very asymmetric or even disk-like CSM. The mass-loss rates indicated by the CSM suggest that viable progenitors could be LBVs (Gal-Yam et al. 2007, Taddia et al. 2013) as well as extreme RSGs or YHGs (Smith et al. 2009) (see Fig 3). Although the immediate pre-SN eruptive mass loss is less extreme than required for SLSNe IIn, some SNe IIn show strong CSM interaction that continues for years or decades (like SN 1988Z, Aretxaga et al. 1999) as well as long-lasting IR echoes from distant dust shells illuminated by the SN (Fox et al. 2011, Gerardy et al. 2002) — both of these indicate a considerable amount of mass lost by the progenitor star for centuries before core-collapse, either in previous eruptions or very strong dusty winds. Since the IIn spectral signature depends on mass loss rates and not the underlying explosion mechanism, then from the point of view of massive-star mass loss, we may naturally expect a continuum between normal SNe IIn and either II-L or II-P. Identifying this may require larger numbers of SNe to be observed, or high-quality early-time spectra.

• The subclass of SNe IIn with plateau light curves, SNe IIn-P, was proposed recently (Mauerhan et al. 2013b), represented by SNe like SN 1994W, SN 2009kr, and SN 2011ht. Among the wide diversity of SNe IIn, this subset is surprisingly homogeneous, with nearly identical spectral evolution and very similar light curves that all plummet sharply after ~120 days (other SNe IIn have smoothly declining or very slowly declining light curves). These may be relatively low-energy ($10^{50}$ erg) electron-capture SNe from $M_{ZAMS} = 8-10 \, M_\odot$ super-AGB stars that achieve luminosities of normal SNe through intense CSM interaction (Smith 2013b).

• Explosions classified as SNe Ibn are very similar to SNe IIn, except that instead of narrow H lines, they exhibit narrow He lines. Their peculiar spectra arise from the same basic scenario as SNe IIn, with a SN shock interacting with dense CSM, but here the CSM is H-poor. There are also a few reported transitional cases between SNe Ibn and IIn, including SN 2005la and SN 2011hw and 2005la (Pastorello et al. 2008, Smith et al. 2012), suggesting a possible continuum in progenitor H envelope stripping, similar to SNe II-P, IIb, and Ib. The best studied Type Ibn is SN 2006jc (Foley et al. 2007, Pastorello et al. 2007), for which an LBV-like outburst was detected 2 yr prior to the eventual SN. If SNe Ibn come from single stars, they are likely to be very massive WR stars; however, lower initial masses (10-20 $M_\odot$) can yield H-depleted progenitors through binary RLOF, and such stars may have dense H-poor CSM. There are not yet any detections of a quiescent SN Ibn progenitor. Interestingly, Sanders et al. (2013) report the detection of a SN Ibn in a giant elliptical galaxy with no evidence for ongoing star formation at the explosion site, which challenges the idea that these arise exclusively from very massive progenitor stars. This may echo the observation that some SNe IIn appear to be caused by an underlying thermonuclear Type Ia interacting with dense CSM (Silverman et al. 2013).

Until recently, pre-SN eruptive mass loss and connections to LBVs were mostly hypothetical, limited to (reasonable) conjectures supported by the circumstantial evidence that something must deposit a large mass of outflowing H-rich CSM so close to the star (Chugai et al. 2004, Smith et al. 2008, 2010b). However, we now have a handful of directly detected progenitor stars that seem consistent with LBVs, as well as a few examples of SN
explosions where an outburst was actually detected photometrically in the few years before a SN. In all cases the SN had narrow emission lines indicative of CSM interaction, but for each it is also difficult to prove conclusively that the event was a true core-collapse SN. So far all these objects have continued to fade and there is no clear evidence that the stars survived.

**SN 1961V.** This is Zwicky’s prototype Type V SN, later associated with LBV-like giant eruptions, but it may have been a true core-collapse SN IIn that was not recognized at that time because the Type IIn class didn’t exist yet. A luminous (~12.2 mag absolute at blue wavelengths) progenitor was detected at several epochs for ~20 yr preceding the SN 1961V event (Humphreys, Davidson, & Smith 1999), and this source has now faded. The pre-SN detections include small (~0.5 mag) fluctuations that resemble S Dor-like episodes, and in the year before the SN there is one detection at an absolute magnitude of roughly ~14.5, similar to LBV giant eruptions. Currently, a source at the same position is about 6 mag fainter than the progenitor, and still shows narrow Hα emission (Van Dyk & Matheson 2012) that could represent ongoing CSM interaction. The progenitor source has not been discussed in the context of SN progenitors because the 1961 event was considered an LBV eruption (a “super-η Car-like event”), not a true SN (see Van Dyk & Matheson 2012). Recently it was argued that SN 1961V was actually a true core-collapse SN IIn (Kochanek et al. 2011, Smith et al. 2011a), which would provide evidence for a ~100 $M_\odot$ LBV-like progenitor that experienced eruptive mass loss before a SN IIn.

**SN 2005gl.** This was a normal SN IIn with pre-explosion *HST* images that showed a source at the SN position, which then faded below detection limits after the SN had faded (Gal-Yam et al. 2007, Gal-Yam & Leonard 2009). Its high luminosity suggested that the progenitor was a massive LBV similar to P Cygni, with an initial mass of order 60 $M_\odot$ and a mass-loss rate before core-collapse of ~0.01 $M_\odot$ yr$^{-1}$.

**SN 2006jc.** A precursor eruption was discovered in 2004 and noted as a possible LBV or SN impostor. It had a peak luminosity similar to that of η Car (Pastorello et al. 2007). No spectra were obtained, but the coincident SN explosion 2 years later was a Type Ibn with strong narrow He i emission lines (Foley et al. 2007, Pastorello et al. 2007). There is no detection of the quiescent progenitor.

**SN 2009ip.** This source was initially discovered and studied in detail as an LBV-like outburst in 2009, before finally exploding as a much brighter SN in 2012. A quiescent progenitor star was detected in archival *HST* data, indicating a very massive 50-80 $M_\odot$ progenitor (Foley et al. 2011, Smith et al. 2010a). It showed slow variability consistent with an S Dor LBV-like episode (Smith et al. 2010a), followed by a series of brief LBV-like giant eruptions (Mauerhan et al. 2013, Pastorello et al. 2013, Smith et al. 2010a). SN 2009ip is so far unique among SN progenitor detections: not only did it have a detection of the quiescent progenitor and multiple pre-SN eruptions, but unlike any other object we also have detailed high-quality spectra of the pre-SN eruptions (Foley et al. 2011, Smith et al. 2010a). The presumably final SN explosion of SN 2009ip in 2012 looked like a normal SN IIn, as the fast ejecta crashed into the slow material ejected 1-3 years earlier (Mauerhan et al. 2013, Smith et al. 2014). A number of detailed studies of the bright 2012 transient have now been published, although there has been some controversy about whether the 2012 event was a core-collapse SN (Mauerhan et al. 2013, Ofek et al. 2013, Prieto et al. 2013, Smith et al. 2014) or some type of extremely bright non-terminal event (Fraser et al. 2013, Margutti et al. 2013, Pastorello et al. 2013). More recently, Smith et al. (2014) have shown that the object continues to fade and its late-time emission is consistent with late-time CSM interaction in normal SNe IIn. If SN 2009ip was indeed a SN, it provides the strongest case that very

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massive stars above $30 \, M_\odot$ do in fact experience core collapse, and LBV-like stars are linked to SNe IIn.

**SN 2010mc.** Ofek et al. (2013b) reported the detection of a precursor event $\sim 40$ d before the peak of the Type IIn SN 2010mc. It is unclear if this was a pre-SN outburst or the SN itself. Smith et al. (2014) showed that the double-peaked light curve of SN 2010mc was nearly identical to SN 2009ip, for which it has been suggested that the $\sim 40$ d precursor was actually the faint SN explosion of a blue supergiant, and the later rise to peak was caused by CSM interaction.

**SN 2010jl.** This was a SLSN IIn, with a peak absolute magnitude brighter than $-20$ mag. Smith et al. (2011d) identified a source at the location of the SN in pre-explosion HST images, suggesting either an extremely massive progenitor star or a very young massive star cluster; in either case it seems likely that the progenitor had an initial mass above $30 \, M_\odot$.

These direct detections of LBV-like progenitors and of pre-SN outbursts provide unambiguous evidence for violent eruptive mass loss associated with the latest phases in a massive star’s life. This only occurs in $\sim 9\%$ of core-collapse SNe (Smith et al. 2011b). The extremely short timescale of only a few years probably hints at severe instability in the final nuclear burning sequences, especially Ne and O burning (Arnett & Meakin 2011, Quataert & Shiode 2012, Shiode & Quataert 2013, Smith & Arnett 2014), each of which lasts about 1 yr. These instabilities may be exacerbated in the most massive stars, although much theoretical work remains to be done. The increased instability at very high initial masses is extreme in cases where pre-SN eruptions result from the pulsational pair instability (Woosley et al. 2002, 2007), but eruptions may extend to other nuclear burning instabilities as well (Arnett & Meakin 2011, Smith & Arnett 2014). Although the events listed above are just a few lucky cases, they may also be the tip of the iceberg. Undoubtedly, continued work on the flood of new transient discoveries will reveal more of these cases. The limitation will be the existence of high-quality archival data over long timescales of years before the SNe, but these sorts of archives are becoming more populated and improved as time passes. When LSST arrives, it may become routine to detect pre-SN outbursts, although constraining their physical nature with spectra will still be a challenge.

Not all SNe with strong CSM interaction necessarily require LBV-like progenitors, but many of them do, and most of the detected progenitors or progenitor outbursts are consistent with this hypothesis. If the progenitors of SNe IIn are not actually LBVs, they do a very good impersonation of the eruption energy, luminosity, spectral morphology, ejecta mass, H composition, and outflow speeds observed in LBV giant eruptions. In any case, the basic observation that very massive stars are reaching core collapse with massive H envelopes still intact is in direct conflict with single-star evolution models. Once again, this may be related to the issue of overestimated mass-loss rates adopted in these models and the neglect of binary evolution.

### 6.4 Extrapolating to low-Z and Pop III Stars

Stellar evolution is complicated, and fraught with tremendous uncertainties about mass loss. Faced with such road blocks, one can sympathize with the desire to divert one’s attention to Population III stars, where theorists are unencumbered by observational data. More seriously, though, there is indeed great interest in thinking about what the earliest stars in the Universe might have been like, since they had a strong impact on their environment and...
on galaxy evolution in general. These stars may have been very massive, and they made
the first SNe, the first stellar mass black holes, the first dust, ejected the first metals back
into the ISM, enhanced or dominated reionization, and probably triggered the formation
of the earliest generations of low-mass stars (Bromm & Larson 2004, Heger et al. 2003).
However, as we attempt to extrapolate from the huge uncertainty associated with local
stars to a regime where there is no data, we must be cautious.
In studying stars at very low $Z$, a standard approach is to extrapolate the smooth Z
dependence of line-driven winds to very low or even zero $Z$, essentially assuming that
massive stars at the lowest $Z$ will have no mass loss (Heger et al. 2003). This leads to
interesting fates for very massive stars, such as pair instability SNe (Heger et al. 2003,
Woosley et al. 2002). However, more recent results suggest that $Z$-dependent winds are
weaker than we used to think, even at $Z_{⊙}$. On the other hand, binary RLOF and eruptive
LBV-like mass loss are much more important than was appreciated in the past, and they
are relatively insensitive to $Z$. Thus, it is not safe to assume that massive stars at very low
$Z$ suffer much less mass loss on average.
As noted above, LBVs are seen in nearby low-$Z$ dwarf galaxies. Pre-SN mass loss also
provides some clues in this regard. Many SNe II and SLSNe occur in low-$Z$ dwarf galaxies
(Neill et al. 2011, Stoll et al. 2011), demonstrating that low $Z$ does not inhibit strong eruptive
mass loss. The influence of these pre-SN eruptions may have an interesting effect on the
predicted outcomes of SN explosions at low $Z$ (Couch & Ott 2013, Smith & Arnett 2014).

GRBs, of course, present one of the most puzzling observable mysteries about mass loss
and massive star evolution at low $Z$. The fact that GRB progenitors have shed most of their
envelopes while still retaining a great deal of angular momentum (MacFadyen & Woosley 1999)
would seem to strongly favor their origin in binary evolution with mass transfer to spin up
the star, or even a merger. GRBs are quite rare, so attributing them to a special circumstance
like a late-phase merger is plausible.

7 SUMMARY AND PERSPECTIVE

7.1 Take-home points
We now have a fairly firm understanding of stellar winds of hot O-type stars (Puls et al. 2008),
relevant for most of their lives on the H-burning MS phase. There remain substantial issues
in understanding the physics of wind driving, magnetic fields, and angular momentum
loss, and how these correspond to various observational diagnostics — but in terms of the
total mass-loss rates and their impact on stellar evolution, we know that wind mass
loss is weaker than we used to think, due to the effect of clumping. The consensus seems
to be that mass-loss rates need to be reduced by a factor of at least 2–3 compared to
rates derived observationally from standard $\rho^{2}$ diagnostics assuming homogeneous winds
(de Jager et al. 1988, Nieuwenhuijzen & de Jager 1990). Reduction by a factor of $\sim 10$ is
probably an overestimate for most O-type stars, but not for later O-types and early B-type
MS stars subject to the weak-wind problem.
Astronomers often scoff at a factor of 2 in any individual measurement, but we must
recognize that systematically lowering $\dot{M}$ by even a factor of 2 in models is very significant,
and a factor of 3 is huge (current debate generally centers around a factor of 2 or 3). A factor
of only 2 lower $\dot{M}$ would be like replacing mass-loss rates at $Z_{⊙}$ with mass-loss rates currently
used for 0.37 $Z_{⊙}$ (i.e. lower than the LMC), whereas a factor of 3 would correspond to 0.2
$Z_{⊙}$, similar to models for SMC stars (using $\dot{M} \propto Z^{0.69}$ Vink et al. 2001). With moderately

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weaker mass loss, we know that SMC models exhibit significantly different evolution than Milky Way stars. Most importantly, they do not produce such a large population of H-free WR stars. However, it is over this same metallicity range (Massey 2003) that we are testing the validity of the physical ingredients in stellar evolution models. This isn’t good.

For post-MS supergiant phases and binary RLOF, the uncertainty in mass loss is far worse — but these are also times when mass loss is strongest! Given that single-star models neglect eruptive mass loss and binaries, but match many properties of the observed distributions anyway, predictions beyond the end of H burning are not unique. Extrapolations to low Z and prescriptions for feedback from early stellar populations are therefore highly uncertain. Researchers working in other fields where massive star feedback is relevant — galaxy evolution, reionization, chemical evolution, low-metallicity stars, etc. — should be cognizant of this.

### 7.2 Perspectives and Directions

With such a high level of uncertainty in the most important phases of mass loss for massive stars, astronomers working on mass loss and massive star evolution have a few choices on how to proceed: 1) restrict their attention to MS stars, 2) work on Population III stars (see above), or 3) confront the complicated effects of binaries and time-dependent mass loss, as well as their influence on observed populations.

A major hurdle is disentangling the observed effects of single-star mass loss and binary RLOF. On the one hand, Occam’s razor encourages us to keep things simple, motivating us to understand single stars before we can hope to tackle the “free parameter heaven” of binaries. On the other hand, the massive stars we observe are mostly binaries: A wise man once said that we should “Make things as simple as possible, but not simpler”. The message here is that ignoring binaries, but testing single-star models against observed statistical properties of massive stars (which are mostly binaries) leads us to misinterpret single stars too, because we are relying upon strong winds and rotation to compensate for actual outcomes of binary RLOF.

Since the observed statistics of massive-star populations are unavoidably contaminated by the effects of binary stars, one alternative approach for testing single-star models would be to place less emphasis on matching these observed statistics, and more emphasis on matching individual observed stars with well-constrained physical parameters. Masses for “effectively single” stars can be measured in wide binary systems where the stars will not interact (or O-type stars that have not yet interacted on the MS), and for these a detailed modern quantitative analysis can yield estimates of $\dot{M}$, $T_{\text{eff}}$, $L$, rotational speed, abundances, etc. The distance must be known, but the Magellanic Clouds and clusters with known distances can help, and $\text{GAIA}$ will soon lower distance uncertainties for the nearest massive stars in the Milky Way. Doing this for a number of stars at various evolutionary stages and luminosities will build up a “grid” of observational constraints that models can aim to fit. Much of this observational work has already been done.

Given the huge level of uncertainty in post-MS mass loss (for both RSGs and LBVs), another general approach for theorists could be to use stellar evolution codes as “toy models”, to investigate the final outcome for a wide range of possible mass-loss prescriptions that include episodic mass loss. For example, one could calculate evolutionary tracks for very massive stars that have lower wind $\dot{M}$ during H burning, and then simply invoke one, two, or multiple sudden ejections of 10 $M_\odot$ in post-MS phases to mimic LBV eruptions, in order to learn how the star’s further evolution responds. This approach may seem artificial, but...
the goal would be to reverse-engineer stars, not to provide uniquely correct evolutionary tracks. In any case, much additional work on constraining post-MS mass loss of all forms is needed. A number of specific possible future directions for theory and observations are listed below.

8 FUTURE ISSUES: For theorists

1. A major task is to calculate stellar evolution models with lower wind mass-loss rates for MS phases, including rates appropriate for the weak-wind problem in later O-type and early B-type stars. These can be compared to precise measurements of physical parameters for well-studied individual stars, rather than populations, as noted above. For post-MS phases, mass-loss is simply too uncertain to predict unique outcomes. Toy models with various prescriptions for unsteady \( \dot{M} \) can help constrain the possible outcomes and their influence on SNe. Perhaps new open-source codes like MESA (Paxton et al. 2011) will facilitate this.

2. For episodic mass-loss in the latest pre-SN evolutionary phases, further work on stellar evolution with hydrodynamics and advanced nuclear burning is essential. Pre-SN eruptions constitute a new and very important unsolved problem in astrophysics, which may influence the outcome of core-collapse itself.

3. Theoretical investigations are needed to probe the underlying cause of LBV eruptions and its impact on the subsequent stellar evolution. Predictions for observed consequences of envelope instabilities, mergers/collisions, and explosive burning events are needed to link various possible physical mechanisms to observables for transient sources.

4. The hydrodynamics of RLOF and its dependence (or not) on metallicity is an important issue. A better understanding of mass and angular momentum transfer vs. mass loss from binary systems is needed to determine what conditions lead to mergers. In principle, mass transfer itself should be insensitive to \( Z \), but in practice, \( Z \) affects opacity, the stellar radius, and thus the onset of RLOF. In the end we may find that observed trends with \( Z \) hinge upon the formation of massive binaries (Kratter et al. 2010) and its dependence on fragmentation and cooling as a function of \( Z \).

5. We need additional theoretical investigations of RSG mass loss and its scaling with initial mass, \( Z \), and as function of evolutionary time. How does the global \( \dot{M} \) depend on the interplay between pulsational instability and dust formation?

9 FUTURE ISSUES: For observers

1. To help constrain single-star evolution, we need precise estimates of physical parameters for a number of nearby “effectively single” stars at various evolutionary stages that can serve as anchors for stellar evolution models. Relatively wide binaries that have not yet interacted are good targets for this.

2. To better understand how binarity influences observed trends, continued work on the binary fraction and orbital parameters as a function of environment: clusters vs. field, and \( Z \). Orbits are often assumed to be circular in models, but the eccentricity distribution may also be critical for some problems.

3. We need better constraints on the episodic mass loss of LBVs, including the lifetime of the LBV phase, the total mass lost per eruption, the duty cycle of eruptions, and how these vary with \( Z \) and the initial masses and binarity of central stars. The large number of shell nebulae recently discovered by IR surveys (Gvaramadze et al. 2010, Wachter et al. 2010) may be very helpful in improving statistics and associations with the central stars. This is
needed to guide prescriptions for including episodic mass loss in models.

4. Regarding observational constraints on the total mass lost in binary RLOF as compared to mass-transfer rates, studies of RLOF binaries or post-RLOF systems can help constrain under what conditions mass transfer is conservative, or to what degree it is.

5. Ongoing studies of RSGs in clusters may help provide better constraints on measured RSG \( \dot{M} \) as a function of evolutionary stage for a range of \( Z \). For how long and for which stars is the strongest mass loss (self-obscurred, masers) at work? Connections to pulsation amplitudes and stars on blueward tracks are also important.

6. SN progenitors and SNe with CSM provide critical clues about the mass loss of massive stars, and well constrained individual cases are limited to relatively nearby SNe. This provides important links between stars and their end fates, and has opened a new window for observing episodic mass loss in the very final stages of evolution. Also, among nearby stars, we need better constraints on the properties of the faint He-rich stars in binaries that have lost their H envelope to a companion in RLOF, because they may be the dominant stripped envelope SN progenitors.

7. Stellar evolution codes adopt time-averaged mass-loss prescriptions, but increasing evidence suggests that brief disruptive events are very important. Observational work on transient phenomena in general is still a relatively new topic, providing important constraints on physical parameters and rates for these events. Are there observational signatures that will tell us if they are binaries?

8. Studies of SN and transient environments, including their surrounding stellar populations, can help disentangle the relative evolutionary phases of their progenitors (ages, burning stages, etc). This may help to identify types of stars that don’t fit with the expected age of their surrounding populations, perhaps flagging stars that are mainly binaries.

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This is the end of the main article text. The following sections include a
glossary of terms and sidebars.

11 GLOSSARY
SN: Supernova. For massive stars this usually corresponds to the collapse of the iron core, but a SN could also result from an electron-capture SN (8–10 $M_\odot$) or pair instability explosion.

Metallicity ($Z$). Relative abundance of elements heavier than He. Plays an important role for radiatively driven winds and for the opacity in parts of a star’s envelope.

MS: Main Sequence. Core-H burning lifetime of massive stars, when they appear as O-type stars or early B-type stars. Some WNH stars are also MS stars.

ZAMS: Zero-Age Main Sequence.

Massive star: defined here as initial mass $M_{ZAMS}$ above 8 $M_\odot$, which experiences a core collapse or other SN at death. Note that some stars below this limit initially might gain mass in a binary system and explode as a SN.

non-LTE: Radiative transfer calculations not invoking local thermodynamic equilibrium.

P Cygni profile. Blueshifted absorption from an outflowing wind.

Eddington limit ($Γ$=1). Point where a star’s luminosity is so strong that radiation force balances gravity. One expects such a situation to be accompanied by severe mass loss.

RLOF: Roche lobe overflow. A phase in the evolution of binary systems when either star has a radius that exceeds the inner Lagrange point (L1) and begins to transfer mass to the other star.

CSM: circumstellar material, or circumstellar medium.

ecSN: electron-capture SN. Collapse of degenerate ONeMg core due to electron capture in lower-mass (8-10 $M_\odot$) SN progenitors.

PPI: pulsational pair instability.

PISN: Pair instability SN.

12 SIDEBAR: Types of H-burning massive stars (Sec 2)
OB dwarfs: Hot massive main-sequence stars with luminosity class V, early in core-H burning. Examples: $\theta^1$ Ori C, $\zeta$ Oph

Of, Oe, Ofpe/WN9 (etc) supergiants: O stars with evidence for strong winds in their spectra (i.e. emission lines). These are thought to be more evolved than O dwarfs, either in the later phases of core-H burning, or in transition to He burning. Examples: $\zeta$ Puppis, Hen 3-519, S61.

WNH: or more colloquially, “O-stars on steroids”. These are H-rich stars with WR signatures in their spectra. If single, these stars are in the late stages of core-H burning MS evolution of the most massive stars. If in binary systems, these are the possible products of mergers, like more massive analogs of blue stragglers. These are the most massive stars in young massive star clusters, and the most massive stars measured in binaries. Examples: WR25, WR20a.

13 SIDEBAR: Evolved Massive Stars I: Cool Types (Sec 3)
RSG: Red supergiant. Coolest evolved massive stars. Strongest mass-loss phase for single stars with initial masses below about 30 $M_\odot$. Examples: Betelgeuse.
Extreme RSG (OH/IR star): The most luminous RSGs whose mass loss is so strong that they are self-obscured at visual wavelengths, with strong IR excess from dust and maser emission from OH, SiO, and H$_2$O. *Examples:* VY CMa, NML Cygni.

YSG: Yellow supergiant. Rare stars that appear in the middle of the HR diagram, possibly as post-RSGs, and usually with strong mass loss ([Drout et al. 2012](#)). This is a short-lived phase in both binary and single-star models. *Examples:* progenitor of SN 2011dh.

YHG: Yellow hypergiant. The most luminous YSGs, usually with extreme mass loss. Often designated with a luminosity class of Ia$^+$ ([de Jager 1998](#)). *Examples:* IRC+10420, HR 5171A, ρ Cas.

### 14 SIDEBAR: Evolved Massive Stars II: Hot Types (Sec 4)

**WR.** Wolf-Rayet star. He burning massive stars with very strong emission lines of He in their spectra, caused by very strong winds. WN (WR with N) and WC (with C lines) are exposed He cores of massive stars that have lost their H envelopes through prior mass loss. *Examples:* γ$^2$ Vel, EZ CMa

**LBV:** Luminous blue variable. A group of evolved massive stars that exhibit eruptive mass loss or irregular variability. A union of various subtypes, including giant eruptions (η Car variables), S Dor variables, α Cyg variables, P Cygni stars, Hubble-Sandage variables, etc. Most have strong winds and strong emission-line spectra. Candidate LBVs are stars which have similar spectra and/or dust shells, but have not yet exhibited variability. *Examples:* η Car, P Cygni, AG Car, S Dor, HR Car.

**BSG:** Blue supergiant. Post-MS sequence massive stars with B spectral types. The relative number of BSGs in observed HR diagrams of stellar populations is not well understood. *Examples:* Sk −69 202, Sher 25.

**Be and B[e] Stars:** B-type stars with strong and usually time-variable emission lines, often showing evidence for disk-like CSM. Be stars are rapid rotators, possibly resulting from increased angular momentum through mass accretion in binaries. The B[e] stars have strong forbidden line emission and IR excess from dust, thought to arise in a circumstellar disk or torus. Some are high-luminosity evolved supergiants similar to LBVs. *Examples:* γ Cas (Be), R4 in the SMC (B[e]).

### 15 SIDEBAR: SN Subtypes (Sect 6)

SN explosions exhibit a wide diversity of observed properties. Proliferating classifications are based on their spectra and light curves, not a physical mechanism. Types I and II are determined by the presence (II) or absence (I) of H lines in the spectrum. Main categories of SNe are listed here (see also [Filippenko 1997](#)).

**Type II-P.** These are the most common type of core-collapse SN, exhibiting broad H lines in the spectrum, and showing a plateau of typically ~100 days in the visual-wavelength light curve. These arise primarily from RSGs with initial masses of 8–20 $M_\odot$ ([Smartt 2009](#)) and mass-loss rates of $10^{-6}$–$10^{-5}$ $M_\odot$ yr$^{-1}$.

**Type II-L.** Spectroscopically these are very similar to SNe II-P, but their light curves show a linear decay. The faster decline probably results from a lower-mass H envelope, indicating heavier pre-SN mass loss by the progenitor.

**Type II-pec.** Similar to SNe II-P spectroscopically, but with a light curve that rises slowly from an initially faint state due to a more compact BSG progenitor, with SN 1987A being the prototype.
Type IIn. SNe with prominent narrow H lines in their spectra. The narrow lines arise in nearby (a few \(10^{15}\) cm) CSM that is photoionized or shock-heated by the SN. These SNe require strong mass loss immediately (a few years) preceding the SN and exhibit wide diversity.

Type IIn-P. A new subclass of SNe IIn with plateau-shaped light curves, which show a pronounced (3-6 mag) drop in flux at times around 120 days (Mauerhan et al. 2013b).

Type IIb. These are very similar to Type Ib, except that they show transient broad H lines in their early-time spectra. This is due to a low mass (0.01 \(M_\odot\) or less) residual H envelope remaining on the outer layers of the progenitor.

Type Ib. SNe which do not show H in their spectra, but which have strong narrow lines of He instead of H.

Type Ibn. Analogous to SNe IIn caused by strong CSM interaction, but with strong narrow lines of He instead of H.

Type Ic. SNe which show no H, and little or no He lines in their spectra, requiring the most extreme examples of stripped-envelope progenitors.

Type Ic-BL/GRB. These are SNe Ic with very broad (20,000-30,000 km s\(^{-1}\)) lines in their spectra. This is the only type of SN observed to be associated with GRB explosions.

SLSNe. In principle, this class would include any of the above with a peak absolute magnitude more luminous than about \(-20\) or \(-21\) mag (i.e. brighter than the brightest SNe Ia). In practice, only spectral types IIn, II-L, and Ic have been seen in this class so far.

Type Ia. Thermonuclear SNe from white dwarf progenitor stars.

Type Ia/IIn (Ia-CSM). SNe Ia with narrow H lines in their spectra, indicating dense CSM. When strong CSM interaction veils underlying Ia spectral features, it is difficult to distinguish these from core-collapse SNe IIn.

16 SIDE BAR: Super-luminous SNe without narrow lines (Sect 6.3)

The most luminous SNe seen so far are of Types Ic or II-L, without narrow lines. These SLSNe Ic (Gal-Yam 2012; Quimby et al. 2011) and II-L (Gezari et al. 2009; Miller et al. 2009) might be explained by CSM interaction with a dense shell in special cases where the shell has relatively sharp outer boundary. After shock breakout from the wind, radiation diffuses out from the accelerated CSM, yielding no narrow lines (Chevalier & Irwin 2011, Smith & McCray 2007). However, these SNe may also be explained by magnetar birth (Kasen & Bildsten 2010, Woosley 2010), so they are not necessarily the product of eruptive pre-SN mass loss. SLSNe Ic do, of course, require a stripped H envelope like other SNe Ic, and they are interestingly similar to SNe Ic-BL and GRBs in that they seem to prefer low-Z host galaxies (Neill et al. 2011). This may also suggest a binary origin for these stars.
Table 1: Mapping of SN types to their likely progenitor star properties

| SN    | Progenitor Star<sup>a</sup> | \(M_{ZAMS}\)  | \(M_\text{b}^b\)  | \(V_\infty\)  |
|-------|-----------------------------|-------------|----------------|-------------|
| ...   | ...                         | (\(M_\odot\)) | (\(M_\odot\) \(yr^{-1}\)) | (\(km\) \(s^{-1}\)) |
| II-P  | RSG                         | 8–20        | 10<sup>-6</sup>–10<sup>-5</sup> | 10–20       |
| II-L  | RSG/YSG                     | 20–30 (?)   | 10<sup>-5</sup>–10<sup>-4</sup> | 20–40       |
| II-pec| BSG (b)                     | 15–25       | 10<sup>-6</sup>–10<sup>-4</sup> | 100–300     |
| IIb   | YSG (b)                     | 10–25       | 10<sup>-5</sup>–10<sup>-4</sup> | 20–100      |
| Ib    | He star (b)                 | 15–25 (?)   | 10<sup>-7</sup>–10<sup>-4</sup> | 100–1000    |
| Ic    | He star (b)/WR              | 25–?        | 10<sup>-7</sup>–10<sup>-4</sup> | 1000        |
| Ic-BL | He star (b)/WR              | 25–?        | 10<sup>-6</sup>–10<sup>-5</sup> | 1000        |
| IIn (SL)| LBV                        | 30–?        | (1–10)          | 50–600      |
| IIn   | LBV/B[e] (b)                | 25–?        | (0.01–1)        | 50–600      |
| IIn   | RSG/YHG                     | 25–40       | 10<sup>-4</sup>–10<sup>-3</sup> | 30–100      |
| IIn-P | super-AGB                   | 8–10        | 0.01–1          | 10–600      |
| Ibn   | WR/LBV                      | 40–?        | 10<sup>-3</sup>–0.1 | 1000        |
| In/IIn| WD (b)                      | 5–8 (?)     | 0.01–1          | 50–100      |

<sup>a</sup>Most likely progenitor star type. “(b)” indicates that a binary channel is probably key. Note that stars which shed envelopes in binary RLOF are likely to have a slow (10 km \(s^{-1}\)) equatorial outflow, in addition to the wind speed of the star.

<sup>b</sup>Mass-loss rates for pre-SN eruptions are listed in parentheses, corresponding roughly to the total mass ejected in the few years immediately preceding core-collapse. The mass-loss rates may be lower but still substantial at larger radii traced by the expanding SN shock at late times.