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

Nathan Smith

Steward Observatory, University of Arizona, Tucson, Arizona 85721;
email: nathans@as.arizona.edu

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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 winds of hot stars are lower by a factor of 2–3 compared with rates adopted in modern stellar evolution codes, due to the influence of clumping on observed diagnostics. Weaker hot star winds shift the burden of H-envelope removal to 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 earlier. These eruptions are a prelude to core collapse, and may signify severe instabilities in the latest nuclear burning phases. 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. Moreover, the influence of winds and rotation has been evaluated by testing single-star models against observed statistics that, it turns out, are heavily influenced by binary evolution. Altogether, this may alter our view about the most basic outcomes of massive-star mass loss—are Wolf-Rayet stars and Type Ibc supernovae the products of 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 impacts other areas of astronomy, because it changes predictions for ionizing radiation and wind feedback from stellar populations, it may alter conclusions about star-formation rates and initial mass functions, it affects the origin of compact stellar remnants, and it influences how we use supernovae as probes of stellar evolution across cosmic time.

1. INTRODUCTION

Massive star: star with an initial mass above $M_{ZAMS} = 8M_\odot$ that experiences a core collapse or other SN at death

Supernova (SN): the collapse of the iron core in massive stars, but 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; important for radiatively driven winds and for the opacity in parts of a star's envelope

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. Because massive stars have short lifetimes, their UV radiation (reprocessed in various forms) is the most observable tracer of star formation and is used to calculate star-formation rates (Kennicutt 1998, Kennicutt & Evans 2012). Feedback in the form of UV radiation, stellar winds, and supernovae (SNe) stirs interstellar gas, driving turbulence 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 nuclear burning in the cores of massive stars and explosive nucleosynthesis in SNe provide the elements in the periodic table that pollute the ISM, driving galactic chemical 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 megaparsecs 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 compact 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, and apparent temperature; the hardness of its emitted radiation field; and its He core mass; it will also 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 (Madau et al. 1998, Hopkins & Beacom 2006) hinge upon converting reprocessed massive-star UV luminosity to a collective star-formation rate. Gamma ray bursts (GRBs; Woosley & Bloom 2006, Gehrels et al. 2009) and SNe also provide a probe of very distant populations and stellar evolution in early environments, but this requires that we understand the connection between stars of various types, their mass loss, and the eventual 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 the detailed abundances of the lowest Z stars (Beers & Christlieb 2005, Bromm & Yoshida 2011) polluted by a small number of early SNe. Because 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 (Loeb & Barkana 2001, Fan et al. 2006, Morales & Wyithe 2010).

Although convenient recipes 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 recipes are reliable to better than order-of-magnitude levels. Even in the very local Universe, where we have excellent multiwavelength observations, there is still tremendous uncertainty in derived mass-loss rates for massive stars, and so there is large uncertainty in their 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. This review provides a broad overview of the current understanding of mass loss and its influence on the evolution of massive stars and raises a flag of caution about the uncertainties involved.

Main sequence (MS): core-H burning lifetime of massive stars, when they appear as O-type stars or early B-type stars; also includes some WNH stars

ZAMS: zero-age main sequence

Non-LTE: radiative transfer calculations not invoking local thermodynamic equilibrium

1.1. The Importance of Mass Loss in Massive-Star Evolution

For low- and intermediate-mass stars ($M_{\rm ZAMS} < 8\,{\rm M}_\odot$; zero-age main sequence, ZAMS), 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 (MS)—massive stars above $\sim$20 $\rm M_\odot$ shed mass in fast winds that affect their subsequent evolution (i.e., $\int \dot{M} {\rm d}t$ can be a significant fraction of the stellar mass), and in post-MS 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, because 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 with stellar evolution models without mass loss. Maeder & Meynet (2000) review how the inclusion of rotation can influence single-star evolution models, whereas Langer (2012) reviews 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 concentrates 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 this phase 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. Model tracks on the HR diagram are not plotted with error bars that reflect these uncertain assumptions.

Owing 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 (local thermodynamic equilibrium) modeling of spectra influenced by winds. A previous review by Kudritzki & Puls (2000) dealt with line-driven winds of hot stars, focusing 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 of 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 therefore emphasizes these latter topics, but it also discusses more recent developments in steady winds, in particular the reduction in mass-loss rates and the consequent paradigm shift in stellar evolution.

Roche-lobe overflow (RLOF): phase when either star of a binary system has a radius exceeding the inner Lagrange point and begins to transfer mass to the other star

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 their 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 RSGs (Gehrz & Woolf 1971). With the assumption that mass loss via steady winds is the dominant form of 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 1986, 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) 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 past decade this paradigm has shifted yet again because of two important realizations: (*a*) Due to the effects of clumping (see below), empirical mass-loss rates for line-driven winds are lower than previously thought, and (*b*) other unsteady modes of mass loss are more important than previously recognized, owing 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 stars and their variation with Z. The pendulum appears to be swinging back to binaries as the dominant agent in massive-star evolution, although not everyone is on the bandwagon. Justifiably, this topic occupies much of the current debate and excitement in the field.

TYPES OF H-BURNING MASSIVE STARS

OB dwarfs: Hot massive MS stars with luminosity class V, early in core-H burning. *Examples:* θ^1 *Ori C*, ζ *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:* ζ Puppis, Hen 3–519, S61.

WNH: H-rich stars with WR signatures in their spectra; more colloquially known as "O-stars on steroids." 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.

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 (see the sidebar, Types of H-Burning Massive Stars). Again, see Kudritzki & Puls (2000) 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 (Lucy & Solomon 1970, Castor et al. 1975). 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 the rates of Nugis & Lamers (2000) were adopted 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 increases 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 at which the wind has reached its terminal velocity v_∞. Connecting these ideal values to observations is nontrivial and requires detailed models including realistic opacities, because the radius from which 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

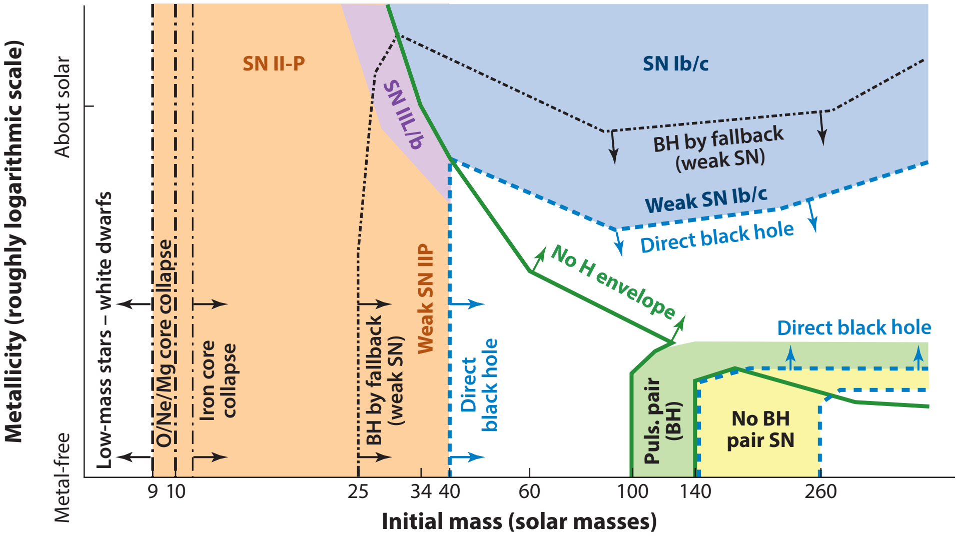

Figure 1

Example of the standard expectations for the fates of massive stars as a function of initial mass and metallicity. Adapted from Heger et al. (2003) with permission. Abbreviations: black hole, BH; supernova, SN.

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) and recombination emission lines like Hα or others, as well as 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 Hα, HeI, and HeII are recombination processes, so their emissivity varies as ρ^2, whereas P Cyg absorption varies linearly with ρ. 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 is 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 Hα 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 $\sqrt{f_{\rm cl}}$, where it is standard practice to define the "clumping factor" as $f_{\rm cl} = \langle\rho^2\rangle/\langle\rho\rangle^2$. (This assumes that the gas is optically thin.) Constraining the value of $f_{\rm cl}$ observationally is paramount for understanding stellar evolution.

Significant wind clumping is expected on theoretical grounds (Owocki & Rybicki 1984, Owocki et al. 1988, Feldmeier 1995, Owocki & Puls 1999, Dessart & Owocki 2005, Sundqvist & Owocki 2013), due mostly to the line-driven instability (this arises because the force of line driving is velocity dependent; gas parcels that 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 because of subsurface convection

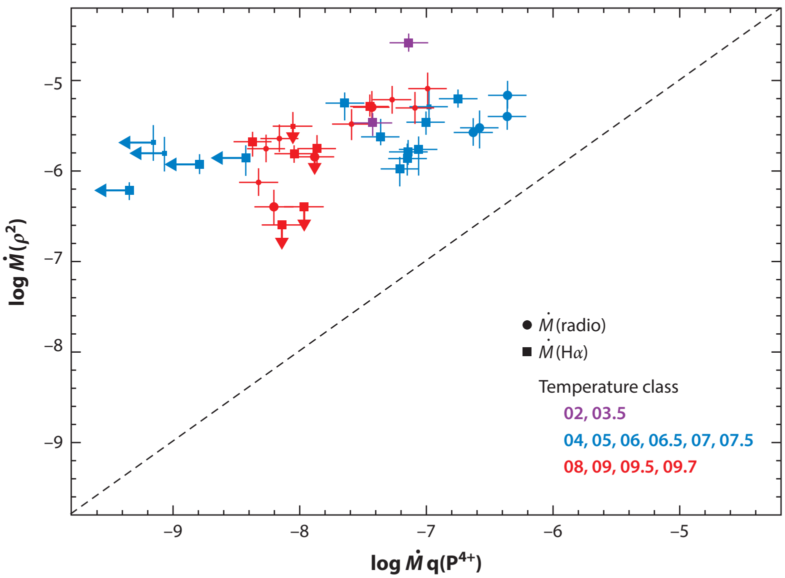

Figure 2

A comparison of the mass-loss rates derived from diagnostics that are linearly proportional to wind density, like UV P Cyg absorption, and that are proportional to ρ^2, like free-free and Hα emission. Reproduced from Fullerton et al. (2006) with permission. Although there is still discussion about the P V lines used for this study and whether they overestimate the reductions in $\dot{M}$ that are applied, this research nevertheless forced an important discussion in massive-star research by highlighting the potential influence of clumping.

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 (Hillier 1991, Drew et al. 1994, Moffat & Robert 1994) and inhomogeneous on larger scales; large scales include such complexities as the time-variable discrete absorption components (Howarth et al. 1995, Massa et al. 1995, Cranmer & Owocki 1996, Fullerton et al. 1997) 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 ρ^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) proposed a reduction by a factor of 10 or more from traditional mass-loss rates (f_{cl} values of 100 or more), whereas Bouret et al. (2005) require reductions by factors of ∼3 (see **Figure 2**). For the Milky Way, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC), various studies using modern non-LTE analysis find $f_{cl} \simeq 10$ (Crowther et al. 2002, Figer et al. 2002, Hillier et al. 2003, Massa et al. 2003, Evans et al. 2004, Puls et al. 2006), corresponding to $\dot{M}$ reductions by a factor of ∼3 with typical uncertainties of ∼30%. Based on unifying Hα measurements with the theoretical wind momentum relation, both Repolust et al. (2004) and Markova et al. (2004) found $f_{cl} = 5$ or a mass-loss reduction by 2.3. [Note 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 (Hillier 1991, Moffat & Robert 1994). 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 $f_{cl} \simeq 10$.

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 V lines that the large clumping factor is based upon as well as because of possible mediating effects of porosity in the wind. These topics are not completely settled [the interested reader can consult the proceedings volume of a recent conference on this topic for more detailed information (Hamann et al. 2008)], but nevertheless, most observational studies agree that for mid/early O-type stars, clumping is significant enough to warrant mass-loss rates reduced by at least 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 (Kramer et al. 2003; Cohen et al. 2010, 2011). Thus, reductions in mass-loss rates for normal O-type stars by a factor of 3 ($\pm$30%) are 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 ρ^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 $\dot{M}$ climbs by a factor of 3–4 as an O-type star evolves along the MS, giving rise to observed properties in 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. 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_∞, 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 that are too high by a factor of ~3 during the MS lifetimes of massive stars. [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

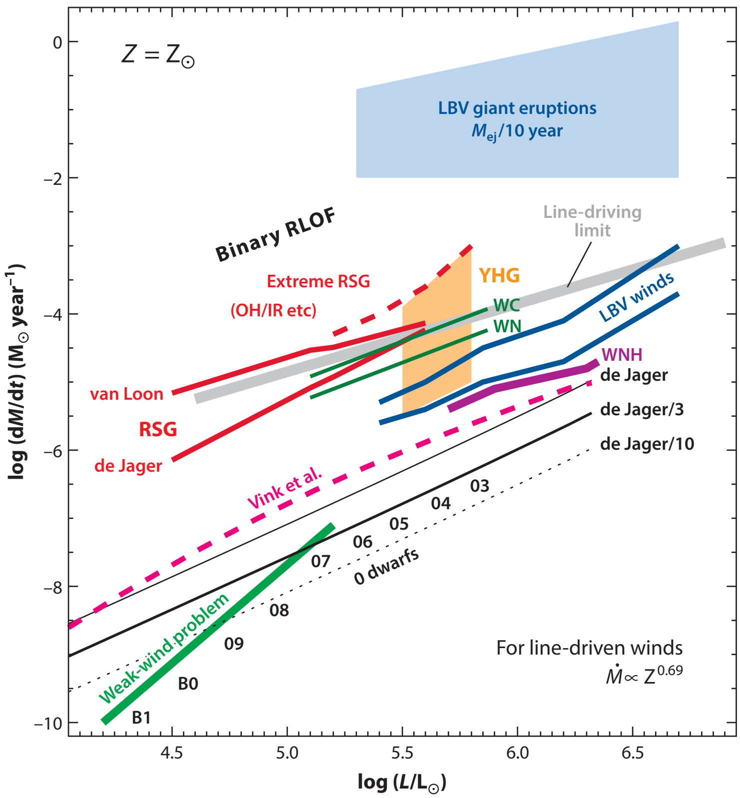

Figure 3

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 by Vink et al. (2001) are shown, along with "standard" observational rates using the prescription by 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. Rates for nitrogen-sequence Wolf-Rayet (WN) and carbon-sequence Wolf-Rayet (WC) stars are from Crowther (2007). Red supergiant (RSG) mass-loss prescriptions are from de Jager et al. (1988) and van Loon et al. (2005), as indicated. For yellow hypergiants (YHGs), see de Jager (1998). For $\dot{M}$ corresponding to normal winds of luminous blue variables (LBVs), values were compiled from a number of studies (Hillier et al. 2001, Vink & de Koter 2002, Smith et al. 2004, Groh et al. 2009). For LBV eruptions, the "rates" shown are calculated from total masses observed in LBV circumstellar shells (Smith & Owocki 2006) divided by a nominal eruption duration of 10 years (see **Figure 5**). For "binary RLOF," an order-of-magnitude value for the strongest mass-transfer rates expected in brief RLOF (Roche-lobe overflow) 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).

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 $\Gamma = 1$, where $\Gamma = \kappa L/4\pi GMc$ is the Eddington ratio. High Γ values in hot stars can substantially affect the winds and increase

Eddington limit ($\Gamma = 1$): point at which a star's luminosity is so strong that the radiation force balances gravity

mass-loss rates (Gräfener 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.

Although 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 (Puls et al. 2008, Muijres et al. 2012) and may indicate inefficient line driving in hot dwarfs. Analysis of the bow shock around the O9.5 V runaway star ζ 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 $\dot{M} = 2 \times 10^{-9}\,M_\odot\,\mathrm{year}^{-1}$ for the O9.5 V star μ Col lies on the green line for weak winds in **Figure 3**. Note that similar considerations of UV diagnostics were noted earlier as well (Drew et al. 1994; Cohen et al. 1997, 2008).

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 (carbon-sequence Wolf-Rayet) 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 caused by line-driven winds and are Z dependent. Vink & de Koter (2005) 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 $M_{\mathrm{ZAMS}} = 60\,M_\odot$ will shed half its mass on the MS, 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 MS with $\log(L/L_\odot) = 5.7$ and $\log(T_{\mathrm{eff}}) = 4.7$ according to standard evolutionary models, and $\dot{M} = 10^{-5.86}$ 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 solar masses during the entire 3.5 Myr of 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 $M_{\rm ZAMS} = 40-60\,M_\odot$ don't become RSGs, and the observed $\dot{M}$ values of steady winds of post-MS stars at these luminosities [i.e., blue supergiants (BSGs) 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 couple options (Smith & Owocki 2006): (*a*) eruptive LBV mass loss makes up the difference or (*b*) single stars with $M_{\rm ZAMS} = 40-60\,M_\odot$ 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 $M_{\rm ZAMS} = 40-60\,M_\odot$, the problem is worse. Below $M_{\rm ZAMS} \simeq 35\,M_\odot$, 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 Γ 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. Because the most massive stars are rare, it is uncertain whether 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

Although the winds of OB-type MS stars may be less important for a star's evolution than previously thought, having relatively precise (better than a factor of $\sim$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., Vink et al. 2001, Mokiem et al. 2007) is probably reliable enough to estimate the global contribution of feedback of MS O-type stars from solar to mildly subsolar 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 Kudritzki & Puls (2000) and adopted by Heger et al. (2003) (**Figure 1**) owing 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.

EVOLVED MASSIVE STARS I: COOL TYPES

Red supergiants (RSGs): Coolest evolved massive stars. Strongest mass-loss phase for single stars with initial masses below about 30 $M_\odot$. *Example:* Betelgeuse.

Extreme RSGs (OH/IR stars): 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_2O. *Examples:* VY CMa, NML Cygni.

Yellow supergiants (YSGs): 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. *Example:* progenitor of SN 2011dh.

Yellow hypergiants (YHGs): 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.

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, because weaker winds during H burning could modify the burning lifetime, core size, and end fate of the star and, hence, the characteristics of the resulting SN explosion.

3. DENSE WINDS FROM COOL SUPERGIANTS

Winds of cool supergiants (see the sidebar, Evolved Massive Stars I: Cool Types) 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) reviewed mass loss from cool stars, although that paper focused 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_*, where the equilibrium temperature becomes low enough (1,000–1,500 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 by 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. (2005), which is intended for dust-enshrouded RSGs. Both these relations are shown in **Figure 3**. Depending on which RSG mass-loss recipe is chosen for a model, RSGs can

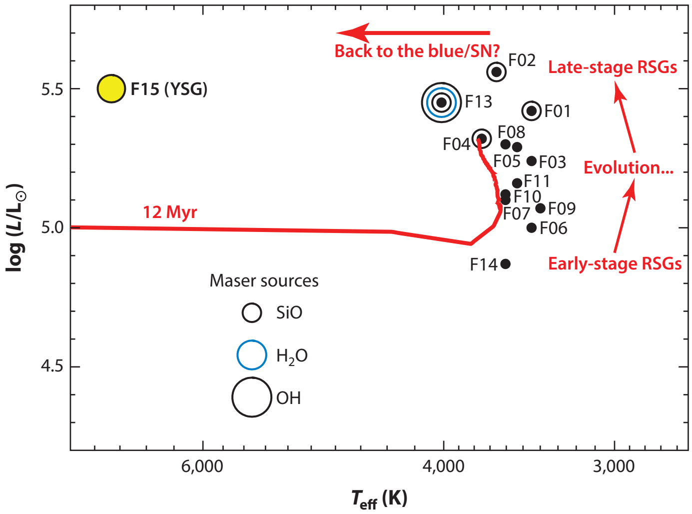

Figure 4

A Hertzsprung-Russell diagram of the cluster RSGC1, with red supergiants (RSGs) and a yellow supergiant (YSG). Sources that are circled include maser emission from dense envelopes, indicating especially strong mass loss. Adapted from Davies et al. (2008) with permission.

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 and 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) like 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 evidence suggestive 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 with a 12-Myr isochrone (Maeder & Meynet 2000), indicating that these 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_2O, 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 supergiant (YSG) at a luminosity comparable to the most luminous RSGs with masers in the same cluster. This provides compelling evidence that at 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 *Hubble Space Telescope* (HST) images (Smith et al. 2001). In the case of VY CMa, the density of its nebula drops off sharply at ∼8,000 AU from the star, indicating that its high average mass-loss rate of $\sim 10^{-3}$ $M_{\odot}$ $year^{-1}$ has been limited to the previous 10^3 years or so (Smith et al. 2001, 2009; Decin et al. 2006). The nebula around VY CMa is quite similar to that around the yellow hypergiant (YHG) 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 (Heger et al. 1997, Yoon & Cantiello 2010, Arnett & Meakin 2011).

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 (Section 5). 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, Γ, 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 in which the high Γ leads to instability in the star and highly time-dependent mass loss or in which advanced nuclear burning stages may play a role (Arnett & Meakin 2011). When this variability is observed, the stars are designated as LBVs, or they are designated as LBV candidates (see the sidebar, Evolved Massive Stars II: Hot Types) if they are suspected to be dormant versions of the same stars.

4.1. Luminous Blue Variables: History and Phenomenology

The most dramatic instability arising in post-MS evolution is the class of objects known as LBVs. These were recognized early as the brightest blue irregular 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 seventeenth and nineteenth centuries, respectively, but their connection to other eruptive massive stars was unclear. Conti (1984) recognized that many different classes of hot,

EVOLVED MASSIVE STARS II: HOT TYPES

Wolf-Rayet star (WR): 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*.

Luminous blue variable (LBV): 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 that have similar spectra and/or dust shells, but have not yet been seen to exhibit variability. *Examples:* η *Car*, *P Cygni*, *AG Car*, *S Dor*, *HR Car*.

Blue supergiant (BSG): Post-MS 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*, *SBW1*.

Be and B[e] stars: B-type stars with strong and usually time-variable emission lines, often showing evidence for disk-like circumstellar material. 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 that are 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*]).

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 (Humphreys & Davidson 1994; van Genderen 2001; Smith et al. 2004, 2011d; Clark et al. 2005; Van Dyk & Matheson 2012). Their initial masses are uncertain, but comparing their luminosities with 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 resemble 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 whether 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.

4.1.1. 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 bolometric 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 as early/mid B supergiants at the lower luminosity end (Humphreys & Davidson 1994, Smith et al. 2004). Visual maximum occurs at a constant temperature of ~8,000 K, causing the star to resemble a late F supergiant. S Dor events were originally proposed to occur at constant bolometric luminosity (Humphreys & Davidson 1994), but quantitative studies do reveal variations in L_{Bol} (Groh et al. 2009). The traditional explanation for the apparent temperature change was that the star dramatically increased 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 outbursts do not increase enough to cause a pseudo photosphere (de Koter et al. 1996) 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 subsurface 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**).

4.1.2. Luminous blue variable 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 et al. 1999). The best-studied example is the Galactic object η Carinae, which has provided us with its historically observed light curve (Smith & Frew 2011) as well as its complex ejecta that contain 10–20 $M_\odot$ and $\sim 10^{50}$ ergs of kinetic energy (Smith et al. 2003, Smith 2006). Light echoes from the Great Eruption of η Carinae have just recently been discovered (Rest et al. 2012), and their continued study through the use of 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 $\sim$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 in which 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 $M_\odot$ $year^{-1}$ and 1 $M_\odot$ $year^{-1}$ 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).

4.1.3. Extragalactic supernova impostors. LBV giant eruptions are rare, so our only other observed examples are a few dozen found in nearby galaxies (Smith et al. 2011d, Van Dyk & Matheson 2012). Owing 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. 2011d, Van Dyk & Matheson 2012). Typical expansion speeds observed in outburst spectra are 100–1,000 km s^{-1} (Smith et al. 2011d), 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 review, 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 Section 4.2.1 below).

4.1.4. Luminous blue variable 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 with 1,000–2,000 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} $M_\odot$ $year^{-1}$ (de Koter et al. 1996, Vink & de Koter 2002, Smith et al. 2004, Groh et al. 2009) or even 10^{-3} $M_\odot$ $year^{-1}$ 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 years, and eruptions further enhance (or actually dominate)

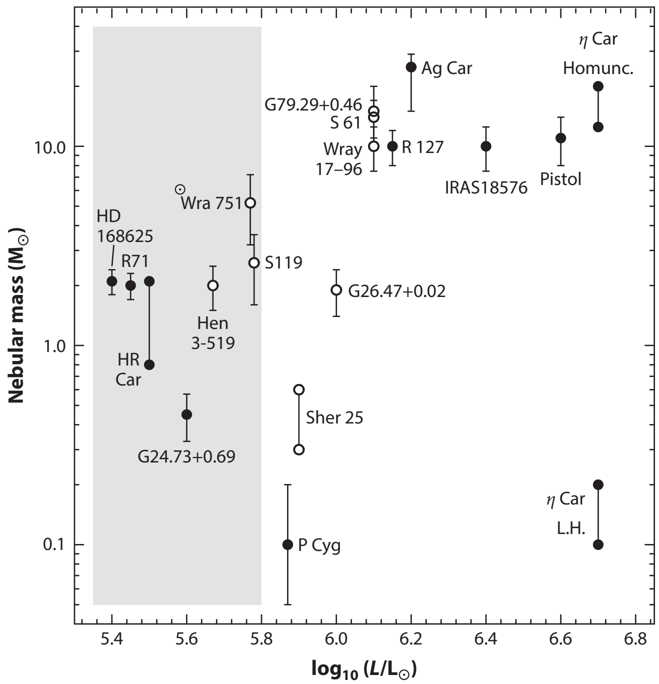

Figure 5

Masses of circumstellar shells around luminous blue variables (LBVs) and LBV-like stars, as a function of luminosity, modified from Smith & Owocki (2006). The left side of the plot (*gray box*) corresponds to stars below $\log(L/L_{\odot}) = 5.8$, so these LBVs could be post-RSGs (red supergiants) 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.

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.

4.1.5. 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. 2005, Smith & Owocki 2006, Gvaramadze et al. 2010, Wachter et al. 2010). Thus, eruptive LBV mass loss is 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 around bright central stars. In some cases a very large range in mass is seen in multiple shells around the same star, as for η 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 year duration of the eruptions of

η 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 years to several thousand years. It is, however, difficult to use this age as an indication of the duration of the LBV phase, because expanding shells can decelerate. The duration of the LBV phase may be further complicated, because 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 the 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 et al. 1999, Shaviv 2000, Owocki et al. 2004, Smith & Owocki 2006). This is motivated mostly by the fact that η Car's Great Eruption had an observed luminosity that indicated $\Gamma \simeq 5$ for about a decade or more and that extragalactic SN impostors show similar high luminosities. With Γ 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 (Shaviv 2000, Owocki et al. 2004). 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 (Shaviv 2000, Owocki et al. 2004). SE winds may also account for the bipolar shape of nebulae around LBVs like η Car if the star is a rapid rotator, because equatorial gravity darkening leads to a higher $\dot{M}$ and faster speed in the polar wind (Owocki et al. 1996, Dwarkadas & Owocki 2002).

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 η Car's nineteenth-century eruption are of order 15 $M_\odot$ or more (Smith et al. 2003, Smith & Ferland 2007). 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 η Car, with most of the mass moving at speeds of 500–600 km s^{-1}. Moreover, η Car also shows a smaller mass of extremely fast material moving at 5,000 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 η Car's nineteenth-century eruption. As for the extra radiative energy output that initiates the SE wind, its source is not known. Lastly, SE winds are assumed to be launched from the surface of the star, but it is also not yet clear whether 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 nonterminal hydrodynamic explosions. Part of the motivation for this is based on detailed study of η 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 $E_k/E_{\rm rad} > 3$, 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 5,000 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 IIn SNe and also show evidence for extremely fast ejecta that may signify a shock-powered event, such as the precursor outbursts of SN2009ip (Smith et al. 2010b, Foley et al. 2011).

CSM: circumstellar material or circumstellar medium

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 circumstellar material (CSM) interaction can generate a high sustained luminosity, as in core-collapse SNe IIn. 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 IIn-type model but with lower explosion energy. The resulting slower shock speed from a subenergetic explosion (10^{50} instead of 10^{51} ergs) produces a lower CSM interaction luminosity compared with a core-collapse SN IIn 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 (van Marle et al. 2010), depending on the extent of the dense pre-explosion wind. Because 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. 2011d). The catch is that even this model requires something else to create the dense CSM into which the shock expands, which may be where SE winds or binary interaction play an important role.

4.2.3. Eruption triggers The reasons for the onset of an LBV eruption along with 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. (2011d). In brief, there is no clearly favored explanation, but some ideas can be ruled out based on the required energy and mass budgets. These can be thought of in two broad categories: instability and energy deposition.

4.2.3.1. 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; Maeder 1992, Humphreys & Davidson 1994), or the critical rotation limit (a.k.a. the "Ω limit"; Langer 1998, 2012). Although 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.

PPI: pulsational pair instability

4.2.3.2. 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 (PPI; 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 2014), and stellar collisions or mergers in a binary system (Podsiadlowski et al. 2010, Smith 2011, Smith & Arnett 2014). [Soker and collaborators discussed a model to power the luminosity in LBV eruptions using accretion onto a companion star (Kashi & Soker 2009), 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.] Although any of these provide a plausible result, the main criticism for explaining LBV eruptions is that the mechanisms that 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 years after a giant eruption. Such an objection turns into an advantage, however, in the case of the violent pre-SN eruptions needed for SNe IIn (see Section 6.3 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 Luminous Blue Variable 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 partly 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 correspond 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

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

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 duration of the LBV phase is presumed to be only a few 10^4 years (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 greater 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 years to several 10^5 years. This is comparable with 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 AD 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.

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 Section 6.3 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 $M_{ZAMS} = 40\,M_{\odot}$ 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, because LBVs have the highest known mass-loss rates of any stars (**Figure 3**).

4.4. Low Metallicity

Although 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 (Smith & Owocki 2006). Because 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, because they are argued to have been preferentially very massive. There may, of course, be some unrecognized way that metallicity creeps into the problem (e.g., 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, Isotov 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 Section 6.3 below) often occur in dwarf galaxies. Thus, there is clear 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 lives (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; such campaigns typically find an observed binary fraction of 20–60% (Gies 1987; Garcia & Mermilliod 2001; De Becker et al. 2006; Evans et al. 2006; Kobulnicky & Fryer 2007; Sana et al. 2008, 2009, 2012; Mahy et al. 2009; Chini et al. 2012; Kiminki & Kobulnicky 2012; Kiminki et al. 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 separations small enough that the stars will actually interact and exchange mass; whether or not they will interact is typically determined by the maximum radius of an 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 (Kobulnicky & Fryer 2007, Kiminki & Kobulnicky 2012, Sana et al. 2012). Of the total population of massive stars, Sana et al. (2012) estimate that ∼25% will merge, ∼33% will have their H envelopes stripped before death, and ∼14% will be spun up by accretion, whereas only about 25% 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 being single stars born with a very high rotation rate. This, in turn, suggests that the influence of rotation and rotational mixing in current single-star models may be overestimated (Vanbeveren 2009, de Mink et al. 2013).

5.2. Physics of Mass Loss in Binaries

From the ZAMS until the H envelope is substantially stripped or removed completely, a massive star tends to increase its radius owing 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 MS (orbital periods of a few days) or when it expands to a much larger size in post-MS supergiant phases (orbital periods of tens 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 (Podsiadlowski et al. 1992, Petrovic et al. 2005, Langer 2012). Mass transfer becomes increasingly unstable and rapid from Case A to C, in some cases involving dynamical events, common envelopes, or inspiral to a merger. 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 of 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:

$$\dot{M} = (M_0 - M_{\rm WR})/\tau_{\rm KH},$$

where $\tau_{\rm KH}$ is the thermal (Kelvin-Helmholtz) timescale of the envelope, M_0 is the initial mass, and $M_{\rm WR}$ 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 $10^{-3}\,M_\odot$ year^{-1} or higher (Taam & Sandquist 2000, Langer 2012), although there is a wide range (only order-of-magnitude values are represented in **Figure 3**). With thermal timescales of order 10^4 years, 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 shrinks 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 the degree to which mass transfer is conservative ("conservative" mass transfer means that no significant mass is lost from the binary system in RLOF) (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. 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 and LBV candidates have only a single massive CSM shell). Podsiadlowski et al. (2010) have discussed extreme cases in which 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. Because the most active phases are very brief ($\sim10^4$ years; 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 $8\,M_\odot$ 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. 2011a). A noteworthy object for wider orbital separations (probably Case C) is the famous YHG 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 products of single-star RSG mass loss. Because 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 owing 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/transferred, and the time dependence of these are influenced by several initial conditions: (*a*) the primary/secondary initial mass ratio q, (*b*) the primary star's initial mass, (*c*) the initial orbital separation, (*d*) the orbit eccentricity, and (*e*) the relative wind mass-loss rates of both stars. It may also matter that 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 (Podsiadlowski et al. 1992; Vanbeveren et al. 1998, 2007; Petrovic et al. 2005; Eldridge et al. 2008; Eldridge & Stanway 2009; Yoon et al. 2010; Dessart et al. 2011; Sana et al. 2012). 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 Ibc to Type II SNe (Prantzos & Boissier 2003, Prieto et al. 2008a, Boissier & Prantzos 2009). However, we should be cautious that even binary RLOF may have some dependence on metallicity, because metallicity affects the opacity in the star's envelope and, hence, the hydrostatic stellar radius. With lower opacity, low-Z stars are more compact (Maeder & Meynet 2000, Heger et al. 2003). 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 Ibc/II 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: Wolf-Rayet 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 do only those in interacting binaries or in certain initial mass ranges become WR stars? 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 an H-poor WR star, $M_{\rm WR}(Z)$. Standard single-star models predict $M_{\rm WR} \simeq 35\,{\rm M}_\odot$ at ${\rm Z}_\odot$ (Heger et al. 2003, Georgy et al. 2012), increasing to about 45 ${\rm M}_\odot$ and $70\,{\rm M}_\odot$ at $Z_{\rm LMC}$ and $Z_{\rm SMC}$, respectively (Heger et al. 2003). $M_{\rm WR}$ can be lowered by adopting substantially enhanced mass-loss rates in models (Meynet et al. 1994, Ekström et al. 2012) or by including the effects of relatively rapid rotation (Georgy et al. 2012). [Vanbeveren et al. (2007) criticize 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, they argue that most O-type stars rotate more slowly at 100–120 km s^{-1}.] At first glance, models and observations would seem to be reasonably well aligned (Massey 2003): $M_{\rm WR}$ is inferred to be about $25\,{\rm M}_\odot$ at ${\rm Z}_\odot$ (Crowther 2007), increasing to about $30\,{\rm M}_\odot$ and $70\,{\rm M}_\odot$ at $Z_{\rm LMC}$ and $Z_{\rm SMC}$, respectively (Massey et al. 2000). However, theoretical expectations for $M_{\rm WR}$ 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 ${\rm Z}_\odot$ 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 $M_{\rm WR}$ upward significantly in single-star models for each Z range to a point that probably cannot be reconciled with observed $M_{\rm WR}$.

In a binary evolution paradigm, by contrast, He stars stripped of their H envelope can occur over a wider range of initial mass (Vanbeveren et al. 2007, Claeys et al. 2011). In that case, the dominant factors controlling observationally inferred values of $M_{\rm WR}$ 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 favors sources of higher L and Z. It may be hard to detect exposed He cores resulting from binary RLOF in $M_{\rm ZAMS} = 10-25\,{\rm M}_\odot$ stars, and their low luminosity and weak emission lines would prevent them from being classified as WR stars. The 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 Section 6.2 below).

Two other key considerations are the observed WC/WN ratio that increases with Z (Massey 2003) and 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 is dominated by a line-driven wind (Vanbeveren et al. 2007, Claeys et al. 2011). Binary RLOF usually leaves a thin H layer, and stars at lower Z or lower L have a harder time removing it. Similarly, the evolution from a WN to a WC star (if this progression is monotonic) is 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, because 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. Unfortunately, finding examples of apparently single WR stars does not provide a conclusive answer, because 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 $\log(L/{\rm L}_\odot) = 5.5$ to 5.8 (Hamann et al. 2006, Crowther 2007), which also corresponds to the strongest RSG mass loss (**Figure 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, which is discussed next.

6.2. Outcomes II: The Main Supernova Subtypes

Core-collapse SNe exhibit a wide diversity of properties, summarized briefly in the sidebar titled Supernova Subtypes. 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 Ibc with "normal" SN atmospheres. Types IIn 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, because 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 subtypes (excluding SNe Ia) measured in a controlled sample are now available (Smith et al. 2011b); these come from the Lick Observatory SN Search, which targeted mainly large galaxies representative of $\sim{\rm Z}_\odot$ (Li et al.

SUPERNOVA SUBTYPES

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. The main categories of SNe are listed here (see also Filippenko 1997).

Type II-P: They 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. They arise primarily from RSGs with initial masses of $8-20\,M_{\odot}$ (Smartt 2009) and mass-loss rates of $10^{-6}-10^{-5}\,M_{\odot}\,\mathrm{year}^{-1}$.

Type II-L: Spectroscopically these are very similar to SNe II-P, but their light curves show a linear decay. The faster decline may result 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 that do not show H in their spectra, but which have strong broad He lines.

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

Type Ic: SNe that show no H and little or no He lines in their spectra, requiring them to be 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.

Superluminous SN (SLSN): 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.

2011). The most common core-collapse SNe are Type II-P (48.2 ± 6%), marking the explosions of relatively low-mass RSGs. Types II-L and IIn contribute 6.4 ± 3% and 9 ± 3%, respectively. The remainder (36.5 ± 6%) are stripped envelope SNe of Types IIb (10.6 ± 3.6%) and Ibc (26 ± 5%, 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. (2011b) 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 Ibc progenitors are assumed to be WR stars, then the observed fraction of SNe Ibc (not including SNe IIb) would require $M_{\mathrm{WR}} = 22\,M_{\odot}$ (Smith et al. 2011b). Although this is not

Table 1 Mapping of supernova (SN) types to their likely progenitor star properties

SN	Progenitor Star[a]	M_{ZAMS} ($M_\odot$)[b]	$\dot{M}$ ($M_\odot$ year^{-1})[c]	V_∞ (km s^{-1})
II-P	RSG	8–20	10^{-6}–10^{-5}	10–20
II-L	RSG/YSG	20–30 (?)	10^{-5}–10^{-4}	20–40
II-pec	BSG (b)	15–25	10^{-6}–10^{-4}	100–300
IIb	YSG (b)	10–25	10^{-5}–10^{-4}	20–100
Ib	He star (b)	15–25 (?)	10^{-7}–10^{-4}	100–1,000
Ic	He star (b)/WR	25–?	10^{-7}–10^{-4}	1,000
Ic-BL	He star (b)/WR	25–?	10^{-6}–10^{-5}	1,000
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^{-4}–10^{-3}	30–100
IIn-P	Super-AGB	8–10	0.01–1	10–600
Ibn	WR/LBV	40–?	10^{-3}–0.1	1,000
Ia/IIn	WD (b)	5–8 (?)	0.01–1	50–100

[a]Most likely progenitor star type. "(b)" indicates that a binary channel is probably key. Note that stars that shed envelopes in binary Roche-lobe overflow are likely to have a slow (10 km s^{-1}) equatorial outflow, in addition to the wind speed of the star.
[b]Masses with "(?)" indicate high uncertainty. Mass ranges with "?" as the upper end of the range indicate that these types might extend to a high and highly uncertain upper mass limit.
[c]Mass-loss rates for pre-SN eruptions are listed in parentheses and correspond 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.
Abbreviations: blue supergiant, BSG; luminous blue variable, LBV; red supergiant, RSG; Wolf-Rayet, WR; yellow hypergiant, YHG; yellow supergiant, YSG.

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, ∼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 ∼80% of SNe come from initial masses $< 25\,M_\odot$, assuming a Salpeter IMF in which 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 (Yoon et al. 2010, Dessart et al. 2011, Hachinger et al. 2012), which seem to rule out the idea that SNe IIb and Ib 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 having initial masses of roughly 8–20 $M_\odot$ dying as SNe II-P [the upper bound of this range is uncertain and higher than that found by Smartt (2009) if one accounts for progenitor reddening (Walmswell & Eldridge 2012)], 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, and in fact, there are currently three 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. 2013, 2014). Two other SNe IIb, SN 2001ig and SN 2008ax, also show possible indications of a companion star (Ryder et al. 2006, Crockett et al. 2008). Moreover, there are as yet no detections of progenitors of SNe Ibc. Their nondetection 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 (Prantzos & Boissier 2003, Prieto et al. 2008a, Boissier & Prantzos 2009), as noted earlier. However, Smith et al. (2011b) pointed out that the relevant ratio really is (IIb + Ibc)/(II-P + II-L + IIn), because SNe IIb are almost identical to SNe Ib except for $<0.1\,M_\odot$ of H in their outermost layer (Dessart et al. 2011, Hachinger et al. 2012). [Many 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 1**). 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.] The recent study by Arcavi et al. (2010) finds that, compared with 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. Because 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 rather than SNe IIb. This result is, however, expected in binary evolution, because 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 in which 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$1,000 km s^{-1}, observations suggest a very wide range of mass-loss rates for SN Ibc progenitors, from $10^{-7}\,M_\odot$ year^{-1} up to values near the line-driving limit, with an average around $10^{-5}\,M_\odot$ year^{-1} (Wellons et al. 2012). The examples near the lower end of this range are inconsistent with WR winds, whereas those near the upper end of the range are consistent (see **Figure 3**). This is further evidence that SNe Ibc may arise from a large range of initial masses, including relatively low-luminosity stars with weak winds 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 (note that slower outflows would reduce the value of $\dot{M}$ inferred from radio observations) 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. Much more extreme cases of eruptive pre-SN mass loss are also seen, and this is discussed next.

6.3. Outcomes III: Enhanced Pre-Supernova Mass Loss and Luminous Supernovae

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} $M_\odot$ year^{-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:

- Superluminous SNe (SLSNe) with Type IIn spectra represent the most extreme cases of eruptive pre-SN mass loss; luminosities are ∼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 (van Marle et al. 2010, Chevalier & Irwin 2011, Chatzopoulos et al. 2013, Moriya et al. 2013). 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 2008fz (Drake et al. 2010) (see also the sidebar, Superluminous Supernovae without Narrow Lines).
- 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 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. 2014, Smith et al. 2014) are consistent with very asymmetric or even disk-like CSM. The

SUPERLUMINOUS SUPERNOVAE WITHOUT NARROW LINES

The most luminous SNe (i.e., SLSNe) seen so far are of Types Ic or II-L, without narrow lines. These SLSNe Ic (Quimby et al. 2011, Gal-Yam 2012) and II-L (Gezari et al. 2009, Miller et al. 2009) might be explained by CSM interaction with a dense shell in special cases in which the shell has a relatively sharp outer boundary. After shock breakout from the wind, radiation diffuses out from the accelerated CSM, yielding no narrow lines (Smith & McCray 2007, Chevalier & Irwin 2011). 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.

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 **Figure 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 (Gerardy et al. 2002, Fox et al. 2011)—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.

- 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 $M_{\rm ZAMS} = 8-10\ M_\odot$ super-AGB stars that achieve luminosities of normal SNe through intense CSM interaction (Smith 2013b).

Electron-capture SN: collapse of degenerate O-Ne-Mg core due to electron capture in lower-mass (8–10 $M_\odot$) SN progenitors

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 an 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 2005la and SN 2011hw (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 years 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, 2010a). 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 in which 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.

6.3.1. 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 hadn't been defined yet. A luminous (−12.2-mag absolute at blue wavelengths) progenitor was detected at several epochs for ∼20 years preceding the SN 1961V event (Humphreys et al. 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. 2011d), which would provide evidence for a $\sim$100–$M_\odot$ LBV-like progenitor that experienced eruptive mass loss before a SN IIn.

6.3.2. SN 2005gl. This was a normal SN IIn in 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 $\sim 0.01\,M_\odot$ year^{-1}.

6.3.3. 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 two years later was of Type Ibn with strong narrow HeI emission lines (Foley et al. 2007, Pastorello et al. 2007). There is no detection of the quiescent progenitor.

6.3.4. 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 (Smith et al. 2010b, Foley et al. 2011). It showed slow variability consistent with an S Dor LBV-like episode (Smith et al. 2010b), followed by a series of brief LBV-like giant eruptions (Smith et al. 2010b, Mauerhan et al. 2013a, Pastorello et al. 2013). 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 (Smith et al. 2010b, Foley et al. 2011). 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. 2013a, 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. 2013a; Ofek et al. 2013a,b; Prieto et al. 2013; Smith et al. 2014) or some type of extremely bright nonterminal event (Fraser et al. 2013a, Pastorello et al. 2013, Margutti et al. 2014). More recently, Smith et al. (2014) showed 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 massive stars above 30 $M_\odot$ do in fact experience core collapse and LBV-like stars are linked to SNe IIn.

6.3.5. SN 2010mc. Ofek et al. (2013b) reported the detection of a precursor event $\sim$40 days before the peak of the Type IIn SN 2010mc. It is unclear whether 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 that of SN 2009ip, for which it has been suggested that the -40-day precursor was actually the faint SN explosion of a BSG, and the later rise to peak was caused by CSM interaction.

6.3.6. SN 2010jl. This was an SLSN IIn, with a peak absolute magnitude brighter than -20 mag. Smith et al. (2011c) identified a source at the location of the SN in pre-explosion HST images that suggested 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 ∼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 2014, Smith & Arnett 2014), each of which lasts about 1 year. 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 in which pre-SN eruptions result from the PPI (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. [Indeed, as this review went to press, Fraser et al. (2013b) reported the recovery in archival data of an outburst one year before the SN IIn-P 2011ht.] 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 the Large Synoptic Survey Telescope 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 Population 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, because they had a strong impact on their environment and on galaxy evolution in general. These stars may have been very massive. They made the first SNe, the first stellar mass black holes, and the first dust. They ejected the first metals back into the ISM, they enhanced or dominated reionization, and they probably triggered the formation of the earliest generations of low-mass stars (Heger et al. 2003, Bromm & Larson 2004). However, as we attempt to extrapolate from the huge uncertainty associated with local stars to a regime in which 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 (Woosley et al. 2002, Heger et al. 2003). In contrast, more recent results suggest that Z-dependent winds are weaker than we used to think, even at $Z_\odot$. However, 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 IIn 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 it remains challenging to understand 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 owing 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 with rates derived observationally from standard ρ^2 diagnostics assuming homogeneous winds (de Jager et al. 1988, Nieuwenhuijzen & de Jager 1990). Reduction by a factor of ~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 $Z_\odot$ with mass-loss rates currently used for $0.37\,Z_\odot$ (i.e., lower than the LMC), whereas a factor of 3 would correspond to $0.2\,Z_\odot$, which is similar to models for SMC stars (using $\dot{M} \propto Z^{0.69}$; Vink et al. 2001). With moderately 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: (*a*) restrict their attention to MS stars, (*b*) work on Population III stars (see above), or (*c*) 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.

Because 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 in which 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 $\dot{M}$, $T_{\rm eff}$, L, rotational speed, abundances, etc. The distance must be known, but the Magellanic Clouds and clusters with known distances can help, and *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. Several specific possible future directions for theory and observations are listed below.

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 with 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. Until we have a firmer understanding of the mass loss in post-MS stages, end states of models are mostly hypothetical. 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 their 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 lack thereof) on metallicity is an important issue. A better understanding of mass and angular momentum transfer versus 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 and 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 a function of evolutionary time. How does the global $\dot{M}$ depend on the interplay between pulsational instability and dust formation?

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, we need continued work on the binary fraction and orbital parameters as a function of environment: clusters versus 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. These improved constraints are 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 with mass-transfer rates, studies of RLOF binaries or post-RLOF systems can help constrain under what conditions mass transfer is conservative or the degree to which it is conservative.
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-obscured, 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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