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ON THE ROLE OF CONTINUUM-DRIVEN ERUPTIONS IN THE EVOLUTION OF VERY MASSIVE STARS AND POPULATION III STARS

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ABSTRACT

We suggest that the mass lost during the evolution of very massive stars may be dominated by optically thick, continuum-driven outbursts or explosions, instead of by steady line-driven winds. In order for a massive star to become a Wolf-Rayet star, it must shed its hydrogen envelope, but new estimates of the effects of clumping in winds from O-type stars indicate that line driving is vastly insufficient. We discuss massive stars above roughly 40–50 $M_\odot$, which do not become red supergiants and for which the best alternative is mass loss during brief eruptions of luminous blue variables (LBVs). Our clearest example of this phenomenon is the 19th century outburst of η Carinae, when the star shed 12–20 $M_\odot$ or more in less than a decade. Other examples are circumstellar nebulae of LBVs and LBV candidates, extragalactic η Car analogs (the so-called supernova impostors), and massive shells around supernovae and gamma-ray bursters. We do not yet fully understand what triggers LBV outbursts or what supplies their energy, but they occur nonetheless, and they present a fundamental mystery in stellar astrophysics. Since line opacity from metals becomes too saturated, the extreme mass loss probably arises from a continuum-driven wind or a hydrodynamic explosion, both of which are insensitive to metallicity. As such, eruptive mass loss could have played a pivotal role in the evolution and ultimate fate of massive metal-poor stars in the early universe. If they occur in these Population III stars, such eruptions would also profoundly affect the chemical yield and types of remnants from early supernovae and hypernovae thought to be the origin of long gamma-ray bursts.

Subject headings: instabilities — stars: evolution — stars: mass loss — stars: winds, outflows

1. INTRODUCTION

Mass loss is a critical factor in the evolution of a massive star. In addition to the direct reduction of a star's mass, it profoundly affects the size of its convective core, its core temperature, its angular momentum evolution, its luminosity as a function of time, and hence its evolutionary track on the H-R diagram and its main-sequence (MS) lifetime (e.g., Chiosi & Maeder 1986). Wolf-Rayet (W-R) stars are the descendants of massive stars as a consequence of mass loss in the preceding H-burning phases, during which the star sheds its H envelope (Abbott & Conti 1987; Crowther 2006). While the maximum initial mass of stars is thought to be ∼150 $M_\odot$ (Figer 2005; Kroupa 2005), W-R stars do not have masses much in excess of 20 $M_\odot$ (Crowther 2006).[4] Thus, very massive stars have the immense burden of removing 30–130 $M_\odot$ during their lifetime before the W-R phase, unless they explode first. Stellar evolution calculations prescribe $\dot{M}(t)$ based on semiempirical values, so it is important to know when most of this mass loss occurs.

In this Letter we address the question of whether this mass loss occurs primarily via steady stellar winds or instead through violent, short-duration eruptions or explosions. Recent studies of hot star winds indicate that mass-loss rates on the MS are much lower than previously thought. These mass-loss rate reductions are significant enough to affect MS evolution, but they also raise an important question: *If mass loss via stellar winds is insufficient to strip off a star's* H *envelope and form a W-R star, then how and when does it occur*? Simultaneously, observations of nebulae around luminous blue variables (LBVs) and LBV candidates have revealed very high ejecta masses—of order 10 $M_\odot$. In η Car we know that the mass was ejected in a single outburst and is not swept-up ambient material. Together, these facts suggest that short-duration outbursts like the 19th century eruption of η Car could dominate mass lost during the lives of the most massive stars and that they would be critical to the formation of W-R stars.

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

2. THE PROBLEM: LINE-DRIVEN WINDS PROVIDE INSUFFICIENT MASS LOSS

In order to shed a massive star's envelope and reach the W-R stage, models must prescribe semiempirical mass-loss rates, which can be scaled by a star's metallicity (e.g., Chiosi & Maeder 1986; Maeder & Meynet 1994; Meynet et al. 1994; Langer et al. 1994; Langer 1998; Heger et al. 2003). Often-adopted "standard" mass-loss rates are given by de Jager et al. (1988), Nieuwenhuijzen & de Jager (1990), and Schaller et al. (1992). In order for stellar evolution models to match observed properties at the end of H burning, such as W-R masses and luminosities, and the relative numbers of W-R and OB stars, these mass-loss rates need to be enhanced by factors of ∼2 (Maeder & Meynet 1994; Meynet et al. 1994).

However, such enhanced mass-loss rates contradict observations. Recent studies suggest that mass-loss rates are in fact 3–10 or more times *lower* than the "standard" mass-loss rates, not higher. Mass-loss rates based on density-squared diagnostics like Hα and free-free radio continuum emission lead to overestimates if the wind is strongly clumped. Significant clumping in stellar winds is expected based on theoretical considerations (Feldmeier 1995; Owocki et al. 1988; Owocki & Puls 1999), as well as

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[4] By "W-R stars" we mean H-deficient W-R stars (core–He-burning phases or later) and not the luminous H-rich WNL stars (Crowther et al. 1995), which are probably still core-H burning.

observations like time-variable discrete absorption components (Howarth et al. 1995; Massa et al. 1995). Recent efforts have thus focused on using diagnostics that scale linearly with density, such as UV resonance absorption lines; Fullerton et al. (2006) have suggested a reduction of 10–20 or more from traditional mass-loss rates, while Bouret et al. (2005) require reductions by factors of 3 or more (see also Puls et al. 2006; Crowther et al. 2002; Hillier et al. 2003; Massa et al. 2003; Evans et al. 2004).[5] In any case, large reductions in $\dot{M}$ are also needed to match the unexpectedly symmetric X-ray line profiles in hot supergiant stars (Kramer et al. 2003).[6]

Such reduced mass-loss rates mean that steady winds are simply inadequate for the envelope shedding needed to form a W-R star. This is not such a problem for stars below $10^{5.8}\,L_{\odot}$, where the red supergiant (RSG) wind may be sufficient. However, above $10^{5.8}\,L_{\odot}$ (initial mass above 40–50 $M_{\odot}$), stars do not become RSGs (Humphreys & Davidson 1979), posing a severe problem if these stars depend on line-driven winds for mass loss.

For example, consider the fate of a star with an initial mass of 120 $M_{\odot}$. The most extreme O_2 If* supergiant HD 93129A has a mass-loss rate derived assuming a homogeneous wind of roughly $2 \times 10^{-5}\,M_{\odot}\,\mathrm{yr}^{-1}$ (Repolust et al. 2004). If the true mass-loss rate is lower by a factor of 3–10 or more as indicated by clumping in the wind, then during a ~2.5 Myr MS lifetime (Maeder & Meynet 1994), the star will only shed about 5–20 $M_{\odot}$, leaving it with $M \gtrsim 100\,M_{\odot}$ and an additional 80 $M_{\odot}$ deficit to shake off before becoming a W-R star. After this, the stellar wind mass-loss rates are higher during post-MS phases, but they are still insufficient to form a W-R star. They therefore cannot make up for the lower $\dot{M}$ values on the MS. For a typical LBV lifetime of a few times 10^4–10^5 yr (Bohannan 1997) and a typical $\dot{M}$ of $\sim 10^{-4}\,M_{\odot}\,\mathrm{yr}^{-1}$ for most LBVs, the LBV phase will only shed a few additional solar masses through its line-driven wind. Thus, some mechanism other than just a steady wind is needed to reduce the star's total mass by several dozen solar masses.[7]

One obvious—if not wildly speculative—way out would be if W-R stars are *not* the descendants of the most massive stars because massive stars explode at the end of the LBV phase. This, however, would be an even more severe paradigm shift in our understanding of stellar evolution, because it would require that LBVs have already reached advanced core-burning stages. Even if that were the case, our central hypothesis that continuum-driven LBV outbursts dominate the presupernova mass loss would still be true because of the substantial mass lost in LBV eruptions.

3. AN ALTERNATIVE: LBV ERUPTIONS

The most likely mechanism to rectify this hefty mass deficit for single stars is giant eruptions of LBVs (e.g., Davidson 1989; Humphreys et al. 1999), where the mass-loss rate and bolometric luminosity of the star increase substantially. While we do not yet fully understand what causes these giant LBV outbursts, we know empirically that they do indeed occur and that they drive substantial mass loss from the star.

Our best example of this phenomenon is the 19th century "Great Eruption" of η Carinae. The event was observed visually, the mass of the resulting nebula has been measured (12–20 $M_{\odot}$ or more; Smith et al. 2003b), and proper-motion measurements of the expanding nebula indicate that it was ejected in the 19th century event (e.g., Morse et al. 2001). The other example for which this is true is the AD 1600 eruption of P Cygni, although its shell nebula has a much lower mass of only ~0.1 $M_{\odot}$ (Smith & Hartigan 2006). Both η Car and P Cyg are surrounded by multiple, nested shells indicating previous outbursts (e.g., Walborn 1976; Meaburn 2001). While the shell of P Cyg is less massive than η Car's nebula, it is still evident that P Cyg shed more mass in such bursts than via its stellar wind in the time between them (Smith & Hartigan 2006). This difference between P Cyg and η Car hints that LBV outbursts become progressively more extreme the closer a star gets to the Eddington limit.

For other LBVs surrounded by nebulae, we cannot be certain that the observed shells result from a single outburst, free of swept-up stellar wind (e.g., Robberto et al. 1993). However, upon comparison with η Car, it seems plausible that the observed range of nebular masses originated in giant eruptions. Deduced masses of LBV and LBV-candidate nebulae from the literature are plotted in Figure 1 as a function of each central star's luminosity. We see that for stars with $\log\,(L/L_{\odot}) \gtrsim 6$, nebular masses of 10 $M_{\odot}$ are quite reasonable, *perhaps suggesting that this is a typical mass ejected in a giant LBV eruption*.

Figure 1 does not recover the clean "nebular mass–stellar luminosity" relation of Hutsemekers (1994), which was based on just six objects. In hindsight, we should not expect such a clean relation, because it would indicate that a star of a given luminosity can only eject a nebula of a particular mass. In the case of η Car, we know this is false: it ejected the very massive Homunculus in the 1840s, it ejected the 0.1–0.2 $M_{\odot}$ "Little Homunculus" in 1890 (Smith 2005; Ishibashi et al. 2003), and it may suffer smaller ejections every 5.5 yr (Davidson 1999; Smith et al. 2003a; Martin et al. 2006). Instead, we might expect a luminosity-dependent upper threshold to the plot, populated underneath by a range of masses.

Although LBV eruptions are rare, a number of extragalactic η Car analogs or "supernova impostors" have been observed, such as SN 1954J in NGC 2403 and SN 1961V in NGC 1058 (Humphreys et al. 1999; Smith et al. 2001; Filippenko et al. 1995; Van Dyk et al. 2002, 2005), V1 in NGC 2363 (Drissen et al. 1997), and several recent events seen as Type IIn supernovae, like SN 1997bs, SN 2000ch, SN 2002kg, and SN 2003gm (Van Dyk et al. 2000, 2006; Wagner et al. 2004; Weis & Bomans 2005; Maund et al. 2006). Furthermore, massive circumstellar shells have also been inferred to exist around supernovae and gamma-ray bursters. Some examples are the radio-bright SN 1988Z with a nebula as massive as 15 $M_{\odot}$ (Aretxaga et al. 1999; Van Dyk et al. 1993; Chugai & Danziger 1994) as well as similar dense shells around SN 2001em (Chugai & Chevalier 2006), SN 1994W (Chugai et al. 2004), SN 1998S (Gerardy et al. 2002), GRB 021004 (Mirabal et al. 2003), and GRB 050505 (Berger et al. 2006).

These outbursts and the existence of massive circumstellar nebulae indicate that the 19th century eruption of η Car is not an isolated, freakish event but instead may represent a common rite of passage in the late evolution of the most massive stars. A massive ejection event may even initiate the LBV phase, by lowering the star's mass, raising its L/M ratio, and drawing it

[5] Puls et al. (2006) express concerns in UV-derived rates because of wind ionization and the corresponding reliability of tracers like P V.

[6] Suggestions (Oskinova et al. 2004) that the effective reduction in bound-free X-ray absorption might instead be attributed to a porous absorbing medium may require a separation scale between clumps that is too large (Owocki & Cohen 2006).

[7] An important question surrounds the lifetimes and evolutionary status of rare WNL stars (e.g., Crowther et al. 1995), which have strong winds and may temper the burden placed on LBVs if the WNL phase lasts $\gtrsim 10^6$ yr. However, in that case, η Car could not be a post-WNL star as one might expect, because the mass of its ejecta, added to its present-day stellar mass, leaves no room for such substantial mass loss if there is an upper limit of 150 $M_{\odot}$ to the initial masses of stars (Figer 2005; Kroupa 2005).

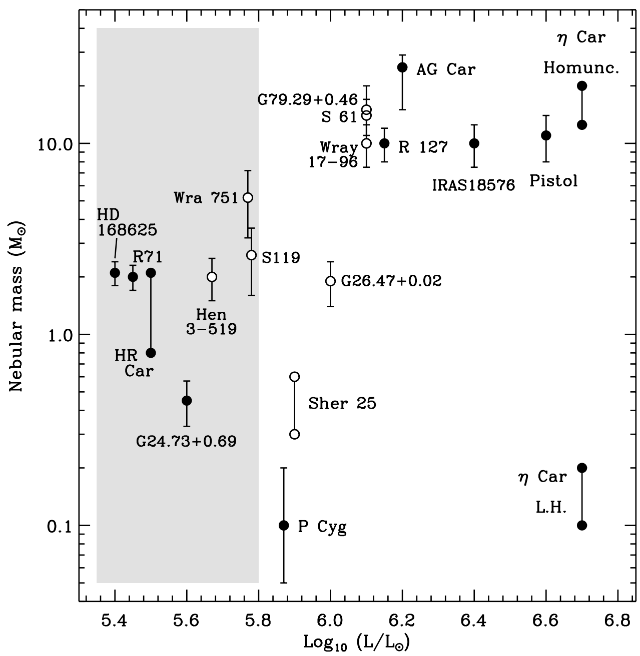

FIG. 1.—Masses of ejecta nebulae from LBVs (*filled circles*) and LBV candidates (*open circles*) as a function of the central star's bolometric luminosity. Luminosities are taken from Smith et al. (2004), while masses are taken as follows: the Homunculus of η Car (Smith et al. 2003b), the Little Homunculus of η Car (Smith 2005), the Pistol star (Figer et al. 1999), IRAS 18576+0341/AFGL 2298 (Ueta et al. 2001), AG Car and Wra 751 (Voors et al. 2000), G79.29+0.46 (Higgs et al. 1994), Wray 17-96 (Egan et al. 2002), Sher 25 (Brandner et al. 1997), P Cygni (Smith & Hartigan 2006), He 3-519 (Smith et al. 1994), and the remaining values adopted from Clark et al. (2005). When masses are determined from measurements of dust masses, we assume a gas-to-dust mass ratio of 100. When uncertainties are not specified by authors, we adopt roughly $\pm 25\%$. The lightly shaded part on the left side of the graph corresponds to luminosities of stars that may be post-RSGs (see Smith et al. 2004).

closer to instability associated with an opacity-modified Eddington limit (Appenzeller 1986; Davidson 1989; Lamers & Fitzpatrick 1988). Mass loss in these giant eruptions may play a role in massive star evolution analogous to thermal pulses of asymptotic giant branch stars. In any case, meager mass-loss rates through stellar winds, followed by huge bursts of mass loss in violent eruptions at the end of core-H burning, may significantly alter stellar evolution models.

4. EXTREME MASS-LOSS RATES AND OPTICALLY THICK CONTINUUM-DRIVEN WINDS

Observational constraints require extremely high mass-loss rates during giant LBV eruptions. For η Car, we have a lower limit of 0.5 $M_\odot$ yr^{-1} averaged over the 20 yr duration of the eruption (Smith et al. 2003b). However, the thin walls of the Homunculus (Smith 2006) and the small age spread from proper motions (Morse et al. 2001) both imply that the dominant mass-loss phase was $\lesssim$5 yr. This would indicate an astonishing mass-loss rate of several solar masses per year or more. Furthermore, the 20 yr bright phase of η Car was unusually long-lasting; eruptions of extragalactic η Car analogs typically last less than a decade (Van Dyk 2005). P Cygni presents the lower end of the spectrum for likely mass-loss rates. Its outburst in AD 1600 ejected ~0.1 $M_\odot$ (Smith & Hartigan 2006), implying $\dot{M} \approx 10^{-2}\ M_\odot$ yr^{-1}.

Such extreme mass-loss rates mean that strong lines must be heavily saturated, so that these outflows cannot be launched by the conventional CAK (Castor et al. 1975) mechanism for line-driven winds. As discussed by Owocki et al. (2004), the maximum mass-loss rate for line driving can be written as

$$\dot{M} = \frac{L}{c^2}\frac{\alpha}{1-\alpha}\left(\frac{\bar{Q}\Gamma_e}{1-\Gamma_e}\right)^{-1+1/\alpha}, \qquad (1)$$

where L, c, and Γ_e are the stellar luminosity, speed of light, and Eddington parameter (for pure electron scattering), respectively, and α and $\bar{Q}$ are the power index and normalization of the line opacity distribution (Gayley 1995), respectively. This mass loss scaling arises from the need for the line acceleration—which scales inversely with density and thus mass-loss rate—to overcome gravity in driving the wind. For stars close enough to the Eddington limit that the effective gravity becomes small, the mass loss can formally become large. However, this would also result in outflow speeds that are smaller than inferred from observations of LBVs. To characterize the maximum mass loss that can be driven without this kind of augmentation from a separate continuum assistance, let us take the factor $\Gamma_e/(1-\Gamma_e)$ to be roughly unity. Then for optimal realistic values $\alpha = \frac{1}{2}$ and $\bar{Q} = 2000$ for the line opacity parameters (Gayley 1995), the maximum mass loss from line driving is given by

$$\dot{M} \approx 1.4 \times 10^{-4} L_6\ M_\odot\ \mathrm{yr}^{-1}, \qquad (2)$$

where L_6 is $L/(10^6\ L_\odot)$. Even for peak luminosities of a few times $10^7\ L_\odot$ during η Car's eruption, this limit is still several orders of magnitude below the mass loss that created the Homunculus. If mass loss during these eruptions occurs via a wind, it must be a super-Eddington wind driven by continuum radiation pressure (i.e., Thomson scattering opacity and not lines; Owocki et al. 2004; Belyanin 1999; Quinn & Paczyński 1985).

An alternative to a continuum-driven wind is a deep-seated hydrodynamic explosion that blasts off the star's outer layers. In the star's envelope, convection will set in before the Eddington limit is reached, but if convection is inefficient, a density inversion can develop (e.g., Joss et al. 1973). Potentially, this could lead to a violent explosion (e.g., Arnett et al. 2005; Young 2005). Gravity-mode oscillations or nonlinear growth of other instabilities within the star may also play a role (Glatzel et al. 1999; Townsend & MacDonald 2006; Guzik 2005). It is not yet clear which of these phenomena is responsible for giant LBV eruptions, but none of them invoke metallicity-dependent line driving as the physical mechanism for imparting momentum to the ejecta.

5. POTENTIAL IMPLICATIONS FOR THE FIRST STARS

The first stars, which should have been metal-free, are generally thought to have been predominantly massive, exhibiting a flatter initial mass function than stars at the present epoch (e.g., Bromm & Larson 2004). With no metals, these stars should not have been able to launch line-driven winds, and thus they are expected to have suffered no mass loss during their lifetimes (however, see Vink & de Koter 2005). The lack of mass loss profoundly affects the star's evolution and the type of supernova it eventually produces (Heger et al. 2003), as well as the yield of chemical elements that seeded the early interstellar medium of galaxies.

This view rests on the assumption that mass loss in massive stars at the present time is dominated by line-driven winds—an assumption that is problematic in view of recent observational constraints. As discussed above, massive shells around LBVs and the so-called supernova impostors in other galaxies indicate that short-duration eruptions dominate the mass loss of very massive stars, while steady, line-driven winds contribute little to the total mass lost during their lifetime. Unlike line-driven winds, the driving mechanism for these outbursts could well be insensitive to metallicity.

Since we still do not know what triggers LBV eruptions, we cannot yet claim confidently that these eruptions will in fact occur in the first stars. However, the possibility should raise caution signs for theoretical work on Population III stars. If mass loss of massive stars at the present epoch is dominated by mechanisms that are insensitive to metallicity, then we must question the prevalent notion that the first stars did not lose substantial mass prior to their final supernova event.

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