ON THE ROLE OF THE WNH PHASE IN THE EVOLUTION OF VERY MASSIVE STARS: ENABLING THE LBV INSTABILITY WITH FEEDBACK

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ABSTRACT

We propose the new designation “WNH” for luminous Wolf-Rayet (WR) stars of the nitrogen sequence with hydrogen in their spectra. These have been commonly referred to as WNL stars (WN7h, for example), but this new shorthand avoids confusion because there are late-type WN stars without hydrogen and early-type WN stars with hydrogen. Clearly differentiating WNH stars from H-poor WN stars is critical when discussing them as potential progenitors of Type Ib/c supernovae and gamma-ray bursts—the massive WNH stars are not likely Type Ib/c supernova progenitors, and are distinct from core He burning WR stars. We show that masses of WNH stars are systematically higher than for bona fide H-poor WR stars (both WN and WC), with little overlap. Also, hydrogen mass fractions of the most luminous WNH stars are higher than those of luminous blue variables (LBVs). While on the main sequence, a star’s mass is reduced due to winds and its luminosity slowly rises, so the star increases its Eddington factor, which in turn strongly increases the mass-loss rate, pushing it even closer to the Eddington limit. Accounting for this feedback, observed properties of WNH stars are a natural and expected outcome for very luminous stars approaching the end of core H burning. Feedback from the strong WNH wind itself plays a similar role, enabling the eruptive instability seen subsequently as an LBV. Altogether, for initial masses above 40–60 M⊙, we find a strong and self-consistent case that luminous WNH stars are pre-LBVs rather than post-LBVs (for lower initial mass, the case is less clear). The steady march toward increased mass-loss rates from feedback also provides a natural explanation for the continuity in observed spectral traits from O3 V to O3 If* to WNH noted previously.

Subject headings: stars: evolution — stars: mass loss — stars: winds, outflows — stars: Wolf-Rayet

1. INTRODUCTION

The role of mass loss in the evolution of the most massive stars with initial masses of ~60–150 M⊙ is still poorly understood, partly because the most luminous stars are so rare and each one seems unique at some level, and partly because accurate physical parameters are difficult to determine. Consequently, the connection between spectral characteristics and evolutionary state is often mangled.

One persistent mystery concerns the placement of the very luminous late-type H-rich WN stars (referred to here as “WNH stars,” as justified below) in the evolutionary sequence of very massive stars (see Crowther et al. 1995a; Hamann et al. 2006; Langer et al. 1994). Because of their high mass-loss rates and consequent emission-line spectra, they are often discussed alongside or confused with core He burning Wolf-Rayet (WR) stars (for reviews of WR stars, see Abbott & Conti [1987] and Crowther [2007]), and it is sometimes suggested that their H content indicates that they represent the early phases of core He burning. In this interpretation, the WNH phase occurs immediately after—or sometimes instead of—the luminous blue variable (LBV) phase, marking the beginning of the core He burning WR stages (see, for example, Schaller et al. 1992; Meynet et al. 1994; Maeder & Meynet 1994).

A different suggestion has been made based on the very high luminosity of some of the WNH stars and especially based on their membership in very young massive star clusters like R136 in 30 Doradus, NGC 3603, and the Carina Nebula (e.g., de Koter et al. 1997; Drissen et al. 1995; Crowther et al. 1995a; Moffat & Seggewiss 1979). Namely, these authors suggest that it may be the case instead that the WNH stars are essentially core H burning stars that precede the LBV phase. This suggestion has also been made based on the continuity in spectral types from O3 V to O3 If* to WNL+h, as noted, for example, by Walborn (1971, 1973, 1974), Walborn et al. (2002), Lamers & Leitherer (1993), Drissen et al. (1995), and Crowther et al. (1995a).

This continuity has led to the suggestion that the most luminous stars may even skip the LBV phase altogether (Crowther et al. 1995a)—i.e., that they evolve directly from O stars to WR stars (Conti 1976). However, this direct path is not taken in all cases because it is contradicted by the existence of very luminous LBVs such as η Carinae and the Pistol Star. Langer et al. (1994) have discussed the two possibilities above from the perspective of evolution models, and they suggest instead that both may be true—i.e., that a star may look like a WNH star both before and after the LBV phase. Langer et al. (1994) investigated a 60 M⊙ initial mass model, and as we will see later, the distinction between stars of 60 and 100 M⊙ may be important in terms of their evolutionary path.

Our main conclusion in this paper is that available evidence strongly favors the latter interpretation above that WNH stars are pre-LBVs, at least for the highest luminosities above log (L/L⊙) = 5.8–6.0. As discussed below, this is based on the fact that their distributions of stellar mass are distinct from H-poor stars, and that their hydrogen mass fractions are generally higher than LBVs (although there is a caveat to this last point depending on initial mass, as discussed below). We also argue that one might expect them to be pre-LBVs if feedback from mass loss on the main
sequence is accounted for in a simple way. In § 2 we justify the new naming convention “WNH,” in § 3 we examine the masses of WNH stars, and in § 4 we examine their hydrogen mass fractions compared to LBVs. Then in § 5 we take a look at how mass loss on the main sequence might naturally lead to a WNH-like phase, and how that higher mass-loss phase might drive the star toward the Eddington limit to become an LBV. In the last few sections we discuss further related implications of the scenario in which WNH stars are pre-LBVs.

2. THE SHORTHAND “WNH” TO DESIGNATE A DISTINCT CLASS

We propose the new designation “WNH” for luminous WR-like stars of the nitrogen sequence exhibiting evidence for hydrogen in their spectra. In current practice, these are commonly referred to collectively as “WNL stars,” with individual objects classified as WN6ha, WN7h, etc. (see Smith et al. 1994, 1996, 2000; Crowther et al. 1995a; Conti 1999). We do not propose to change this more specific classification scheme for individual stars. However, we do advocate that the common usage of WNL stars as a group should be changed to “WNH stars” for two main reasons, one being a practical matter and the other having to do with their evolutionary state and questionable relationship to other WR stars.

The terms WNL, WNE, WCL, and WCE were first used by Vanbeveren & Conti (1980) as a shorthand for “late-” and “early-” type WR stars of the nitrogen and carbon sequences. Its use was quickly adopted as a convenience by other authors. Later on, the WNL term came to mean late-type WN stars with hydrogen, as most of them have this element present. However, observations have firmly established that there are both late-type WN stars without hydrogen (the bona fide WN stars), and, more problematic, early-type WN stars with hydrogen. A number of early-type (WN3ha, WN4ha, and WN5ha) WN stars with hydrogen have been identified recently in the SMC (Foellmi et al. 2003a; Foellmi et al. 2004), and some in the LMC as well (Foellmi et al. 2003b). One such WNE star with hydrogen is the famous object HD 5980, an eclipsing massive binary in which the hydrogen-rich component had been classified as WN6h, WN11, LBV, or B1.5 Ia at different times during its LBV-like outburst in the 1990s (Koenigsberger 2004), but had been classified as WN4h before that. WN5h is arguably on the border between early and late type, and several of these have been seen in 30 Dor and Westerlund 1 (Crowther & Dessart 1998; Crowther et al. 2006). Other Galactic examples are WR 3 (WN3ha), WR 10 (WN5ha), WR 48c (WN3h+WC4), WR 49 (WN5h), WR 109 (WN5h), WR 128 (WN4h), and WR 152 (WN3h) (Marchenko et al. 2004; Hamann et al. 2006; van der Hucht 2001). Clearly, the phenomenon of hydrogen in WN stars is not limited to late types, rendering “WNL” an inappropriate designation, as it refers mainly to WN7/WN8 (Moffat & Seggewiss 1979). The shorthand “WNH” would encompass both early- and late-type WN stars with hydrogen.

Second, the designation WNH is also useful to emphasize the apparent fact that while they exhibit WR-like spectral features because of their strong winds (they are sometimes referred to as “O stars on steroids”), the WNH stars are distinct from core He burning WR stars in several observed characteristics and most probably in their evolutionary state. The assertion that they represent a distinct evolutionary state is justified in the following sections, where we show that, like LBVs, the WNH stars are consistently more massive than WN and WC stars, and that they have H mass fractions more in line with LBVs. We argue that their observed masses, mass-loss rates, luminosities, wind speeds, and other properties can all be understood naturally if they represent the later stages of core H burning of very massive stars with ages ~2 Myr, making them immediate precursors of LBVs, or perhaps, quiescent LBVs at lower luminosities. Finally, the high mass-loss rates seen in the WNH phase might be a necessary condition to push the star toward the Eddington limit, again arguing that WNH stars are the best candidates for the immediate precursors of high-luminosity LBVs.

We reiterate that we intend the term WNH only as collective shorthand for the class of WN-like stars that show hydrogen in their spectra, because we believe them to be distinct from H-free WN stars. While this new terminology is arguably imperfect because one star or another might challenge categorization or blur the boundaries, the term is needed simply to avoid confusion, and it makes a clear distinction that is also useful for purposes of discussion. Because they show a range in H mass fraction (see below), the WNH stars constitute a somewhat heterogeneous class and may even overlap with the LBVs. In that sense, however, the term WNH has a usefulness similar to that of “LBV,” since the LBV class contains stars labeled variously as S Doradus variables, η Car variables, α Cygni variables, P Cygni stars, O6pe/WN9 stars, etc., yet we still refer to them all collectively as “LBVs.” The term LBV has been useful for broadly discussing stars that we think share a common evolutionary phase, even though it is not always agreed whether an individual object is a bona fide LBV or not.

The term WNH is also critical to distinguish these stars from H-free WN stars, because massive stars are the progenitors of various types of core-collapse supernovae (SNe). The single most important observable trait in classifying a SN spectrum is the presence or absence of hydrogen, making it a Type II or a Type Ib/c, respectively. The “H” in WNH therefore serves as a clear reminder that hydrogen is present, and that these are not to be confused with the H-free WR stars that are the likely progenitors of Type Ib SNe and possibly also long-duration gamma-ray bursts. More specifically, the classification criteria of WN stars are not relevant or useful in this context, as they mainly describe the temperature and ionization level of the wind. Observationally, one cannot determine if the progenitor of a SN is WNE or WNL, but in principle, one can tell the difference between WN and WNH.

3. MEASURED MASSES OF WNH STARS

Figure 1 collects mass estimates for WR stars from the literature, including masses measured both spectroscopically and in binary systems. It compares present masses of WNH stars to H-poor WN and WC stars (spectroscopic masses are unreliable for WC stars). The spectroscopic masses are taken mostly from Hamann et al. (2006), who derived the masses using the mass-luminosity relation for helium stars from Langer (1989). They noted that this relation might not be adequate for WNH stars, but they also note that when masses measured in binary systems are available for the same stars for which they estimated a spectroscopic mass, the two methods show no wild disagreement. For example, the spectroscopic mass they derive for the WNH star WR 22 in the Carina Nebula is 74 $M_\odot$, compared to 72 $M_\odot$ determined from the binary orbit by Rauw et al. (1996). Thus, while the exact values for the masses in the top panel of Figure 1 might be somewhat suspect, the main trend of the separation between WN and WNH stars is

1 There are rare objects that confuse the issue, like SN 2006jc (Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2008), but this only emphasizes the importance of highlighting the presence of hydrogen. Also, it is worth noting that some compact binary scenarios might produce Type Ib/c SNe with lower mass stars (e.g., Pols & Dewi 2002; De Donder & Vanbeveren 1998).

2 Although see also Schweikhardt et al. (1999), who derive a mass of 55 $M_\odot$ for the WNH component.
not five.) measured in binary systems, there are only four WN stars in the 15
grams, numbers of different types of objects are “stacked.” For example, Moffat (1991), WR 151 (Villar-Sbaffi et al. 2006), HD 5980A and B (Koenigsberger (Lefevre et al. 2005), V444 Cygni (Flores et al. 2001), WR 141 (Grandchamps & 2001), but are augmented or superseded in several cases as follows: WR 137 (Lefevre et al. 2005), V444 Cygni (Flores et al. 2001), WR 141 (Grandchamps & Moffat 1991), WR 151 (Villar-Shaffi et al. 2006), HD 5980A and B (Koenigsberger 2004; Foellmi et al. 2008), WR 22 (Rauw et al. 1996), WR 20a (Rauw et al. 2005; Bonanos et al. 2004), WR 25 (Gamen et al. 2006), and R145/30 Dor and NGC 3603/A1 (A. F. J. Moffat 2006, private communication). (Note that in these histograms, numbers of different types of objects are “stacked.” For example, measured in binary systems, there are only four WN stars in the 15–20 $M_\odot$ bin, not five.) Masses measured for WR stars in binary systems are more reliable, but there are not many of them available, shown in the bottom panel of Figure 1. The results for the distribution of masses for different WR types measured spectroscopically and in binaries show very good general agreement.

The clear lesson to be learned from Figure 1 is that WN stars have systematically higher masses than H-poor WN and WC stars. With binaries and spectroscopic masses, the mass distribution of H-poor WN stars clearly peaks at 15–20 $M_\odot$, while WN stars are spread more evenly over a large range of masses mostly above 30 $M_\odot$. There are only a few cases of mass overlap between the WN stars and a small fraction of the WNH stars. This may be because of WN stars in binary systems where H is present, or it may signify a real evolutionary overlap. Note that the overlap is more prevalent in the spectroscopic masses where unrecognized binaries are more likely to contaminate the sample, and where the general shape of the WNH mass distribution in the 10–25 $M_\odot$ range matches that for WN stars, as one might expect if they are not true WNH stars. All the H-poor WR stars have relatively low masses below 30 $M_\odot$. The WNH star masses peak around 50 $M_\odot$ (for the more numerous spectroscopic masses), and masses measured in binaries extend to very large masses—as high as more than 120 $M_\odot$ for the WNH star R145 in 30 Dor (A. F. J. Moffat 2006, private communication).

Overall, then, Figure 1 makes a strong case that WNH stars are in fact a separate and distinct group of stars from the H-poor WR stars. It is obviously logical to assume that WNH stars are more massive than WN and WC stars because they have not yet shed their H envelopes, and that they may eventually become H-poor WR stars. In that case WNH stars must be at a significantly earlier evolutionary stage, which is consistent with the fact that they are preferentially seen in massive clusters within giant H II regions like the Carina Nebula, NGC 3603, and 30 Dor, whereas H-free WN stars are not. On the other hand, WNH stars may be consistently more massive than WN or WC stars simply because they evolve from stars with higher initial masses and follow different evolutionary paths.

Furthermore, the wide mass discrepancy between WNH and H-poor WR stars and the fact that the two populations hardly overlap at all provides a vital clue to their evolutionary states. It argues strongly against the notion that WNH stars are simply the initial stages of the core He burning WR phase, where they are still in the process of shedding the last remaining layers of their hydrogen envelopes, gradually transitioning into H-free WN stars. (Besides, shedding the required 20–80 $M_\odot$ in $\leq 10^7$ yr in this transition requires mass-loss rates higher than observed for WNH stars.) Instead, the discontinuity in mass of tens of solar masses between WNH and WN stars suggests that some other intermediate stage must quickly remove the large mass remaining in the hydrogen envelopes of the WNH stars before they can become WN stars. The obvious choice for the subsequent removal of that mass is the violent eruptions of LBVs (Smith & Owocki 2006). In other words, based on their masses, WNH stars are likely to be pre-LBVs, not post-LBV stars. Interestingly, unlike the H-poor WR stars, LBVs exhibit a range of masses (with current masses of roughly 30–100 $M_\odot$) that does overlap with that of the WNH stars, arguing that the two are closely related.

We also note a systematic difference in the masses of WC and WN stars in Figure 1. The WC star mass distribution peaks in the 5–15 $M_\odot$ range, whereas the WN distribution peaks at higher masses in the 15–20 $M_\odot$ range. One might expect this if WC stars are more evolved descendants of WN stars (Paczynski 1973), as the products of further mass stripping by the powerful WN stellar wind (Conti 1976) or sudden events like that inferred for the progenitor of SN 2006jc (Smith et al. 2008; Pastorello et al. 2007; Foley et al. 2007). A prediction of this trend is that SNe of Type Ib should result from more massive progenitors than Type Ic SNe. If not, then an interesting mystery needs to be solved. In any case, the disparity in mass between the WNH stars and all the other WR types (Fig. 1) supports the main thrust of this paper, and is obviously relevant for interpreting the progenitors of Types Ib and Ic SNe.

4. HYDROGEN MASS FRACTIONS

Figure 2 shows the hydrogen mass fraction, $X_H$, as a function of stellar luminosity for WNH stars compared to LBVs. This is obviously an important quantity for unraveling the evolutionary relationship between these two classes of stars. A similar plot
and its implications have already been discussed by Langer et al. (1994), but we update it here with several additional values from the literature. This updated information is most relevant at the highest luminosities, as there were only a few data points above $\log (L/L_\odot) = 6.0$ in the similar plot by Langer et al. The behavior of those high-luminosity objects is the focus here.

Excluding $\eta$ Car and the Pistol Star, the LBVs seem to cluster around $X_H \approx 0.35$, while the WNH stars occupy a large range of $X_H$ values from 0.05 to 0.5, above and below the values for LBVs. However, the way that this range of $X_H$ values for WNH stars compares to those of the LBVs changes with luminosity, and it depends on which set of WNH luminosities is adopted. In cases when both Crowther et al. (1995a) and Hamann et al. (2006) analyzed the same target stars, values for $X_H$ generally agree to within a few percent if they differ at all. The disagreement is in the stellar luminosities, with the luminosities from Hamann et al. (2006) being systematically higher by roughly 0.5 dex for the same target stars. This may be due to the fact that Hamann et al. assumed that WNH stars had relatively high luminosities. Shifting the WNH stars horizontally in Figure 2 significantly impacts our interpretation of the relative evolutionary status of WNH stars compared to LBVs. Figures 2a and 2b suggest the following different implications, respectively:

1. Figure 2a presents a suggestive picture that the relationship between WNH stars and LBVs is dependent on luminosity (and hence, on initial mass). Below $\log (L/L_\odot) = 5.8$ (the upper limit for red supergiants [RSGs] and for H-free WR stars), we see that the WNH stars are generally more evolved with lower hydrogen content than LBVs. At an intermediate luminosity range of $\log (L/L_\odot) = 5.8–6.0$, the case is less clear; WNH stars bracket the $X_H$ values for LBVs, suggesting that they could be both pre- and post-LBVs, as in the scenario suggested by Langer et al. (1994) for a star of initial mass 60 $M_\odot$ corresponding to P Cygni.

At high luminosities above $\log (L/L_\odot) = 6.0$, however, no WNH stars are seen to have smaller hydrogen mass fractions than LBVs—they generally lie above the LBVs, indicating that they should be pre-LBVs.

2. With the higher WNH luminosities in Figure 2b (Hamann et al. 2006), on the other hand, one would conclude that the LBVs are intermixed with and are essentially indistinguishable from WNH stars in their abundances, except that LBVs occupy a narrower range. This would imply that WNH stars can be both pre- and post-LBVs, regardless of luminosity. Given the comments above, this is a fair possibility at lower luminosities, but seems less likely for the high-luminosity stars above $\log (L/L_\odot) \approx 5.8$.

At this time, we cannot be certain which of these luminosity estimates to trust, and this highlights the need for accurate estimates of $L$ and $X_H$ in order to understand the evolution of massive stars. There are a few reasons to favor the somewhat lower luminosities of Crowther et al. (1995a) and the corresponding interpretation implied by Figure 2a. First, for the Carina Nebula WNH stars WR 22, 24, and 25 (shown with bold triangles in Figs. 2a and 2b), the lower luminosities of Crowther et al. are in much closer agreement with the spectroscopically similar WNH stars in R136 and NGC 3603 (de Koter et al. 1997; Drissen et al. 1995), shown with squares in Figure 2. Also, the higher luminosity for WR 25 from Hamann et al. (2006) makes this star more luminous than $\eta$ Car, making it difficult to understand why $\eta$ Car is so much more unstable and more evolved with a larger N abundance, even though they are members of the same star cluster. Second, the implication in Figure 2a that WNH stars precede the LBV phase at high luminosities (above $\log (L/L_\odot) = 5.8–6.0$) is in much better agreement with the conclusions drawn from considering their current (high) masses discussed in the previous section, as well as the discussion of the mass-loss rates to follow. In Figure 2b, on the other hand, the occurrence of many high-luminosity...
WNH stars with $X_{\text{H}}$ values significantly lower than LBVs is at odds with the impression that they typically have higher stellar masses than LBVs. This argument is admittedly somewhat circular. Therefore, we cannot consider the measured abundances as giving any definite answer to the relative evolutionary states of WNH stars and LBVs—we can only say that the scenario in Figure 2a fits together in a more consistent way with the idea that high-luminosity WNH stars are pre-LBVs, while the implication from Figure 2b that WNH stars are both pre- and post-LBVs would present an unresolved puzzle (which may nevertheless be true). One last reason to favor Figure 2a concerns the environments in which these stars are found. The most luminous WNH stars with higher H content than LBVs reside in massive giant H II regions like 30 Dor, Carina, and NGC 3603. The WNH stars with lower H content than LBVs (and at lower $L$) do not reside in such massive young regions (like most of the LBVs, incidentally). This argues for a lower initial mass and larger age for the lower $L$ WNH stars. In any case, further work on the H abundances of WNH stars is needed.

Of course, factors other than initial mass may influence the apparent values of $X_{\text{H}}$ as well, such as the star’s rotation rate and consequent level of mixing during core H burning phases (Maeder & Meynet 2000). This is beyond the scope of our consideration here, but it obviously may be important.

5. MASS-LOSS FEEDBACK AND THE EVOLUTIONARY STATES, MASSES, AND AGES OF WNH STARS

Our primary goal in this paper is to determine how the WNH stars fit into the evolutionary sequence of massive stars. When does the WNH phase “turn on,” how long does it last, how much mass is lost from the star, and what are the preceding and subsequent evolutionary phases? In the previous sections, we showed that WNH stars are considerably more massive than H-poor WR stars, arguing that they are more massive because they have not yet shed their H envelopes and that they therefore represent an earlier evolutionary phase, before the heavy mass loss encountered as an LBV. We also showed that the most luminous WNH stars tend to be more H-rich than LBVs, arguing again that they are pre-LBVs.

Another way to attack the problem is to ask when in the lifetime of a massive star we should expect the WNH phase to occur, given some initial mass, luminosity, and mass-loss rate. These expectations can then be compared with the measured masses, mass-loss rates, luminosities, and other properties of WNH stars.

To this end, in the following discussion we consider what the expected properties of luminous O-type stars should be as they reach the end of core H burning. We are primarily interested in the rate at which the mass-loss rate grows from an initial value during core H burning. We consider the generic effect of mass loss on the stellar properties, and on the evolution of the mass-loss rate itself through a “feedback” effect. The parameterization of mass loss discussed below is quite simple, and is not claimed to be an adequate substitute for renewed calculations of stellar evolution codes. Rather, it is meant only to illustrate the principle that the effect of mass loss can account for the properties of WNH stars if they are luminous and massive stars near the end of core H burning. Our results argue that renewed efforts to calculate the evolution of massive stars with lower mass-loss rates are essential in light of recent observational estimates of lower mass-loss rates due to wind clumping. Our arguments here strengthen the case that mass-loss rates of O-type stars need to be revised downward from the “standard” observed rates (de Jager et al. 1988; Nieuwenhuijzen & de Jager 1990) due to the observational effects of clumping, and more in line with (but probably even lower than) the theoretically expected values of Vink et al. (2001).

In Figure 3 we consider the expected properties of stars with initial masses of 120, 85, and 60 $M_{\odot}$, where feedback is included such that the mass-loss rate is proportional to $L/\Gamma_{1}(1 - \Gamma)$. Adopted quantities are the luminosity during core H burning from Schaller et al. (1992) for each initial mass, the initial radius for the main-sequence star (only relevant for $V_{\text{esc}}$), and the initial mass-loss rate. The initial mass-loss rates (dots) are those appropriate for the corresponding initial luminosity and mass, with moderate clumping factors of 2–5 ($S_{\text{cl}}$ reduced by $\sqrt{5}$), taken from Repolust et al. (2004). For comparison, the dotted line in the top panel shows the predicted mass-loss rates from Vink et al. (2001) for the same $M$ and $L$. From the prescribed initial values, the subsequent mass-loss rate, stellar mass, Eddington factor (4/3), and escape velocity are calculated iteratively until the end of core H burning, as described in the text. The plot of stellar mass (solid lines) also shows the cumulative mass lost (dot-dashed lines).
the initial mass, the initial value for the mass-loss rate, and the bolometric luminosity $L(t)$ throughout the core H burning lifetime. We adopt $L(t)$ from the solar metallicity models of Schaller et al. (1992), which include mass loss. Although it would be better to calculate new stellar evolution models self-consistently instead of adopting a luminosity from an existing model with different mass-loss rates, our approach here is a demonstrative first step. In any case, the adopted luminosities are sufficient to illustrate the main point of this paper, which is that the expected climb of the mass loss with time can account for the apparent properties of the WNH stars.

With these prescribed conditions, Figure 3 shows the time evolution of the mass-loss rate, the stellar mass, the Eddington factor $\Gamma = L/L_{\text{Edd}}$, where $L_{\text{Edd}}$ is the classical Eddington limit due to electron scattering opacity, and the star’s surface escape velocity. At each time step, each quantity is calculated iteratively from the previous time step. For instance, following the initial mass, the mass at each subsequent time step is calculated by simply reducing the mass by $M \times \Delta t$. For reasons that will become obvious later, we consider only the core H burning main-sequence lifetime and not core He burning phases.

The purpose of Figure 3 is to illustrate how these quantities change during the core H burning lifetime of the star, in response to the choice of an initial value for the mass-loss rate. We are especially interested in the way that the mass-loss rate grows due to previous mass loss—what we refer to below as mass-loss feedback.

Essentially all the observable properties of subsequent post-main-sequence phases and the type of SN eventually seen depend critically on the adopted $M(t)$. During core H burning, stellar evolution calculations have typically assumed mass-loss rates adopted from observed standard values such as those given by de Jager et al. (1988) or Nieuwenhuijzen & de Jager (1990), as was done in Schaller et al. (1992) and subsequent studies of Heger et al. (2003), Eldridge & Tout (2004), and several others.

However, adopting these mass-loss rates is arguably not the best treatment of mass loss if one is interested in asking what mass-loss rates to expect as the star evolves, since this method simply prescribes them (not to mention the fact that $\dot{M}$ values need to be revised downward due to clumping; see below). Stars at the same position in the H-R diagram can have different masses, mass-loss rates, and other properties, arguing for a different approach. This may be one of the reasons that the WNH phase is often assumed to be associated with later evolutionary phases; for example, following the end of core H burning, Schaller et al. (1992) impose a WNH phase with a constant $M = 4 \times 10^{-5} M_\odot \text{yr}^{-1}$ until the H envelope is removed.

Here we take a different approach. Instead of prescribing mass-loss rates throughout the star’s evolution, we consider the effect that the mass-loss rate for a line-driven stellar wind from a hot massive star should change during its lifetime, responding to changes in the star’s luminosity with time, as well as to changes in its mass. During core H burning, a star’s luminosity gradually climbs as the core contracts (Fig. 3), providing one mechanism that will act to increase the mass-loss rate, since the wind is radiation driven. Simultaneously, the star’s wind is removing mass from the star’s surface, lowering the star’s mass considerably, which also acts to increase the mass loss, since the star has a shallower gravitational potential well. In essence, both these effects conspire to raise the star’s proximity to the classical Eddington limit, since $\Gamma = L/L_{\text{Edd}}$ is proportional to $L/M$. This increase in mass-loss rate accelerates the growth of $\Gamma$, making the problem worse. Essentially, this behavior introduces a very important feedback loop that is currently not included in stellar evolution calculations.

This feedback effect can be treated in a simple way, sufficient for our limited purposes here. The CAK theory of radiatively driven winds (Castor et al. 1975) provides a prescription for how the mass-loss rate should vary with the star’s luminosity $L$ and the Eddington factor $\Gamma$ (and hence, the star’s mass). Following Owocki (2003), for example, the dependence can be written as

$$\dot{M} \propto L \left( \frac{\Gamma}{1-\Gamma} \right)^{-1+\alpha},$$

where $\alpha$ is the usual CAK power index. For illustrative purposes in Figure 2, we adopt $\alpha = 0.5$, as is common in line-driven winds of O-type stars. Equation (1) then simplifies to

$$\dot{M} \propto L \left( \frac{\Gamma}{1-\Gamma} \right),$$

which is the mass-loss rate dependence that we adopt in Figure 3. When this feedback is included, we see that a star’s mass-loss rate will climb steadily and substantially, even during the core H burning phase alone. Given an initial mass-loss rate at $t = 0$, one can then calculate the mass-loss rate and the stellar mass at subsequent times, self-consistently, given $L(t)$, as long as it is safe to assume that the wind is line-driven. This assumption will break down as the Eddington factor climbs near $\Gamma = 1$ and the mass-loss rate skyrocket, when a continuum-driven wind may take over (Smith & Owocki 2006; Owocki et al. 2004). Given the simplistic treatment and the fact that we extrapolate from a single initial value, it is reassuring that our values of $\dot{M}(t)$ are not too different from the predicted values of Vink et al. (2001; dotted line in the top panel of Fig. 3), especially at the later WNH stages that are the focus here.

In Figure 3 the initial mass-loss rates we have adopted are the moderately clumped rates given by Repolust et al. (2004) appropriate for O-type dwarfs with the adopted luminosity for each of the three initial masses considered. These mass-loss rates and the degree of clumping in stellar winds is a larger issue than we can address here (see, for example, Puls et al. 2006; Fullerton et al. 2006; Bouret et al. 2005; Smith & Owocki 2006; Smith 2007a; Eversberg et al. 1998; Lepine & Moffat 1999).

As a result of the climbing mass-loss rate, we see that $\Gamma$ climbs significantly as well, ramping up at the end of core H burning. The implications of this for triggering the LBV instability are discussed below in §7. Another result of the ramping up of $\dot{M}$ is that more of the mass ultimately shed from the star is lost later in its life, as is also the case if LBV eruptions are a dominant mode of mass loss (Smith & Owocki 2006). This will significantly impact other properties such as the mass of the He core produced, as well as the angular momentum evolution of the star and its rotational mixing. Lower mass-loss rates will cause the wind to shed less angular momentum. In turn, faster rotation will likely enhance axisymmetric/bipolar mass loss in later evolutionary phases (Cranmer & Owocki 1995; Owocki et al. 1996, 1998; Owocki & Gayley 1997; Maeder & Meynet 2000). Such effects

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4 Newer calculations sometimes use the predicted rates of Vink et al. (2001) instead of or in combination with the de Jager et al. (1988) rates, such as Meynet & Maeder (2005) and Eldridge & Vink (2006).

5 This usage of the term “feedback” is different from that referring to the energy input and metal enrichment of the interstellar medium by massive stars.
will not be discussed in detail below, but they need to be re-investigated in future stellar evolution calculations.

6. DISCUSSION

6.1. Mass-Loss Rates and Ages of WNL Stars

If Figure 3 gives the expected behavior of $\dot{M}(t)$ for massive stars, we can then compare it with the observed mass-loss rates of WNH stars to deduce where they might fit in. Figure 4 is the same as Figure 3, but it includes some rough ranges of observed values corresponding to WNH stars for comparison.

We see here that for these very luminous stars, the mass-loss rate only climbs to values seen in WNH stars after about 2 Myr from the beginning of the star’s life. For the luminous WNH stars, typical mass-loss rates are well above $10^{-3} \ M_\odot \ yr^{-1}$ (Crowther et al. 1995a). This favors the interpretation that the WNH stars have ages of 2–3 Myr. It is also consistent with the cohabitation of three WNH stars in the same region alongside $\eta$ Car, whose late evolutionary stage points to an age of roughly 2.5–3 Myr.

An independent check on the ages of WNH stars is given by their observed wind speeds (bottom panel in Fig. 4). We see that the observed WNH wind speeds of several hundred to 2000 km s$^{-1}$ are not consistent with zero-age main sequence massive stars, nor with the very fast winds of H-free WN and WC stars. Instead, these values are only reached late in a star’s core H burning lifetime (after roughly 2 Myr) as a natural consequence of mass loss and the corresponding lowered $g_{\text{eff}}$ as the star gets pushed to higher values of $\Gamma$. Thus, both the observed mass-loss rates and wind speeds of WNH stars would seem to favor ages above 2 Myr.

Caveat: One could of course assume that WNH stars are indeed very young—that they are somehow born with such high mass-loss rates—but what should we expect the star’s subsequent evolution to look like in that case? This is akin to adopting higher mass-loss rates for O stars (homogeneous winds instead of clumped winds; see Puls et al. 2006), and this introduces severe problems, as discussed next.

6.2. WNH Star Masses, and Implications for Clumped Winds and Lowered Mass-Loss Rates of O-Type Stars

If WNH stars do indeed reside near the end of core H burning with ages $\gtrsim$2 Myr, then their measured masses and luminosities may provide us with important clues to the mass-loss rates on the main sequence and the degree of clumping, which is a major issue in stellar evolution. For example, if WNH stars have relatively high masses when they reach the ends of their core H burning lives, then the mass-loss rates throughout core H burning cannot be very high. In fact, some very high masses have been observed for WNH stars. As shown in Figure 1, several examples exist of WNH stars with masses of 80–120 $M_\odot$ measured in binary systems.

If Figures 3 and 4 are accurate representations of the trend of $\dot{M}$ on the main sequence, then we can see that the high masses of WNH stars make sense if they occur at the end of core H burning—but only if the winds are moderately clumped. Remember that in Figure 3 we assumed that the initial mass-loss rates were those of Repolust et al. (2004), which correspond to conservative wind clumping factors of $\sim 5$, reducing the mass-loss rates by factors of $\sim 2$ compared to the standard mass-loss rates$^6$ derived from $H\alpha$ and radio observations with the assumption of homogeneous winds (de Jager et al. 1988; Nieuwenhuijzen & de Jager 1990). In this case, the early phases with lower mass-loss rates as an O-type star are nearly irrelevant to the star’s total mass loss. The mass-loss rate increases later as the star gradually moves into the WNH phase and on into the LBV phase, indicating that most of a star’s mass is lost late in its lifetime at a quickened pace. These moderately clumped mass-loss rates are just about as high as they can be in order for the most massive stars to reach the Eddington limit at the end of core H burning.

$^6$ This is because of the density-squared nature of the $H\alpha$ and radio continuum diagnostics of the mass-loss rates.
Let us turn this question around and view the problem from another perspective: If we still include the feedback effect of mass loss described earlier, as we arguably should, then what will happen if the stellar winds are not clumped and we adopt initial mass-loss rates that are higher? Figure 5 shows the same type of evolution with feedback (solid lines) as in Figure 3, with the only difference being that we started with higher initial mass-loss rates. These initial rates (dots) adopt the prescription for the standard values for homogeneous winds given by Nieuwenhuijzen & de Jager (1990).

These are the values that have most commonly been used in stellar evolution calculations (e.g., Heger et al. 2003), although sometimes rates even a factor of 2 higher than these are used to match observed statistics of massive stars (Meynet et al. 1994). The results of adopting the higher mass-loss rates in Figure 5 are quite dramatic (the same calculations without the feedback effect are shown with dashed lines in Fig. 5, for comparison). Figure 5 shows that with these high initial mass-loss rates, mass-loss feedback quickly drives the star’s Eddington factor up to $\Gamma = 1$ in only 1.3, 2, and 3 Myr for the 120, 85, and 60 $M_\odot$ models, respectively, likely triggering a very early LBV-like phase with catastrophic mass loss. However, this is certainly in conflict with observations, at least for the 85–120 $M_\odot$ models, since—as aside from the one case of $\eta$ Car—the stars in massive young clusters like R136, NGC 3603, and Carina typically do not have very massive shells of recently ejected material around them. Thus, we consider it unlikely that very luminous stars are born with mass-loss rates as high as those seen in WNH stars or with the mass-loss rates corresponding to homogeneous stellar winds. Also, the fact that massive stars reach the end of core H burning as WNH stars with relatively high masses cannot be explained by models in Figure 5 with high mass-loss rates because too much mass has already been lost, whereas the high masses of WNH stars arise naturally for moderately clumped winds. This is the sensitive nature of the feedback effect—that even a small reduction by a factor of $\approx 2$ in the initial mass-loss rate can have dramatic consequences later in a star’s life.

Furthermore, there is also the case of LBVs like $\eta$ Car to consider: it is the most luminous and most evolved member of a rich region containing over 65 O-type stars, as well as the three well-known WNH stars (see Smith [2006] for a review, including details of the age differences among clusters in the region). It is fair to assume that the current LBV phase of $\eta$ Car is not only a post-main-sequence phase, but probably also a post-WNH phase, since its ejecta are more nitrogen-rich than the WNH stars in Carina. It is also safe to assume that $\eta$ Car has advanced further in its evolution sooner than the WNH stars of the same age in this region simply because it is more luminous and started with a higher initial mass. Now, $\eta$ Car is seen today surviving as a very massive star of around 100 $M_\odot$ or more (allowing for a hypothetical $\sim 30 M_\odot$ companion star), and we measure a total of something like 20–35 $M_\odot$ in its circumstellar material ejected in only the last few thousand years (the Homunculus, plus more extended outer material; see Smith et al. 2003, 2005). That means $\eta$ Car began its LBV phase—and ended its main-sequence and/or WNH phase—with more than 120 $M_\odot$ still bound to the star. If there really is an upper limit of about 150 $M_\odot$ to the mass of stars (Figer 2005), then this mass budget demands that the O-star and WNH winds were indeed quite meager before reaching this phase. Similarly, there is the Pistol Star to consider as well, which is also a post-main-sequence object and has a present-day mass that probably exceeds 100 $M_\odot$ (Figer et al. 1998).

In conclusion, then, the relatively high masses of WNH stars, the high masses of the most luminous LBVs, and the intuition that we should include the feedback effect of mass loss all argue that line-driven winds of massive stars must be clumped. This argument is independent of the many spectroscopic clues that these winds are clumped (e.g., Puls et al. 2006; Bouret et al. 2005; Fullerton et al. 2006; Eversberg et al. 1998; Lepine & Moffat 7 Note that when the mass-loss rates climb aggressively, the reduction in the star's mass is likely to quell the core luminosity somewhat. Therefore, when this stage is reached it is likely that our very simple way of treating the mass loss is invalid, and full stellar evolution calculations will be needed. The early push toward those higher mass-loss rates is probably valid, however.

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Fig. 5.— Same as Fig. 3, but showing how stars run into trouble if feedback is included and we adopt the standard unclumped mass-loss rates for the initial state, or if the standard mass-loss rates are assumed throughout. These initial standard mass-loss rates are taken from Nieuwenhuijzen & de Jager (1990), and are only a factor of $\sim 2$ higher than the moderately clumped rates of Repolust et al. (2004) that we used previously in Figs. 3 and 4. We see that these higher mass-loss rates are clearly not feasible because they drive the star to the Eddington limit far too early—long before the end of core H burning for the most massive stars. Also shown with dotted lines are the results if we neglect the effect of feedback. This case is arguably artificial, however.
1999). We find that the mass-loss rate reductions due to clumping must be at least a factor of 2 compared to standard rates for homogeneous winds, consistent with the conservative factors adopted by Repolust et al. (2004). It is encouraging that this amount of mass-loss reduction brings the mass-loss rates of O stars into better agreement with theoretical predictions for line-driven winds of O-type stars (e.g., Vink et al. 2001), although these may still be too high.

6.3. WNH Stars as Pre-LBVs, Not Core He Burning WR Stars

Unfortunately, it is difficult to reliably determine the age of a WNH star directly from observations of its environment. One can easily deduce cluster ages from observations that are either too low or too high by 1 Myr or more: The essential problem is that the lifetimes of these very massive stars are so short that they are often comparable to the uncertainty in the age of their parent cluster. In addition, that parent cluster or association may have a real age spread that makes the problem even worse. Thus, identifying a WNH star in a young 1–2 Myr cluster like R136 or NGC 3603 (if their ages are that low) does not necessarily mean that particular WNH star itself has an age of 1–2 Myr. In any case, the validity of ascribing a single-valued age to a given cluster is highly debatable.

Since we cannot really trust direct estimates of the ages for individual WNH stars based on their environments—at least not at the precision of ±1 Myr—we must try to infer relative ages in other ways. In this paper we have demonstrated that there are four main reasons to favor the interpretation that luminous WNH stars are pre-LBVVs:

1. The stellar masses of WNH stars are systematically higher than H-poor WN stars, and more specifically, they have very different distributions (Fig. 1). Namely, H-free WR stars are all heavily clustered around 15–20 $M_\odot$, whereas WNH stars seem to be spread evenly from 20 $M_\odot$ all the way up to the most massive stars known well above 100 $M_\odot$. This is clearly in conflict with the notion that WNH stars are in the process of continuously becoming WN stars through their own stellar winds. Instead, the strong discontinuity in mass distribution between the WNH and WN stars argues for an intervening phase of episodic mass loss that quickly sheds tens of solar masses and removes essentially all the remaining H envelope. This intervening rapid mass-loss phase is almost certainly the LBV phase (regardless of what the interpretation for the cause of the LBV phase might be; i.e., inherent instability of single stars vs. binary mergers, etc.). Unlike for H-poor WN stars, the stellar masses for LBVs overlap quite well with the WNH stars.

2. At high luminosities, the hydrogen mass fractions, $X_H$, for WNH stars tend to be higher than for LBVs (Fig. 2a). This requires that they are less evolved. We noted that this case is not definitive, since the higher WNH luminosities from Hamann et al. (2006) paint a somewhat different picture than the lower luminosities of Crowther et al. (1995a). However, the properties of WNH stars in the cores of NGC 3603 and 30 Dor would seem to favor the interpretation that they are pre-LBVs based on their abundances (de Koter et al. 1997; Drissen et al. 1995).

3. We showed that if one includes feedback due to mass loss on the main sequence, then starting with a moderately clumped initial mass-loss rate, one naturally expects the star’s mass-loss rate to climb after about 2 Myr to values that would make it appear as a WNH star, near the end of core H burning and before the LBV phase (Figs. 3 and 4). As we showed earlier, if massive stars are born with the high mass-loss rates of WNH stars, then the subsequent evolution does not make sense (Fig. 5).

4. Conversely, if the mass-loss rates are lower, then the effect of feedback is not so severe. Interestingly, the relative rate at which $M(t)$ climbs with the lower initial mass-loss rates of clumped winds (Fig. 3) more closely matches that of the observed mass-loss rates, even though the observed rates are offset to higher values. Therefore, simply lowering the observed standard values of Nieuwenhuijzen & de jager (1990) by a factor of 2–3 gives a fairly accurate match to the expected mass-loss rates with feedback and clumping. This provides a powerful, self-consistent argument that the mass-loss rates are in fact lowered due to clumping in stellar winds.

One of the interesting results of Figure 3 is that this steady march toward increased mass-loss rates from feedback on the main sequence also provides a natural explanation for the apparent continuity in observed spectral traits from O3 V $\rightarrow$ O3 If* $\rightarrow$ WNH noted previously (Walborn 1971, 1973, 1974; Walborn et al. 2002; Walborn & Blades 1997; Conti 1976; Melnick 1985; Massey & Hunter 1998; Lamers & Leitherer 1993; Drissen et al. 1995; Crowther et al. 1995a, etc.), and onward from WNH $\rightarrow$ LBV as well. This sequence is known to show intermediate stages, such as hot slash stars like Melnick 42 in 30 Dor and weak-lined WNH stars like WR 25 (e.g., Walborn et al. 1992), attributed mainly to changes in wind density during stellar evolution. We argue that no special circumstances such as pulsationally enhanced mass loss, rapid rotation, binary mergers, or unusual abundances are needed to account for the presence of WNH stars in massive young clusters with ages of around 2–3 Myr—it is a natural outcome of initially moderate mass loss on the main sequence that gradually grows more severe later on (Fig. 3).

6.4. And Where are the Luminous Post-LBVs?

There are no H-free WR stars with luminosities above log ($L/L_\odot$) $= 5.8$ (Fig. 2), and if we favor the results shown in Figure 2a, there are not even any WNH stars with lower hydrogen mass fractions than LBVs for luminosities above log ($L/L_\odot$) $= 6.0$. One possibility is that the LBV mass loss is so extreme that giant eruptions can completely remove the remaining H envelope to expose the bare He core. Thus, in Figure 2, a star would effectively move instantaneously from the position of an LBV like AG Car to a lower luminosity WR star. However, the clear absence of H-free WR stars above log ($L/L_\odot$) $= 5.8$ is puzzling in that case, as is the general dearth of H-free WN stars in giant H II regions. The sudden removal of the outer layers at the end of core H burning should not much affect the luminosity of the He core that remains behind, so where are these luminous H-free stars? One way out of this predicament, hinted at by Figure 2a, could be if the more massive stars explode before shedding their H envelopes.

In fact, there is mounting evidence that some massive stars may explode during the LBV phase before ever making it all the way to the H-free WR stage (see the discussions in Smith & Owocki [2006], Smith [2007a], and Gal-Yam et al. [2007]). Some examples are the recent Type Ibn event SN 2006gy, which may have been the explosion of a very massive star like η Car (Smith et al. 2007); the Type Ibn event SN 2006gl, whose putative progenitor star identified by Gal-Yam et al. (2007) had photometric properties consistent with an LBV; the variable radio properties of some SNe (Kotak & Vink 2006; for other interpretations, however, see Soderberg et al. [2006] and Ryder et al. [2006]); the SN 1987A—like nebula around the LBV star HD 168625 (Smith 2007b); plus many other Type Ibn SNe with dense environments. There are also some He-rich stars (perhaps LBV/WN transition stars) that appear to have suffered LBV-like mass ejections shortly before a Type Ib/c SN explosion—the
clearest example being SN 2006jc (see Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2008), which was actually observed to have an LBV-like event 2 yr prior to the SN explosion. For the low-luminosity LBVs like HD 168625 or R71, explosion as an LBV is not necessarily a problem—or even a surprise—because those lower L stars are likely to be in a post-RSG phase (see Smith et al. 2004). For the high-luminosity LBVs above log \((L/L_\odot)\) = 5.8, however, it presents a serious challenge to our current paradigms of stellar evolution.

6.5. And What Have We Left Out?

Obviously, we have stopped short of a full calculation of stellar evolution models that would take into account the way that the core luminosity may respond to mass loss. However, in exploring the feedback effect, we adopted the core luminosities from the models of Schaller et al. (1992), which used relatively high mass-loss rates as noted earlier. Therefore, with the lower initial mass-loss rates we argue for here (and a consequent higher core luminosity), the feedback effect we propose could be even more extreme. Nevertheless, we only set out to demonstrate the principle of the feedback effect, and that it can lead to high mass-loss rates of WNH stars if they are in the latter part of core H burning for initially very massive O-type stars. Renewed efforts to calculate full stellar evolution models are encouraged.

Our simple analysis does not account for chemical mixing and possible effects of rotation on that parameter, which is still a central problem in the evolution of massive stars. It is quite possible that rotationally enhanced mixing could lead stars with identical masses to evolve on somewhat different paths; hence, surface abundances could differ. Thus, the exact time of “onset” of the WNH phase might vary from one star to another—even for stars of the same initial mass—based on the initial rotation rate and efficiency of the mixing. Therefore, our quoted age of \(\approx 2\) Myr for the onset of the WNH phase, which is imprecise to begin with, is not meant to be definitive.

It is well known that LBVs can undergo minor outbursts (i.e., “S Dor eruptions”) where they may change their mass-loss rate while remaining at constant bolometric luminosity, causing a corresponding change in apparent temperature and wind speed due to a pseudo photosphere. More relevant here is that they can also suffer giant eruptions with violent sudden mass loss, like those seen in \(\eta\) Car and P Cygni (see, e.g., Davidson et al. 1989), where they may eject \(\sim 10\) \(M_\odot\) in a single burst (Smith et al. 2003; Smith & Owocki 2006), and these events are likely to repeat. There is a suspicion in the hot star community that the most luminous objects (e.g., \(\eta\) Car or the Pistol Star) might have fewer but more severe outbursts, while less luminous LBVs could repeat these episodes many times with each individual event less violent than for \(\eta\) Car (again see, e.g., contributions in Davidson et al. 1989). The mass lost each time, the frequency, and the total number of such outbursts as a function of luminosity or initial mass, combined with the potential regulating/perturbing effect of close binaries, are parameters that are badly needed for modeling the late evolution of massive stars, but we are still far from accurate empirical prescriptions of this mass-loss behavior. Therefore, we must remain skeptical of the predictions of stellar evolution codes beyond the end of core H burning for very massive stars.

How do the WNH stars fit into this scenario? Could a WNH become an LBV and thence return to the WNH stage again? This is thought to be the case, specifically, for some Ofpe/WN9 stars, since the LBVs AG Car and R127 both look like Ofpe/WN9 stars in their quiescent state (Stahl 1986; Stahl et al. 1983). Perhaps something similar is happening for HD 5980 in the SMC. Can we determine if such LBV/WNH transition stars are occurring relatively early or late in a broader LBV phase? How does the initial stellar composition affect the WNH/LBV scenario we propose here? Does the presence of a number of early WN stars in the SMC that are also WNH tell us something?

7. SUMMARY: THE STRONG WINDS OF WNH STARS ENABLE THE LBV PHASE

We have shown that the masses, mass-loss rates, and abundances of luminous WNH stars are distinct from H-free WR stars, that they can be explained naturally if they are in the late stages of core H burning, and that this can be understood as a direct consequence of mass-loss feedback during core H burning. We treat this feedback very simplistically as the dependence of the mass-loss rate on the luminosity and Eddington factor associated with conventional line-driven wind theory, as explained in \(\S\) 5. We have ignored additional effects such as rotationally or pulsationally enhanced mass loss, but those effects may become necessary if O-star mass-loss rates are indeed reduced much below the values corresponding to moderate clumping factors (Repolust et al. 2004) that we have adopted here. The feedback causes a steady climb in the star’s mass-loss rate.

Just as this O-star mass loss provides a sort of feedback that leads to the higher mass-loss rates of WNH stars, so too does the higher mass-loss rate of the WNH phase enable further instability in later phases. Namely, with increased mass loss, the WNH wind lowers the stellar mass even further as the luminosity continues to climb at an even faster pace. This runaway eventually pushes the star to the classical Eddington limit (\(\Gamma = 1\)), as shown in Figure 3. At some point along the way, perhaps at \(\Gamma \approx 0.9\), an opacity modified Eddington limit (e.g., Lamers & Fitzpatrick 1988; Appenzeller 1986; and many contributions in Davidson et al. 1989) presumably takes over and runaway mass loss will ensue, marking the beginning of the LBV phase.

Exactly when this is initiated relative to the brief transition from core H to He burning is unclear, and would seem to vary with the initial mass of the star and with metallicity. For the most massive stars, the sharp increase in luminosity right at this transition pushes the star past \(\Gamma = 1\). However, down near \(60\) \(M_\odot\), for instance, it would appear that the star can linger on well into core He burning before actually triggering the LBV instability. Again, this is very interesting from the point of view of LBVs being potential Type II Nn SN progenitors.

Another consequence of lower mass-loss rates throughout core H burning is that the star will suffer less angular momentum loss. This, in turn, makes rotation have an even more important effect in the later stages as an LBV, as discussed by Langer and others (Langer 1998; Langer et al. 1994; Glatzel 1998; Maeder & Meynet 2000). Perhaps this rotation is critical for triggering the LBV instability for some range of LBVs, since models for initial masses below \(85\) \(M_\odot\) do not quite reach \(\Gamma \approx 1\) by the end of core H burning (Fig. 3). In any case, what happens to the structure of the star after the onset of the LBV phase has not yet been adequately addressed in stellar evolution calculations, because short-duration eruptions and explosions of LBVs seem to be an integral part of exceeding the Eddington limit.

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