Independent signs of lower mass-loss rates for O-type stars

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I discuss observational evidence – independent of the direct spectral diagnostics of stellar winds themselves – suggesting that mass-loss rates for O stars need to be revised downward by roughly a factor of three or more, in line with recent observed mass-loss rates for clumped winds. These independent constraints include the large observed mass-loss rates in LBV eruptions, the large masses of evolved massive stars like LBVs and WNH stars, WR stars in lower metallicity environments, observed rotation rates of massive stars at different metallicity, supernovae that seem to defy expectations of high mass-loss rates in stellar evolution, and other clues. I pay particular attention to the role of feedback that would result from higher mass-loss rates, driving the star to the Eddington limit too soon, and therefore making higher rates appear highly implausible. Some of these arguments by themselves may have more than one interpretation, but together they paint a consistent picture that steady line-driven winds of O-type stars have lower mass-loss rates and are significantly clumped.

1 Introduction

Before giving a list of observational reasons to favor clumped-wind mass-loss rates, I'll just clarify a few terms. When I mention "standard" or "unclumped" mass-loss rates, I am referring to the mass-loss rates derived primarily from Hα or radio continuum observations with the assumption of homogeneous winds (de Jager et al. 1988; Nieuwenhuijzen & de Jager 1990). When I refer to "lower" or "clumped" mass-loss rates, I am referring to these same mass-loss rates reduced by adopting a clumping factor. I do not refer to theoretical mass-loss predictions, such as those by Vink et al. (2001), which appear to be in line with the moderately-clumped rates.

2 Mass Budget: LBV Eruptions

In the evolution of very massive stars with initial masses above $\sim$60 M$_\odot$, the standard mass-loss rates would have an O star shed most of its initial mass by the end of the main sequence, followed by a WNH or LBV line-driven wind that removes the remaining H envelope to yield a $\lesssim$20 M$_\odot$ WR star. This scenario does not allow room for giant eruptions of LBVs, which can remove something like 10 M$_\odot$ in a few years, and which seem to happen multiple times (see Smith & Owocki 2006). I have discussed these events and their role in stellar evolution ad nauseam, but the main point here is that line-driven winds on the main sequence need to be lower by a factor of a few in order leave enough mass on the star at the end of core-H burning so that they can supply enough ejecta for these outbursts.

3 Mass Budget: High Masses of LBVs and WNH Stars

By the same token, O-star mass-loss rates need to be lower than the standard rates in order to agree with measured masses of stars at the end of core-H burning. An example that I sometimes mention is η Carinae, because it is well studied. We think the primary star in the η Car system has a present-day mass of order 100 M$_\odot$ (it could be higher) if it is not violating the classical Eddington limit, and we think it has reached the end or passed the end of core-H burning because of the observed nitrogen enrichment in its ejecta. It has lost at least 20 M$_\odot$, perhaps 30 M$_\odot$, in violent LBV eruptions in just the past few thousand years (Smith et al. 2003), in addition to its steady wind. That means the star made it to the end of the main sequence with a mass of 120–130 M$_\odot$ still bound to the star. If we believe that the upper limit to the initial mass of stars is about 150 M$_\odot$ (e.g., Figer 2005), then η Car could have lost only about 20-30 M$_\odot$ as an O star and WNH star combined during its first 3 Myr. This could only be the case if O star mass-loss rates are reduced by at least a factor of 3, probably more.

Similar arguments apply to the Pistol star and the luminous WNH stars (see Smith & Conti 2008), with estimated present-day masses as high as 80–120 M$_\odot$ measured in binaries. These stars are at or very near the end of core-H burning, having suffered mass loss from steady line-driven winds as O stars for roughly

3 Myr as well. With the standard mass-loss rates, they could not exist with their present-day masses.

4 Feedback and High Mass-Loss

Another problem is that the higher "standard" mass-loss rates lead to an unphysical predicament – they make the star go berzerk too early. I am referring to a feedback loop introduced by high mass-loss rates (see Smith & Conti 2008). Namely, as mass loss reduces a star's mass and its luminosity simultaneously climbs due to core evolution, the star will creep closer to the Eddington limit. However, as the Eddington factor climbs, CAK theory (Castor et al. 1975) tells us that the mass-loss rate will climb even faster. Eventually the star will exceed the classical Eddington limit; when this happens depends essentially on the initial mass-loss rate.
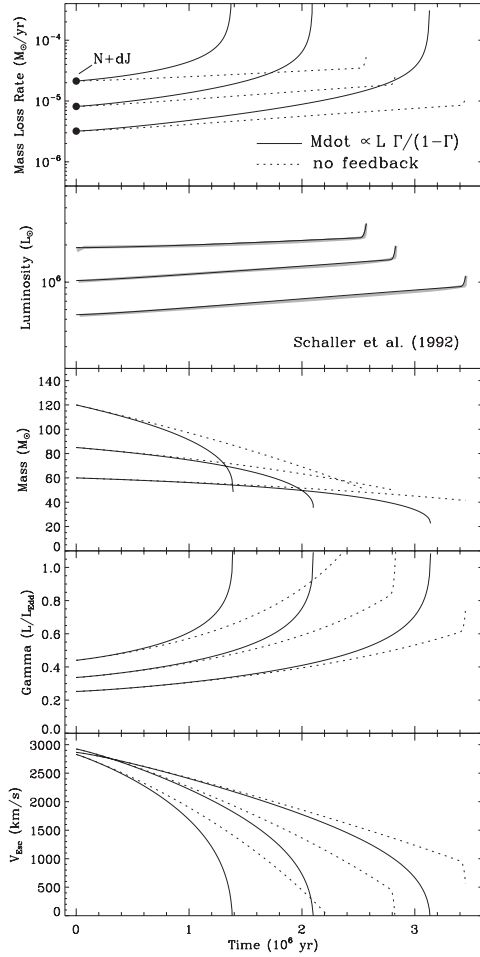

Figure 1: Mass-loss rate evolution adopting standard (NdJ) initial mass-loss rates with feedback (solid) and without (dashed). See Smith & Conti (2008).
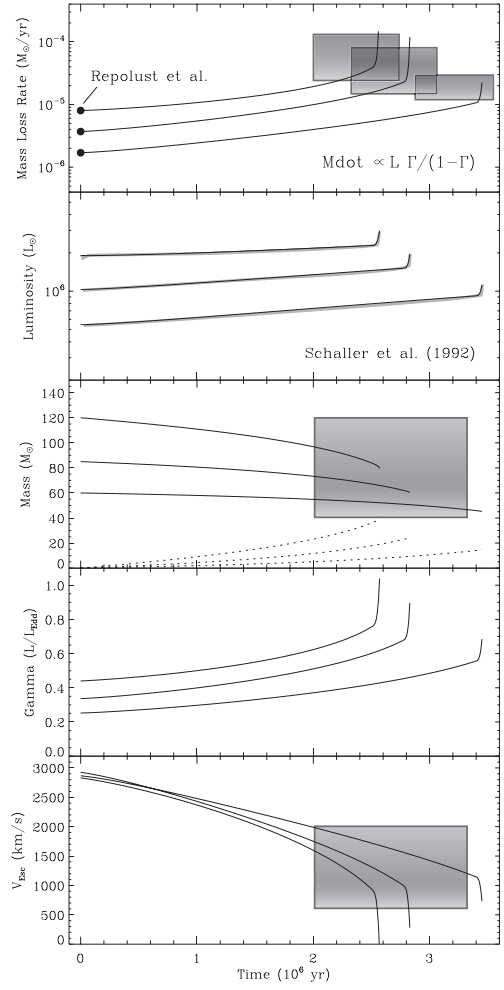

Figure 2: Mass-loss rate evolution adopting moderately-clumped initial mass-loss rates from Repolust et al. (2006) with feedback. Shaded boxes indicate observed range of properties for WNH stars; see Smith & Conti (2008).

Figure 1 shows the mass-loss rate evolution predicted on the main-sequence, taking the standard mass-loss rates as the intial rates. For higher masses and luminosities, the mass-loss rate skyrockets and the star exceeds the classical Eddington limit after only about 1 Myr. This is too early, since almost no massive stars in very young clusters are surrounded by LBV-type shells (η Car is the only one, and its age is thought to be $\sim$3 Myr). Furthermore, the predicted *change* in mass-loss rate with feedback disagrees with the observed trend (dashed in Fig. 1).

By contrast, Figure 2 shows a more sensible mass-loss evolution, starting with initial mass-loss rates for O stars that are reduced by a factor of about 3 (rates from Repolust et al. 2006). These rates, in-

cluding the expected effects of feedback, yield stellar properties near the end of core-H burning that agree with observations of WNH stars. This topic is discussed in more detail by Smith & Conti (2008).

5 Type IIn Supernovae

There exists a population of supernovae that argues against strong mass loss in steady line-driven winds as the dominant mode of mass-loss in massive stars. These are the Type IIn supernovae, named for the "narrow" lines of H in their spectra. There are two reasons they contradict high mass-loss rates.

The first reason is because Type IIn supernovae are thought to mark the deaths of very massive stars – in some cases the *most* massive stars like η Car. Their deaths prove that in some cases, at roughly Solar metallicity, massive stars face death with their H envelopes intact. Second, the Type IIn supernovae show evidence for huge blasts of eruptive mass loss shortly before they exploded. These supernova precursor events are suspiciously similar to giant LBV eruptions (Smith & Owocki 2006), shedding a few to 10s of $M_\odot$ of H-rich material in the decade before core collapse. Thus, Type IIn supernovae argue against the conventional wisdom that all massive stars should shed their H envelopes via line-driven winds to form WR stars. See Smith et al. (2007) and Gal-Yam et al. (2007) for more details.

6 GRBs and WR Stars at Low-Z

A prediction of the relatively high "standard" mass-loss rates is that winds will dominate mass loss for massive stars, steadily removing the outer layers of a star through line-driven winds until a He-rich WR star appears. Because these winds are metallicity dependent, it becomes more difficult to make WR stars at low metallicity. This runs counter to the observations that long-duration GRBs (associated with Type Ic supernovae that result from the deaths of WR stars) are found only in low metallicity galaxies, and that WR stars are seen in abundance in some low-Z galaxies, like IC 10 and I Zw 18. The existence of WR stars at low Z is sometimes explained by close binary mass transfer, but this cannot explain all of them. Moffatt et al. (these proceedings) have shown that the binary fractions among WR stars in the SMC, LMC, and Milky Way are not significantly different (i.e., there are single WR stars or WR stars in very wide binaries in the SMC). This suggests that some mechanism other than binary interaction (i.e. continuum-driven LBV eruptions; Smith & Owocki 2006) must be responsible for the envelope removal that leads to WR stars in all three environments, not line-driven winds. One alternative way to explain the existence of WR stars at low Z is that rapid rotation and efficient mixing leads to homogeneous evolution (e.g., Hirschi, these proceedings), but the high initial rotation rates required will only apply to a small fraction of stars.

7 Z-Independent O-Star Rotation

Mass-loss via steady line-driven winds throughout core-H burning as O stars should lead to significant loss of angular momentum if the "standard" mass-loss rates apply. Thus, there should be a clear trend in rotation rate and metallicity among O stars. Penny et al. (2004) have searched for this effect, but find no convincing difference in the rotation period distribution of O stars in the Galaxy, LMC, and SMC. This, in turn, would argue strongly that the mass and angular momentum loss is in fact much lower than given by the standard rates, arguing that winds are indeed clumped. The mass-loss reduction needs to be enough that line-driven winds no longer dominate the mass lost during a star's lifetime.

8 Summary: Factor of 3

For most of the observational clues that mass-loss rates are lower, a reduction by a factor of three seems to suffice. It could be more, but *at least* a factor of three seems to be needed. These clues are important because they are independent of the mass-loss rates and clumping factors derived from the analysis of O-star winds.

References

Castor, J.I., Abbott, D.C., & Klein, R. 1975, ApJ, 195, 157

de Jager, C., et al. 1988, A&AS, 72, 259

Figer, D.F. 2005, Nature, 434, 192

Gal-Yam, A., et al. 2007, ApJ, 656, 372

Nieuwenhuijzen, H., & de Jager, C. 1990, A&A, 231, 134

Penny, L., et al. 2004, ApJ, 617, 1316

Repolust, T. et al. 2006, 415, 349

Smith, N., & Conti, P.S. 2008, ApJ, submitted

Smith, N., & Owocki, S.P. 2006, ApJ, 645, L45

Smith, N., et al. 2003, AJ, 125, 1458

Smith, N., et al. 2007, ApJ, 666, 1116

Vink et al. 2001, A&A, 369, 574

Oskinova: Kinetic energy input into the ISM is higher when the bulk of mass is lost via stellar winds compared with LBV outflows. Can observations of diffuse X-ray emission from (super-)bubbles in massive star clusters discriminate between these two (LBV vs. stellar wind mass loss)?

Smith: Well, to begin with, I would disagree that kinetic energy input to the ISM is dominated by stellar winds. Instead, giant H II regions and superbubbles are inflated by radiation pressure and supernova. By comparison to these effects, the ram pressure of stellar winds is not terribly relevant. Therefore, reducing Hα and radio mass loss rates by factors of two or three or even ten and replacing them with LBV mass loss would not matter.

Zinnecker: Can you explain again how to produce WR stars in low-metallicity dwarf galaxies such as IZw18? And why some of these WR stars would be rapidly rotating (to become progenitors of GRBs)?

Smith: If O star winds are too weak because of the metallicity dependence (and because of clumping), then it seems likely that continuum driven LBV eruptions might be able to shed the remaining mass. Observationally, it seems that LBV mass loss is in-herently bipolar, but I really do not know if that is enough of an effect for the star to retain enough angular momentum to make a GRB. However, it is likely that LBV mass loss will shed less angular momentum than the same amount of mass shed in a steady spherical wind.

Massa: Do the numbers of LBVs versus WRs and O stars in the Galaxy agree with your expectations? Can you make up for the reduction in WR production?

Smith: The relative number ratio of LBVs, WRs, and O stars really just tells us the relative lifetimes in each phase, and the variety of LBVs just means that their lifetimes are short, like a few 10^4 years. However, that is not really the crux of the problem, because we know that LBV mass loss is dominated by giant eruptions when the star can shed $\sim 10\,M_\odot$ in a couple years. We know that these eruptions can, in principle, happen repeatedly. So, in principle, yes they can make up the deficit of mass loss left by reduced O star rates. The question that we do not know the answer to with confidence is how much mass is lost each time and how many total eruptions there are as a function of luminosity.