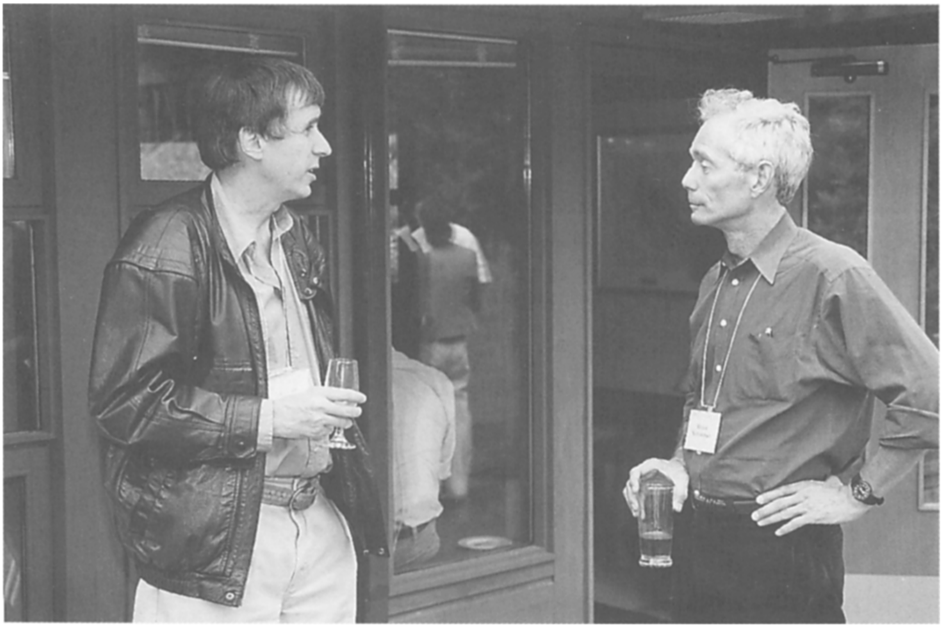
Part 3. Massive Stars and 30 Doradus

Section A. Invited Reviews



Renewing acquaintances at the reception. (Top) Jon Holtzman and John Hutchings, (bottom) Alistair Walker and Bruce Bohannan.

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Massive Stars in the MCs: What They Tell Us about the IMF, Stellar Evolution, and Upper Mass "Cutoffs"

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Abstract.

Studies over the past decade have shown that the initial mass function (IMF) is the same for massive stars born in the OB associations of the LMC and SMC as in the associations of the Milky Way: the slope of the IMF is essentially Salpeter ($\Gamma \sim -1.3$), despite the factor of 4 difference in metallicity between these systems, and despite a factor of several hundred in stellar density between the sparsest and richest OB associations. However, there does appear to be a number of massive stars that are born in relative isolation, and the IMF of this mixed-age, *field* population is quite different than that of OB associations, with $\Gamma \sim -4$ in all three galaxies. The distribution of stars in the HR diagram is in excellent agreement with the Geneva group's evolutionary models for stars with masses $> 25\mathcal{M}_\odot$, with no "main-sequence widening problem" left to be solved. The massive stars born in clusters are formed quite coevally ($\Delta\tau < 1 - 2$Myr), which allows us to use the "turn-off masses" to determine what mass objects become Wolf-Rayet stars of various types, and new results are briefly described. For the LMC, WNEs come from a wide range of masses, WCs come only from the highest mass stars, and Ofpe/WN9 "slash" stars come from lower mass OBs. Recent work on the R136a cluster (described in Hunter's review talk) suggest that there is no such thing as an upper mass cutoff to the IMF, at least not one that has been found observationally: for the youngest clusters (2 Myr and younger), the mass of the highest mass star present is simply dependent upon how populous the cluster is; i.e., the IMF is truncated by statistics, not physics.

1. Introduction

When I was a postdoc at the DAO, Dr. van den Bergh would corner me after each trip and ask me what new, interesting thing I had learned. I remember coming back from Boulder once, circa 1981, and telling him about a result that Katy Garmany and Peter Conti had just obtained for massive stars in the Milky Way: it appeared that the initial mass function (IMF) showed a gradient with galactocentric distance, with proportionally more of the highest mass stars being formed in the inner regions of our Galaxy (Garmany, Conti, & Chiosi 1982). Sidney wrinkled his brow, and said that this really would be quite surprising if true, as one would expect that it would be harder to form higher mass stars where the metallicity is higher. This remark got me thinking about the Magellanic Clouds (MCs), and what fun one could have there in determining massive star IMFs, and then comparing them to those of the higher-metallicity Milky Way (MW). Little did he know he was launching a 17 year study! (He was also right about the result being wrong, for reasons I'll explain below.)

Why study massive stars in the MCs? The MCs have low reddening and are nearby, and hence complete samples of massive stars can be identified, albeit with some effort. The low metallicities serves as a useful contrast to Milky Way studies, as it is reasonable to wonder if the IMF slope or upper-mass cut-off does depend upon metallicity z: if radiation pressure on grains were the dominant effect in the mass of the most massive star we see, then the upper mass cutoff should go as $1/\sqrt{z}$ (Shields & Tinsley 1976). If that were the case, then, we might expect that the most massive star we see in the SMC would be about a factor of 2 higher in mass than in the Milky Way, and the most massive stars we see in the LMC should be a factor of 1.5 times more massive than in the MW ($\log(O/H)$=8.13, 8.37, and 8.70 in the SMC, LMC, and MW, respectively, according to Russell & Dopita 1990 and Esteban & Peimbert 1995). Secondly, we know that massive star evolution *should* depend upon z, as the mass loss rates scale as $\sqrt{z}$, and thus studies of massive stars in the MCs provide a critical test of evolutionary models.

There are two major complications in studying massive stars in the MCs, both of which are discussed extensively elsewhere (Massey et al. 1995a, 1995b; Massey 1998a, 1998b) and which I'll mention only briefly here: (a) In a *mixed-age* population the *visually* brightest stars will not be the most *bolometrically* luminous or massive. The result of this is that luminosities will not tell you *anything* about the underlying IMF. (See Fig. 1 of Massey 1998a.) (b) The colors of hot stars are degenerate with effective temperature ($T_{\rm eff}$), and hence with the bolometric corrections (BCs). (See Fig. 3 of Massey 1998a, and discussion in Massey 1998b.) But it is only through knowledge of the BC that we can get any insight into the total luminosity (and hence mass) of an O-type star, with the BC changing by about 1.5 mag, or a factor of 2 in mass (eq. 4 of Massey 1998a). However, spectroscopy allows us to address these concerns easily, as there is good $T_{\rm eff}$ resolution with spectral type for the hottest stars— at least until O3 is reached ($T_{\rm eff} \sim 50,000°$), beyond which the classification is degenerate.

How much does this really matter? Massey et al. (1995b) derived an IMF slope of $\Gamma = -1.4 \pm 0.2$ for the OB association LH58 in the LMC. Hill, Madore, & Freedman (1994) had analyzed the same cluster, and had found a slope of $\Gamma = -2.5 \pm 0.3$ based upon only photometry. We demonstrated that if we ignored our own spectroscopy—simply used our own photometry, and the transformations of Hill et al.—that the IMF slope we derived would indeed steepen from -1.4 to -2.0! The difference is in fact simply due to the degeneracy for the hottest and massive stars, and this serves as a cautionary tale to those wanting to derive IMFs from luminosity functions even in a coeval association (e.g., Fig. 2 of Massey 1998a).

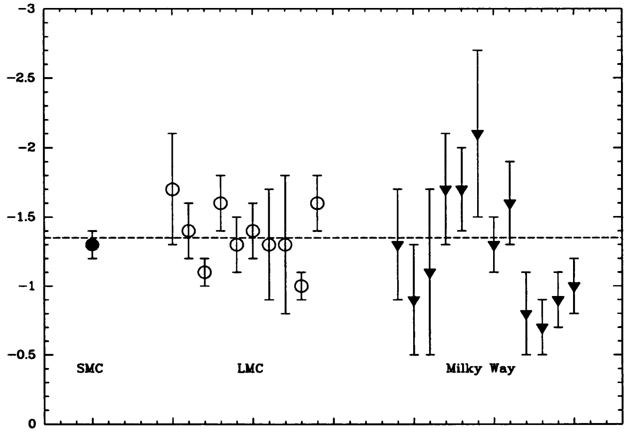

Figure 1. The IMF slope Γ for 23 OB associations in the SMC, LMC, and MW. We have indicated the value of a Salpeter $\Gamma = -1.35$ IMF.

2. Results: Massive Stars in OB Associations in the SMC, LMC, and MW

My colleagues and I have now determined the IMFs for 23 OB associations in the SMC, LMC, and Milky Way (Massey et al. 1995a,b; Massey & Hunter 1998). I review how this is done and some of the associated errors in Massey (1998a). Here, I will just make the two points: (1) If a region is strictly coeval, then the slope of the present day mass function (PDMF) *is* the slope of the IMF, with the only effect of age to deplete the upper-most mass bin. (2) The "absolute" value of the IMF slope is considerably less certain than the *relative* values: we make no allowance for binaries, but implicitly assume that the binary frequency and mass ratios are the same in these systems. One must analyze the data with the same set of models (at the appropriate metallicity) for intercomparisons to be meaningful. If you take values for the IMF slopes from many different sources, analyzed in different ways, you will of course convince yourself that the IMF slope is anything *but* constant—as Scalo (1998) does in his recent review.

However, as Figure 1 shows, the observational evidence suggests that the IMF slope *is* constant, at least for stars with masses $> 10\mathcal{M}_{\odot}$ formed in OB associations in the SMC, LMC, and MW—despite the factor of 4 change in metallicity, and despite a factor of several hundred difference in stellar density (going from the least populous cluster to that of R136a)!

We have also learned that massive stars that form in clusters do so very coevally, with an age spread $< 1 - 2$ Myr. In the case NGC 6611 in the MW, Hillenbrand et al. (1993) conclude that their data are consistent with all the massive stars "having been born on a particular Tuesday." Interesting, the intermediate mass stars continued forming even after the high mass stars had formed, contrary to the conventional wisdom. DeGioia-Eastwood et al. (1999) find the same for the MW associations Tr 14/16. However, in R136, star formation shut down once its extreme population of very massive stars formed (Massey & Hunter 1998), although some star formation continues in the general 30 Dor region to this day (Walborn & Blades 1987; see also Walborn & Barba in these proceedings).

3. Results: Massive Stars in the Field

For a mixed-age population, the PDMF will be related to the IMF via the main-sequence life-time, assuming that the star-formation rate has been relatively constant over the past several million years in the region in question. Massey et al. (1995b) analyzed the *field* population of the LMC and SMC, starting with the Rousseau et al. (1978) catalog updated by Fitzpatrick & Garmany (1990) for the LMC, and the Azzopardi & Vigneau (1975, 1982) catalogs for the SMC. We found that only about half the stars in these catalogs were actually in OB associations. (The fraction "half" is primarily an indication of how sparse our knowledge had been of the individual members of OB associations; only a handful of the massive O stars for which we obtained spectra in our association work were listed in these catalogs.) But, if these stars weren't in OB associations, where were they? Even a cursory examination of the Sanduleak (1969) atlas shows that many of these stars are well isolated—this is not a case of there being numerous OB associations that had been missed by Lucke & Hodge (1970).

Rather, it seems likely that these stars formed near to their current location from more modest star-forming events than those that produced large clusters. After all, we know from the mere existence of R136a that star-formation occurs on a variety of scales. Why should we be surprised that there is a "low end" to star formation that does, stochastically, produce the occasional high-mass star? (See the study of small Galactic H II regions by Hunter & Massey 1990.)

The lifetimes of these stars are short, and during that time these stars could not have simply wandered far from parent OB associations. For instance, a few of these "field" stars are O3 stars, which have an age of < 1 Myr. In that time, not even a runaway star can wander very far: at 50 km s^{-1} such a star would travel 50 pc in 1 Myr. Massey et al. (1995b) found a substantial population of massive stars using the "extreme" criterion of 300 pcs distance to the nearest OB association (see their Figs. 4 and 5).

Rousseau et al. (1978) were well aware of the completeness problems inherent in a V-limited catalog, that their sample would over-represent modest mass B-supergiants relative to stars of higher bolometric luminosities but higher temperatures. In order to correct for selective incompleteness at high temperatures, Massey et al. (1995a) obtained CCD photometry and spectroscopy of several regions, and found they could reliably correct the statistics down to 25 $\mathcal{M}_\odot$.

The rather surprising results of this study are that the IMF slope of these *field* stars is remarkably steep: $\Gamma \sim -4$. The same result is found for MW field stars, and the relative distribution of field and association stars seem to be responsible for the original Garmany et al. (1983) IMF "gradient" that started these inquiries! Massey et al. (1995b) also found that, although they are proportionately rarer, stars as massive as those found in associations are found in the field. Fig. 4 of Massey (1998a) compares the environments of four LMC O3 stars, two in the field, and two in associations.

4. Results: Stellar Evolution

The MCs really *are* the "laboratories" for probing stellar evolution, as many of us have claimed in our proposals. Let me touch briefly on two results. First, in our study of the field population of the LMC and SMC it was possible to provide a very critical test of the Geneva evolutionary models: how well do they match the observations? If the isochrones are "right" then we would expect to find the same number of stars between 1 and 2 Myrs as between 2 and 3 Myrs at a given mass. And, indeed this is just what we find! Thus there can not be very strong contamination by "blue loop" SN1987A precursors (at least not above 25 $\mathcal{M}_{\odot}$!), and there is no "main-sequence widening problem" to be solved. The difference between our results, and those of Fitzpatrick & Garmany (1990), was that we were able to correct the statistics for the hotter stars that would be selectively excluded in any V-limited Rousseau et al. (1978) sample (Massey et al. 1995b).

Secondly, it is possible to use the coeval associations of the SMC, LMC, and MW to test how the later stages of massive star evolution depend upon metallicity. My summer student Liz Waterhouse is working on a project with me currently in which we are measuring the "turn-off" masses in clusters which contain Wolf-Rayet (WR) stars of various types. We will shortly be able to look for metallicity dependent effects by comparing the results for the SMC, LMC, and MW; for now, let me just mention our very preliminary results for WRs in the LMC. We find that early-type WN stars (WN3-5) come from a wide variety of stellar progenitors (40-100 $\mathcal{M}_{\odot}$). The WC stars in the LMC are found only in OB associations with large turn-off masses ($> 70\mathcal{M}_{\odot}$), consistent with the expectations of the "Conti scenario"only the highest luminosity stars will evolve to WC type at lower metallicities due to the decreased mass-loss rates. And, we find that the so-called "slash" stars (Ofpe/WN9) are found preferentially in clusters with very *low* turn-off masses: 20-40 $\mathcal{M}_{\odot}$. The latter is in accord with the recent findings of St-Louis et al. (1998).

5. Is There Such a Thing as an Upper-Mass Cut-off?

In studying the OB associations in the SMC, LMC, and MW, we had found that mass of the highest mass star was very similar in all three galaxies ($\sim 90-100\mathcal{M}_{\odot}$), despite the predictions that there should be a 2× difference due to metallicity. Thus, radiation pressure acting on grains was not what was limiting the highest mass we saw. I continued to puzzle about this until we obtained data on R136a, the central "supercluster" of 30 Dor (Massey & Hunter 1998). Deidre Hunter discusses these results in this symposium; here let me emphasize that the upper mass cut-off that we had been observing was not physical in natural, but rather statistical. R136a is young enough so that its most massive stars have not yet died, and we see stars that are conservatively estimated to be $> 150\mathcal{M}_{\odot}$. But in fact for R136a this is just where the (completely normal!) IMF peters out—where statistically you would expect just one star, because it is so rich and populous. Looking back over the data for the more modest OB associations, we find that the upper mass "cut-offs" were simply what you would expect given the relative richness (and age). Doubtless there is a physical limit to how massive a star actually can form, but so far we have yet to encounter this limit in nature.—instead, the "limits" we've been up against have been statistical rather than physical.

Sidney Wolff had once suggested as much to me, but it had remained untested until the R136a data. So, you can see that two people named Sidney have played important roles here!

Acknowledgments. The work I've described here has been done with excellent collaborators, including summer students. Let me explicitly acknowledge the roles played by Peter Conti, Kathy Eastwood, Katy Garmany, and Sally Oey, and the REU students K. E. Johnson, J. Johnson, C. Lang, and E. Waterhouse. The R136a work was done with my partner Deidre Hunter, whose knowledge and insights have helped shaped my thinking on these matters.

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Discussion

You-Hua Chu: An O3 star born in the field without any interstellar gas left implies a 100% star formation efficiency. This is surprising. It may be possible that the O3 stars were formed by mergers.

Massey: There are about 100 stars with masses $> 25\ M_\odot$ known in the LMC and SMC more than 200 pc from the nearest OB association. Did all of these form by mergers? If so, it's even more remarkable that their distribution in the HRD matches the evolutionary models so well. Why assume 100% efficiency? You can disrupt a $1000\ M_\odot$ cloud pretty quickly via stellar winds and the emission measure drops down past our threshold.

After all - there are entire OB associations without much nebulosity - does the lack of nebulosity mean all the hot stars in these formed by mergers? Or is the ISM just lumpy and stellar winds good at blowing away gas?

Jon Holtzman: How much would you have to relax the assumption of steady-state star formation to get the field IMF to agree with the association IMF?

Massey: It would require the SFR to have been substantially higher 6 Myr ago - and by the same ratio in the Milky Way, LMC, and SMC.

Nolan Walborn: This was a very nice review containing important insights on the relevant issues. However, I have several comments. (1) The steeper IMF slope in the field means that there are proportionately fewer of the most massive stars there. Certainly far more than half of the most massive stars are in associations. (2) Some isolated objects may well be mergers or other peculiar binary evolution phenomena. Sk$-67°22$ is a case in point: it is a very peculiar 03 star, with a main-sequence luminosity but a broad, WR-like HeIIλ4686 emission feature. (3) Some massive associations are coeval, but others clearly have subgroups of different ages, which may be sequential in some cases. (4) The M_V - spectral type relation may not be "great" but for 100 stars in 30 Dor, I find the average difference between derived and calibration M_V's to be 0.05 mag; and for 70 of them, the individual deviations are within ± 0.6 mag, or they are subluminous dwarfs or superluminous supergiants which are reasonable phenomena for future investigation of spectroscopic luminosity criteria.

Massey: Given the incompleteness both of massive stars in associations AND "in the field" I would hesitate to agree with your statement that "certainly far more than half" of the OB stars are in associations. Certainly the current data (Massey et al. 1995, ApJ, 438, 188) don't support your assertion, but I agree that the incompleteness factor for unstudied OB associations is large, but so what? The "low mass" stars we're talking about are $25\ M_\odot$? What I'm saying is that how these stars form "in the field" appears to be different when they form in small groups, or isolation.

I completely agree with you that some catalogued OB associations are coeval, and others are not. For instance, no one could rationally agree that the entire 30 Dor region is coeval or a single OB association. Lucke & Hodge (LH), afterall, catalogued several different associations in the 30 Dor region. So far I've found that most, but not all, of the LH associations are in fact coeval groupings - really a remarkable piece of work that has held up well for 25 years now.

Hans Zinnecker: You showed us several cases of isolated "field" O-stars. With no lower-mass stars around them, the slope of the IMF there would be infinite? How then did you get a slope for the field stars IMF of $\Gamma = -4$? Please explain.

Massey: The IMF is really just the probability of forming a star of a given mass. So for stars outside of coeval group, you can determine an IMF as long as you're careful to account for the star formation history. In the case of the field massive stars, I assumed steady-state that averaged over the entire LMC or SMC that the SFR has not varied significantly over the past 10 Myr. (If you want the relevant equations, see my write up in Gerry Gilmore's IMF Conference last year, but if we couldn't properly talk about the "IMF of the field" a lot of people would be out of work.)

Giuseppe Bono: Stars more massive than 80 $M_\odot$ are dynamically unstable (Pappoloziu 1979). Do you think that this is a statistical or a physical effect?

Massey: Perhaps this is a "statistical effect" in the sense that if you took a large number of theoreticians and had them produce a number they were comfortable with, you would probably not get a delta function, but rather a wide distribution of answers. Seriously, we see stars in the R 136 cluster which appear to be - by conservative assumptions - up at around 150 $M_\odot$. But no massive stars (of $>$ 50 $M_\odot$) are "stable" (whatever that means) - they all have strong outflows, with mass-loss rates of 10^{-5} to 10^{-4} $M_\odot$ yr^{-1}. These mass estimates require that the Geneva evolutionary tracks are more or less right, and we only have observational confirmation of the mass luminosity up to about 30 $M_\odot$ (Burkholder, Massey & Niemela 1997 ApJ).