A Massive Star Odyssey, from Main Sequence to Supernova
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Observational Constraints on Massive Star Evolution

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Abstract. In this paper, I discuss the observational quantities that are useful for judging the successes and failures of current massive star evolutionary theory. The galaxies of the Local Group can serve as important laboratories for providing these diagnostics, as their metallicties vary by a factor of 10. We find that the evolutionary tracks do a good job of matching the distribution of stars in the H-R diagram during the main-sequence phase. However, none of the models produce RSGs that are as cool and as bright as what is observed. The relative number of WC and WN stars is a strong function of metallicity, and the Padova and Geneva "normal mass-loss" models do a reasonably good job of matching the observations at low metallicities, but predict too few WCs at higher metallicity. The "enhanced" mass-loss models of the Geneva group do not match the observations at all. New data is providing excellent statistics on the number of RSGs in these nearby galaxies, and the number ratio of RSGs to WRs is also an extremely sensitive function of metallicity. None of the models reproduce the trend of the RSG/WR ratio with metallicity.

1. Introduction: Using the Local Group as Our Laboratory

The evolution of massive stars is hard to model due in large part to the complications of mass-loss. Stellar winds are constantly stripping the H-rich outer material from an O-type star's surface, and a very massive star might lose half of its mass during its main-sequence evolution. If a star undergoes a Luminous Blue Variable (LBV) phase, then mass-loss becomes episodic, making its inclusion in models even more difficult. The mass-loss rates during the red supergiant (RSG) phase are high, but are poorly understood. And, during the Wolf-Rayet (WR) phase mass-loss rates can be as much as an order of magnitude larger than during the main-sequence phase, due to lower surface gravity, higher abundances, and high effective temperatures. Efforts to model the evolution of massive stars are further hampered by uncertainties in mixing and convection, with most recent work directed towards the inclusion of rotation.

Thus feedback between stellar evolutionary theory and observational data is crucial, both for providing "reality checks" on the models, and for directing observers in useful directions. One caveat in this is that we must make sure that the observational data are *accurate*, else we will lead our theoretician colleagues on a merry chase.

The galaxies of the Local Group provide ideal laboratories for exploring our ideas of massive star evolution: the stars are bright enough, and the galaxies are close enough, so that we can resolve the massive star population. The metallicity changes by a factor of 10 among the galaxies that are currently forming stars, with the SMC and the Andromedea Galaxy forming the two extremes. And, this is a wonderful time for such studies, with improved models becoming available, and with the advent of large Mosaic imagers on 4-m telescopes and multi-object spectrographs on 8-m telescopes.

There are two basic sorts of tests that we can perform. In the first of these we compare global properties, such as the number of RSGs to WRs, or WCs to WNs. Such tests rely upon two assumptions: (a) that we have averaged over enough of a galaxy to be totally heterogeneous with respect to age, and (b) that the initial mass function is the same in the regions we are comparing. The second sort of test is potentially more powerful, but more risky, and that is using coeval regions to determine the progenitor masses of evolved objects from the turn-off masses. This can give us more direct information, but we can be more easily fooled by non-coevality and the effects of small number statistics.

Some of the observational quantities that can be determined reliably at present are: (1) The number of blue and red supergiants more luminous than $M_{\rm bol} < -7.5$. Data on this exists for most of the Magellanic Clouds, and will shortly exist for the other galaxies in the Local Group currently forming stars (e.g., Andromeda, NGC 6822, IC10, IC 1613, M33, WLM, Phoenix, and Pegasus.) Note that identifying the number of blue supergiants is *not* the same as knowing the number of O-type stars; that number is unknown at present even for the LMC. (2) The number of Wolf-Rayet stars within these Local Group galaxies. (3) The turn-off mass in clusters containing WRs and LBVs in the Milky Way and Magellanic Clouds; further work is needed to quantify this in the more distant galaxies of the Local Group.

2. Main-sequence Evolution

Stars spend 90% of their lives undergoing core-H burning on the main-sequence, and so if we get this phase of their lives right we have done very well. It is also obvious that there has to be good agreement between observation and theory here if there is to be any hope of matching the observations for evolved massive stars. The situation in fact appears to be very good, with several critical observational tests giving confidence that we know what is happening pretty well during the main-sequence. Let me mention a few such studies.

Meylan & Maeder (1982) were the first to describe what has become known as the "main-sequence widening" or as the "blue Hertzsprung gap" problem. Using data in young Galactic and Magellanic Cloud clusters, they compared the number of stars in various parts of color-magnitude diagrams to that predicted by the evolutionary tracks. These regions were each presumed to be coeval. They found an overabundance of A-type supergiants, particularly at low metallicities. It is as if the true main-sequence extended all the way to A-type supergiants. Meylan & Maeder (1982) suggested that including enhanced mixing in the models might extend the main-sequence to cooler effective temperatures, which was confirmed by Langer (1991). However, a recent study by the Padova group suggests that this problem is not a main-sequence problem at all. Rather, they have included improved (higher) mass-loss rates during the RSG phase, and find that there are very extended loops in the evolutionary tracks that allow a good match with the distribution of stars (Salasnich, Bressan, & Chiosi 1999).

Fitzpatrick & Garmany (1990) used an updated catalog of LMC members to compare the distribution of stars in the H-R diagram to that predicted by evolutionary tracks. Here the situation was quite different than in the clusters studied by Meylan & Maeder (1982), in that they were looking at a presumed mixed-age population. Their study suggested that blue loops were indeed needed to explain the abundance of stars beyond the main-sequence.

Massey et al. (1995) added several hundred more spectral types to the Fitzpatrick & Garmany (1990) LMC sample, and extended the study to the SMC. They were perhaps the first to emphasize that a 15 $\mathcal{M}_\odot$ A-type supergiant will be ~ 3 mag brighter *visually* than an 85 $\mathcal{M}_\odot$ O-type star on the ZAMS, despite the former being 2 mag fainter *bolometrically*. Thus in any V-limited catalog the younger more massive stars will be under-represented relative to cooler stars. When the catalog numbers were corrected empirically using several deep "incompleteness fields" there was excellent agreement between the number of stars and those predicted by the evolutionary models, with the possible exception of stars very near the ZAMS.

One nagging question about main-sequence evolution has been that of the "mass discrepancy". Herrero et al. (1992) first called attention to the fact that the masses derived from modern atmosphere models could be as much as a factor of 2 lower than that suggested by the masses inferred from evolutionary tracks. This problem has persisted to this day, and there is a special session organized around the problem at this symposium. Various authors have attempted to resolve this issue by using spectroscopic binaries to provide a "true" estimate of the masses. Burkholder, Massey, & Morrell (1997) found good agreement between the orbital masses and the evolutionary tracks up to $25\mathcal{M}_\odot$. Although some higher mass systems showed lower masses than that expected from the tracks, these invariably were cases where the stars were filling their Roche lobes, and enhanced mass-loss could easily account for the results. Generally the problem could not be resolved unless some detached systems of higher mass could be found.

Fortunately, Massey & Hunter (1998) came across four suitable candidates in the R136 cluster. Followup *HST* observations by Massey, Penny, & Vukovich (2002) obtained radial velocity curves and established that three were eclipsing, allowing precise orbital determinations and masses to be determined. One of these appears to be the highest mass binary ever found. A comparison with the evolutionary models suggests excellent agreement for these four systems.

At this time I can only conclude that the observations and theory match very well on the main-sequence!

3. Evolved Stars

There are still fundamental basic questions that remain about massive star evolution past the main-sequence. We still do not know what mass ranges become Wolf-Rayet stars, LBVs, or RSGs, or how these mass ranges depend upon metallicity. Here is what I think we know and what we don't.

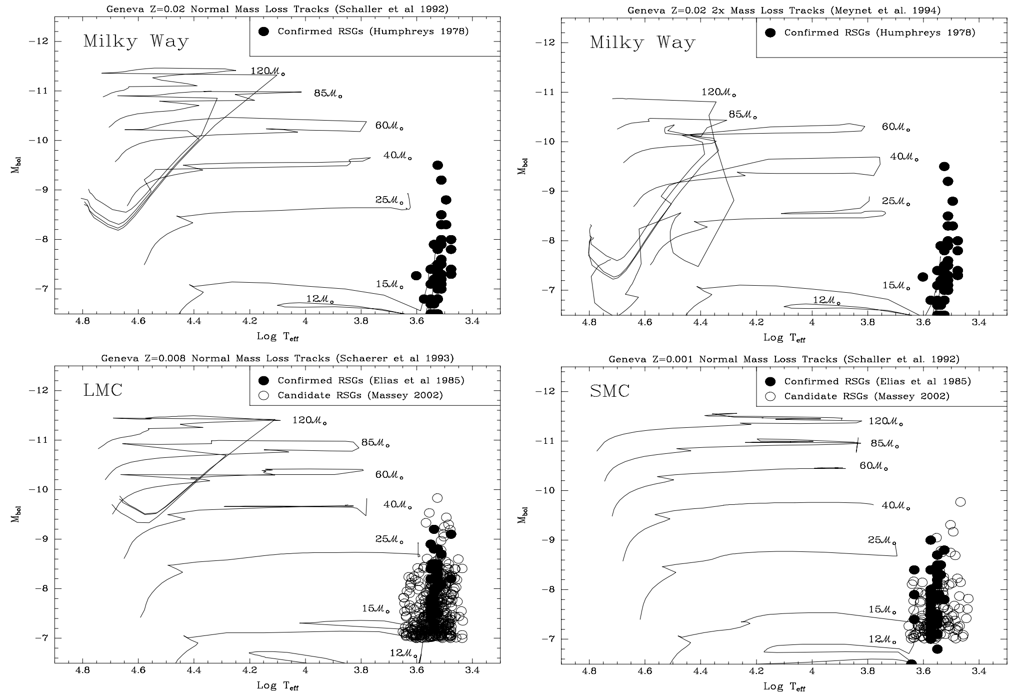

Figure 1. The location of RSGs is compared to the evolutionary tracks for the Milky Way, LMC, and SMC. In the upper two panels we use the $Z = 0.02$ evolutionary tracks of the Geneva group; the tracks on the left have normal mass-loss rates (Schaller et al. 1992), and the ones on the right "enhanced" rates (Meynet et al. 1994). Many of the RSGs (Humphreys 1978) are found at higher luminosities and cooler temperatures than the models allow. The bottom two panels show that the problem persists at low metallicity, where the RSGs come from Elias et al. (1985) and Massey (2002), and the tracks are those of Z=0.008 (Schaerer et al. 1993) and Z=0.001 (Schaller et al. 1992).

3.1. Red Supergiants

For RSGs there are a couple of important points to ponder. First, if our knowledge of the effective temperature scale of M supergiants is correct, then none of the evolutionary models extend to cool temperatures at sufficiently high mass. This is illustrated in Fig. 1, and is probably related to the choice of the mixing-length parameter α (cf. Fig. 15 of Maeder & Meynet 1987).

Secondly, we have begun to actually understand what the statistics are of RSGs in the Magellanic Clouds and other nearby galaxies. The key here is to properly remove the number of pesky foreground M dwarfs (Massey 1998). If we do this we find something very interesting: the number of RSGs as function of luminosity changes drastically as a function of metallicity, with proportionately fewer of the highest luminosity RSGs found at higher metallicity. What was most surprising about this though, was that the higher luminosity RSGs did not simply vanish at higher Z; instead, there are just fewer of them. This suggests that what happens is that the proportional lifetimes of RSGs decrease at higher Z, in accord with what Maeder, Lequeux, & Azzopardi (1980) proposed.

Thirdly, there is the observation by Elias, Frogel, & Humphreys (1985) that the mean spectral type of RSGs changes with metallicity; i.e., that the average RSG is of somewhat earlier type in the SMC (M0) while in the Milky Way it is somewhat later (M2). This certainly suggests that if we are to compare the relative number of blue and red stars from galaxy to galaxy we have to be very careful what we count: for it to be meaningful we should include the K *and* the M stars. In Table 1 I illustrate this from recent data on the Magellanic Clouds (Massey 2002). If we count *both* the K- and M-type supergiants, there isn't much of a difference in the blue-to-red supergiant ratio for these two galaxies.

Table 1. Relative Number of Blue and Red Supergiants in the MCs

Galaxy	B/R
LMC (M)	53
SMC (M)	165
LMC (K+M)	26
SMC (K+M)	20

3.2. Wolf-Rayet Stars and LBVs

Let us now turn to our attention to the Wolf-Rayet stars. The difficulties of being complete for the weaker-lined WNs have been most recently discussed by Massey & Johnson (1998). Our knowledge of the WR content of the Magellanic Clouds is probably close to complete (Breysacher, Azzopardi, & Testor 1999; Massey & Duffy 2001). Beyond the Magellanic Clouds, only a few small regions of NGC 6822, IC 1613, M33, and M31, and IC 10 have been surveyed in any detail (Massey & Johnson 1998, and references therein).

We show in Fig. 2 the relative number of WCs and WNs as a function of metallicity. There is a very smooth relationship, except for IC 10 and for the Milky Way data. The latter is probably incomplete. IC10 is more of a puzzle. This galaxy is undergoing a starburst, and it is possible that something very peculiar related to star formation is going on. Alternatively it could just be that the data for IC 10 are more incomplete than we've thought. Royer et al. (2001) found thirteen new WR candidates in this galaxy based upon imaging with interference filters. One of these turns out to be the already known WR star IC10-WR6 (Massey & Armandroff 1995). Otherwise, none of the new candidates have been looked at spectroscopically. Shay Holmes and I have been analyzing a set of new very deep images and we detected 7 of the remaining 12 Royer et al. (2001) candidates at high significance levels; the exceptions included all of their WC9 candidates. These don't show up as having λ4650 emission in our survey. We also find a large number of other WR candidates. Spectroscopy is needed to confirm these, and determine their spectral subtype. So, I think it's premature to conclude that the IC10 is telling us something fundamental.

We see in Fig. 2 that the normal mass-loss models match the observations pretty well, although they predict too few WCs at high metallicities. The enhanced mass-loss rate models do not match the observations at all. In deriving the model predictions we have followed the precepts of Schaerer & Vacca (1998), although we "define" a WC star as a hot evolved star with a number ratio C/He > 0.1 on the surface (Conti 1988; Crowther, Smith & Willis 1995) rather than using the the C/N ratio.

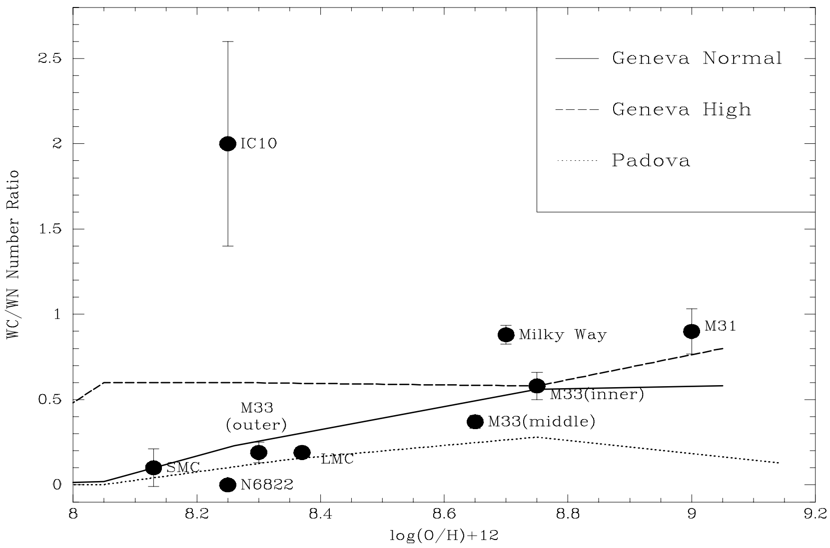

Figure 2. The relative number of WCs and WNs is shown as a function of metallicity. Recent work suggests that the IC10 data may be incomplete. The predictions of the evolutionary models are also shown, with the "Geneva Normal" referring to normal mass-loss rates, and the "Geneva High" referring to the 2× enhanced mass-loss rates. The predictions from the Padova group are also shown. A Salpeter slope $\Gamma = -1.35$ and steady-state has been assumed.

Next, we can combine our results on the number of WRs and the number of RSGs; we show the results in Fig. 3. We find a very clear trend with metallicity, with this ratio changing by 2 orders of magnitude over a change of 0.8 dex in metallicity. None of the models reproduce this trend either. This is probably not surprising given the RSG problem pointed out in the previous section, and I believe that these new data offer a solid goal for new models to match.

Finally let me briefly summarize what I think we have learned recently from coeval regions in the MCs (Massey, Waterhouse, & DeGioia-Eastwood 2000; Massey, DeGioia-Eastwood, & Waterhouse 2001):

(1) In the SMC (low metallicity) Wolf-Rayet stars come only from the highest mass stars ($> 85\mathcal{M}_{\odot}$), while in the higher metallicity Milky Way, we find early WNs in clusters with turn-off masses as low as 20-25$\mathcal{M}_{\odot}$.

(2) Classical LBVs and WN7 stars are found only in clusters with very high turn-off masses, suggesting that they come from only the highest mass stars ($> 120\mathcal{M}_{\odot}$).

(3) The Ofpe/WN9 stars are found in regions with relatively low turn-off masses ($< 35\mathcal{M}_{\odot}$), suggesting that these are not related to the true LBVs.

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References

Breysacher, J., Azzopardi, M., & Testor, G. 1999, A&AS, 137, 117

Burkholder, V., Massey, P., & Morrell, N. 1997, ApJ, 490, 328

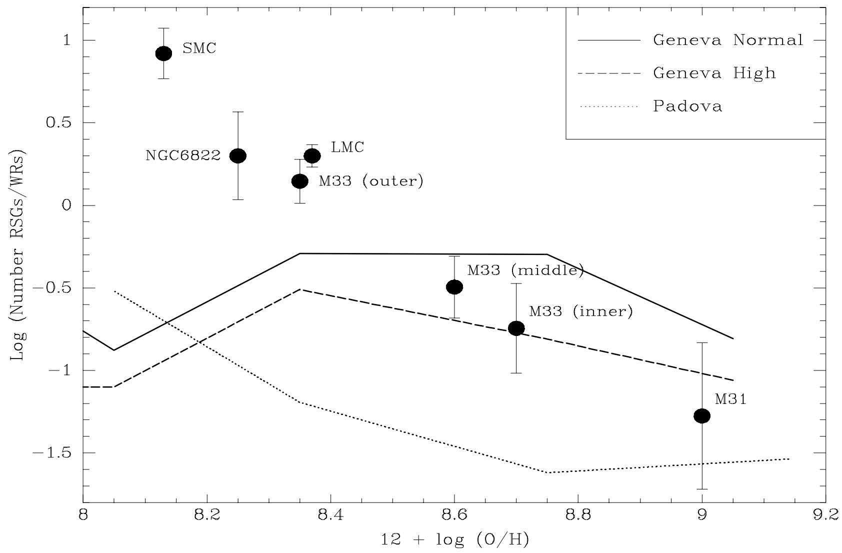

Figure 3. The relative number of RSGs and WRs as a function of metallicity.

Conti, P. S. 1988, in O Stars and Wolf-Rayet Stars (Washington, DC, NASA SP-497)

Crowther, P. A., Smith, L. J., & Willis, A. J. 1995, A&A, 304, 269

Elias, J. H., Frogel, J. A., & Humphreys, R. M. 1985, ApJS, 57, 91

Fitzpatrick, E. L., & Garmany, C. D. 1990, ApJ, 363, 119

Herrero, A., Kudritzki, R. P., Vilchez, J. M., Kunze, D., Butler, K., & Haser, S. 1992, A&A, 261, 209

Humphreys, R. M. 1978, ApJS, 38, 309

Langer, N. 1991, A&A, 252, 66

Maeder, A., Lequeux, J., & Azzopardi, M. 1980, A&A, 90, 17

Maeder, A., & Meynet, G. 1987, A&A, 182, 243

Massey, P. 1998, ApJ, 501, 153

Massey, P. 2002, ApJS, in press

Massey, P., & Armandroff, T. E. 1995 AJ, 109, 2470

Massey, P., DeGioia-Eastwood, K., & Waterhouse, E. 2001, AJ, 121, 1050

Massey, P., & Duffy, A. S. 2001, ApJ, 550, 713

Massey, P., & Johnson, O. 1998, ApJ, 505, 793

Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180

Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188

Massey, P., Penny, L. R., & Vukovich, J. 2002, ApJ, 565, 982

Massey, P., Waterhouse, E., & DeGioia-Eastwood, K. 2000, AJ, 119, 2214

Meylan, G., & Maeder, A. 1982, A&A, 108, 148

Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97

Royer, P., Smartt, S. J., Manfroid, J., & Vreux, J.-M. 2001, A&A, 366, L1

Salasnich, B., Bressan, A., & Chiosi, C. 1999, A&A, 342, 131

Schaerer, D., Meynet, G., Maeder, A., & Schaller, G 1993 A&AS, 98, 523

Schaerer, D., & Vacca, W. D. 1998, ApJ, 497, 618

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269