Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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What the galaxies of the Local Group tell us about massive star evolution

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Abstract. We consider what we've learned about massive star evolution from observations of the resolved stellar content of Local Group galaxies. Studies of mixed-age (galaxy-wide) and coeval (single associations) populations reveal much about massive star evolution, and how it is controlled by metallicity, demonstrating the 'Conti scenario' in action! The number of WC stars to WN stars increases with increasing metallicity, as expected: in regions of higher metallicity stars of somewhat lower luminosity can evolve all the way to the WC stage. The exception is the starburst galaxy IC 10, for which I speculate that the IMF may be weighted towards high mass stars. The highest luminosity red supergiants are lacking in galaxies of higher metallicity, suggesting that the stars that would have become these RSGs are spending more of their time as WRs. The presence of luminous RSGs is highly correlated with the presence of WC and WN stars in OB associations, suggesting that many massive stars evolve through both a RSG and WR stage. The relative number of RSGs and WRs does decrease strongly with increasing metallicity, again consistent with higher metallicity systems leading to increased time in the WR phase. The various WC subclasses appear to be the result of the influence of metallicity on stellar wind structure in these stars, and are not due to to differences in mass or luminosity. Data on the field population in the Magellanic Clouds suggest that stars more massive than $30\,\mathcal{M}_\odot$ become WRs in the LMC, while the limit may be more like $50\,\mathcal{M}_\odot$ in the SMC, again as expected. Studies of the turn-off masses in clusters and associations in the MCs and Milky Way are nearing completion, while investigations in the more distant galaxies of the Local Group are just getting underway. For the LMC we find the following: WNE stars come from a large mass range of progenitor (30–$100\,\mathcal{M}_\odot$), and have very large (negative) bolometric corrections (-6 to -8 mag). The Ofpe/WN9 stars seem to come from lower mass progenitor (20–$30\,\mathcal{M}_\odot$), and have more modest BCs (-1 to -3 mag). WC stars come from stars with masses >60–$70\,\mathcal{M}_\odot$, and have BCs of -3 to -4 mag. Both 'B2I+WN3' systems and LBV stars like S Doradus are found only in clusters containing very high turn off masses (>70–$90\,\mathcal{M}_\odot$).

1. Introduction

Conti (1976) first proposed that massive O-type stars could evolve to Wolf-Rayet stars through the actions of their strong stellar winds. Much progress has been made since that time (see *e.g.*, Vreux *et al.* 1996), but key, fundamental questions remain:

- What is the evolutionary connection between the various WR spectral subtypes? Specifically:

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  - Do all WNLs evolve to WNEs? Or, to put this another way, are WNLs and WNEs two evolutionary phases of an 85 $\mathcal{M}_\odot$ star, or do they come from different mass progenitors?
  - Similarly, what is the evolutionary significance of the various WC subtypes? Do WCEs come from different mass progenitors than do WCLs?

- For that matter, do all stars that go through a WN stage make it to the WC stage?

- Do some stars go through both a RSG and WR phase?

- What mass range go through an LBV phase?

Ideally, we would like to not only answer these questions, but also examine how the answers depend upon the metallicity, as mass-loss rates scale with something like $\sqrt{Z}$.

How do we go about answering these? I think we're at the point where we need to address these questions observationally, rather than relying upon evolutionary models. At the Cozumel meeting, Conti (1982) described 'the observer's view of stellar models' by which a rain of observational data falls on the theoretician's black box, held in place by an edifice of assumptions. The hole in the top of the box (through which some of this rain may enter) was drawn as mighty small. I think that the situation has improved today, that the hole is perhaps *a bit* bigger, letting in a little more data, and the box is slightly more transparent, letting the rest of us know what is going on. But I also think that it's time to provide the model builders with a solid observational database against which their models can be compared. We now have confidence that the main-sequence evolutionary tracks are about right — at least the models do a good job of matching the distribution of of stars in the LMC and SMC (Massey *et al.* 1995b) once incompleteness is properly accounted for, with no sign that additional width to the theoretical main-sequence is needed. (It remains to be seen if the newest generation of stellar models, which attempt to include the effects of stellar rotation, do equally well!) But beyond the main-sequence, critical tests of these models have yet to be made. But the physics gets *harder*, and our assumptions more approximate, as mass-loss rates increase a factor of 10 over the main-sequence rates. And how do we properly include the (episodic) large mass-loss that occurs during the LBV phase in such models?

The galaxies of the Local Group serve as our ideal laboratories for answering these questions today. Modern detectors and improved recognition of selection effects allow us to develop useful samples and provide answers to the above questions; the range of metallicities provided by the Local Group galaxies allows us to then test the effect that metallicity has on the evolution of massive stars.

Much of what I will talk about today has recently been published by Massey (1998b) and Massey & Johnson (1998), and so I will try to keep the summary of this work brief; the most exciting new results are the work on coeval associations in the Magellanic Clouds and Milky Way, which is work still on progress, but I will describe our preliminary results here as well.

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2. Global properties

First let's remind ourselves of a few fundamentals. The first is that if we consider a *galaxy-wide* population of massive stars, we are looking at a *mixed-age* population. If the galaxy is large enough, then the ages are well-mixed. One implication of this is that the number of evolved stars of a certain (initial) mass will be proportional to the number of unevolved stars of the same (initial) mass, with the relative proportions reflecting only their relative lifetimes. This is really just equivalent to saying that the number of stellar births equals the number of stellar deaths at a given mass range. We're blessed here by the fact that all massive stars are short-lived. ('O stars are *today*'.) Therefore we are not averaging over different star-formation epochs in a galaxy — if we were, these assumptions would not be valid. (Studies of stellar populations of lower mass face a much more difficult task as the star-formation history of a galaxy has to be unraveled.)

What might we expect to find? Let us take the 'modified' Conti-scenario (Maeder & Conti 1994) as our touch-stone. In this, the most massive Galactic stars ($> 85\,\mathcal{M}_\odot$?) might first evolve to LBVs, then to WNs, and then to WCs. Stars of somewhat lower mass ($40\,\mathcal{M}_\odot$) might evolve to a WN (possibly becoming a RSG first) but not have sufficient mass-loss to evolve to the WC stage. Stars of even lower mass ($15\,\mathcal{M}_\odot$) might spend their entire He-burning lifetimes as RSGs, never evolving to WNs. In a higher-metallicity galaxy we expect that the masses we've listed would all be lower — because at a given luminosity (mass) the mass-loss rate will be higher in a higher metallicity galaxy. In a low-metallicity galaxy these limits will all be higher — because the mass-loss rates will be lower at a given luminosity. Thus we might expect that in M 31 (high Z) a $40\,\mathcal{M}_\odot$ star might evolve all the way to a WC star, while in the SMC (low Z) even an $80\,\mathcal{M}_\odot$ star can only dream of becoming such an evolved creature.

Thus we expect to see significant differences in the relative number of WCs to WNs as we look at different environments, or in the relative number of WRs to RSGs. These differences should go monotonically with metallicity, in the absence of other effects, such as changing IMF slopes.

An even more fundamental quantity to measure in a mixed-age population would be the relative number of evolved stars of a particular type relative to the number of unevolved stars with masses above some value. This is sometimes crudely referred to as 'the number of WR stars to the number of O stars', and indeed estimates for such number ratios are sometimes bandied about in order to test the accuracy of some evolutionary models. I will continue to use the phrase 'number of O-type stars' but it is really not what we are talking about — we are really talking about the 'number of main-sequence stars' of a given mass, which includes B-type giants and supergiants. Unfortunately, the 'number of O stars' is only marginally known at present even for the Magellanic Clouds, and it is even more poorly known for the Milky Way, because of the complications of reddening. At present, it is totally unknown for the more distant members of the Local Group. The reasons for this are simple: as emphasized elsewhere (Massey *et al.* 1995b; Massey 1998a), the visually brightest, blue stars in a mixed-age population will be the evolved B and A supergiants, dominated by 15–20 $\mathcal{M}_\odot$ stars; the really massive guys are several magnitudes fainter visually, and spectra are needed to correctly assign (bolometric) luminosities and hence

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masses. Nevertheless, this is a really nice 'fundamental' number, and it would be great to know it, as we would then have the means of determining the mass range that become WRs if we assume some a priori knowledge of the relative main-sequence and WR lifetimes. I will include such an estimate later on in this review for the Magellanic Clouds, but even here such a value needs to be taken lightly.

But what we can compare are such things as the relative number of different WR types as a function of metallicity, along with the number and luminosities of RSGs. Let me describe the high-lights of what we've learned.

2.1. The relative number of WC and WN stars

The number of WC stars relative to WN stars increases with increasing metallicity, consistent with stars of lower luminosity evolving all the way to the WC stage thanks to increased mass-loss.

The difficulty in determining the WC/WN stars in nearby galaxies has always been the need for completeness for the weaker-lined WNs. Our recent survey of M 33 (Massey & Johnson 1998) now complements CCD surveys in other Local Group galaxies by by Armandroff & Massey (1985), Massey, Armandroff, & Conti (1986, 1992), and others. We see that the WC/WN ratio is a strong function of metallicity, and follows the following relationship:

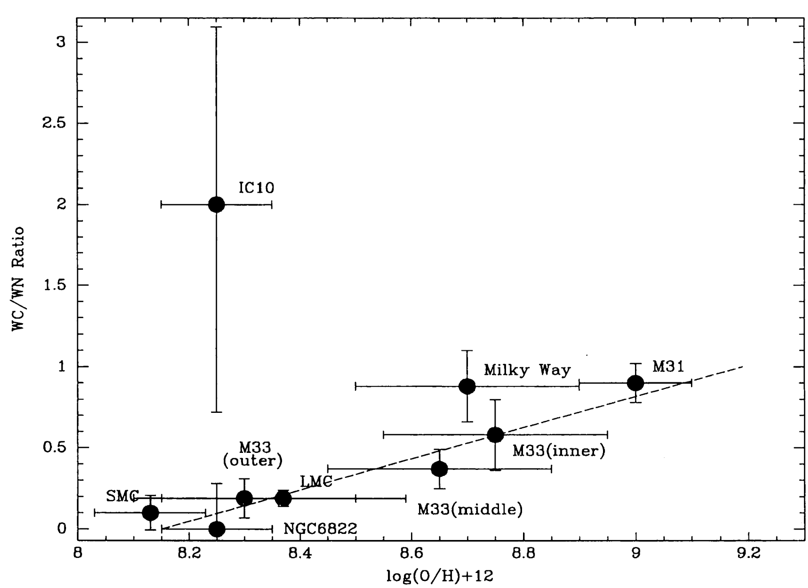

Figure 1. The relative number of WC and WN stars as a function of metallicity. The IC 10 and MW points were excluded from the fit. The error bars along the ordinate correspond to $\sqrt{N}$ statistics, except for the IC 10 point, which also includes the possibility that two remaining candidates are WNs. Errors along the abscissa are from the references given in Table 5 of Massey & Johnson (1998).

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$$\text{WC/WN} = 0.96 \times [12 + \log(\text{O/H})] - 7.82.$$

This is in the sense of our expectations: at higher metallicities stars of somewhat lower luminosity will have sufficient mass-loss to evolve all the way to the WC stage.

The details of this relationship are discussed extensively by Massey & Johnson (1998), and I won't repeat them here, other to comment briefly on two of the galaxies: the Milky Way data even within 3 kpc of the Sun may well be incomplete for WN stars. Hopefully new surveys, such as that begun by Shara *et al.* (1991), will help address such incompleteness. Secondly, the very anomalously high WC/WN ratio in IC 10 is highly suggestive that there is something unusual going on in this galaxy. Massey & Armandroff (1995) argue that IC 10 is a classic 'starburst', and the simplest explanation is that the IMF is skewed in favor of higher mass stars. The alternative explanation would require a single, galaxy-wide, highly coeval burst.

2.2. Red supergiants and Wolf-Rayet stars

The highest luminosity RSGs are lacking in regions of higher metallicity, consistent with the notion that the mass range that becomes RSGs rather than WRs decreases with metallicity. There is an excellent correlation with the presence of RSGs and WRs: wherever one is found, so is the other, and hence many massive stars must go through both a RSG and WR stage. The relative number of RSGs to WRs change strongly as a function of metallicity, again in the sense that the massive stars spend proportionately more of their He-burning lives as

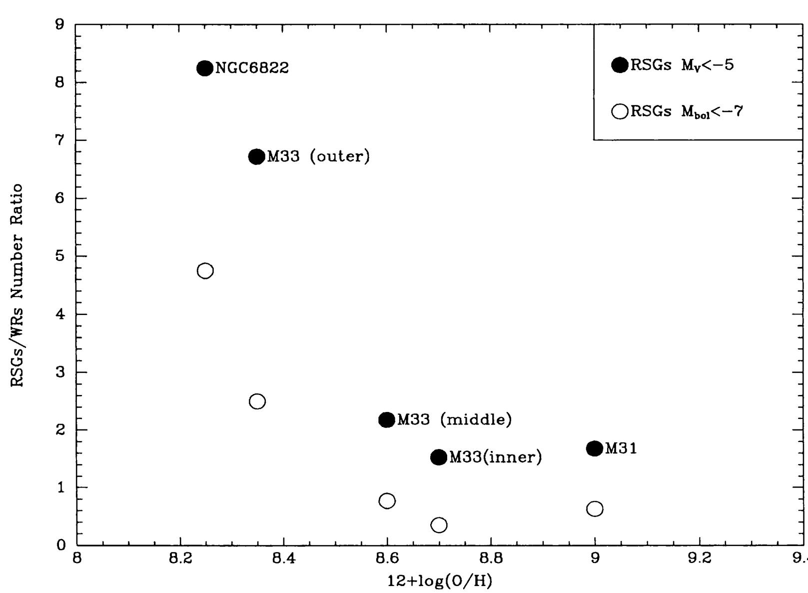

Figure 2. The relative number of RSGs and WRs are shown as a function of metallicity.

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WRs than RSGs as the metallicity increases, as predicted by Maeder, Lequeux, & Azzopardi (1980).

Just as previous studies of the WC/WN ratio in galaxies were hampered by selective incompleteness for WNs, the determination of the relative numbers and distributions of RSGs and WRs has been undermined by foreground Milky Way stars. For the more distant members of the Local Group the difficulty is that Milky Way disk red dwarfs will be found at the same magnitudes and in similar or greater numbers.

Massey (1998b) devised a scheme for separating RSGs from foreground dwarfs photometrically, and substantiated it by spectroscopy for a large sample of red stars seen towards NGC 6822, M 31, and M 33; we now have a good census of RSGs in selected regions of these three galaxies, including the areas previously surveyed for WR stars. For the Magellanic Clouds, the situation is harder: there foreground contamination will be by Galactic red giants, and the smaller difference in gravity between giants and supergiants makes it harder to devise clever photometric methods for distinguishing one from the other. Still, with spectroscopy it is easy to separate the two on the basis of radial velocities, although this is slow going if you are having to do it one star at a time. As for the Milky Way, we suffer here from foreground contamination by both red dwarfs *and* giants, and sorting this out is very difficult, without even the advantage of radial velocity differences.

Based upon this new survey we have discovered three things:

- At higher metallicities there are proportionally fewer of the highest luminosity RSGs, suggesting that the higher-mass loss rates expected result in more time spent as a WR star rather than a RSG. Furthermore, at lower metallicity the histograms just 'dribble off' to higher luminosities, although M 31 appears to have a sharp cut-off (Figure 2). This suggests to me that many many massive stars go through both a RSG and WR stage, at least at metallicities below that of the Milky Way.
- The presence of WR stars and luminous RSGs are well correlated within OB associations: where one finds one, one finds the other. This also strongly suggests that many massive stars go through both a RSG and WR phase.
- There is a very strong correlation in the relative number of RSGs and WRs with metallicity. Figure 3 shows the results for the Local Group galaxies. We see a factor of 5 change within the disk of M 33 ($\Delta\log(O/H) = -0.35$). Furthermore, this trend continues to NGC 6822, despite the only small metallicity difference. The relationship may flatten out at the higher metallicity indicated by the M 31 point, although using a slightly more luminous cut-off ($M_{bol} < -7.5$) makes this relationship monotonic. This is in the exact sense predicted by Maeder *et al.* (1980), although is a factor of 20 smaller than the gradient they believed they had found within the Milky Way, due to, we believe, the large uncertainties in the Milky Way data.

2.3. The spatial distribution of the various WC subclasses

The various WC subclasses are due primarily to the influence of metallicity on the atmospheric structure, and are not due to mass or luminosity.

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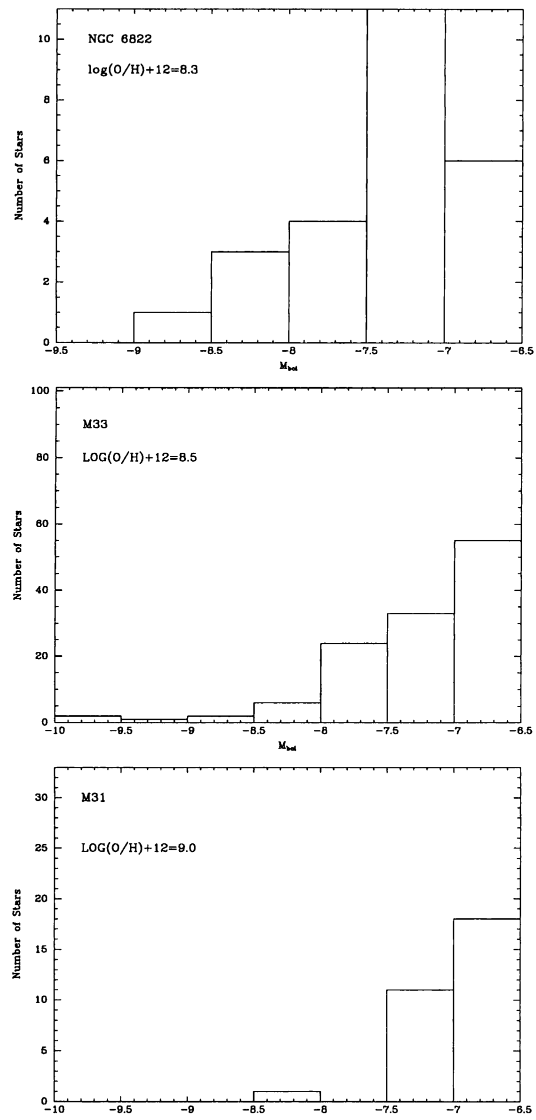

Figure 3. High luminosity RSGs are lacking as we look at higher metallicity systems. Note that there is a sharp cut-off to the luminosities of RSGs in M31, but not in the lower metallicity systems.

It was first noted by Smith (1968) that different WC subclasses were found in the Magellanic Clouds than in the Milky Way: in low metallicity regions early WC stars dominate, while in higher metallicity regions late-type WC stars

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dominate. Schild, Smith, & Willis (1990) found that the line-widths of early WC4-5 stars varied with galactocentric distance within M 33. Further work by Armandroff & Massey (1991) showed that the same was true for the Milky Way — but not for M 31 — and that the differences were correlated with metallicity.

Massey & Johnson (1998) suggest that we should view the various WC subtypes not as stars of differing physical properties so much as simply a reflection of the effect that metallicity has on the stellar winds structure. After all, we expect that the same mass range of O stars are present regardless of metallicity, as demonstrated by the consistency found for the initial mass functions in the OB associations of the SMC, LMC, and Milky Way (Massey *et al.* 1995a, 1995b; Massey 1998c). Let us consider for the moment the *lack* of WC4 in the relatively higher abundance of the Milky Way. How can the *lower* mass-loss rates present in the LMC produce only WC stars of subtype WC4, but none are produced in higher metallicity regions? If it were simply a matter of the mass-loss rates being higher in the inner part of the Milky Way, then we would expect to see WC4 stars that were born of somewhat lower luminosity stars. But, instead we don't see any.

Another slant on this is offered by Smith & Maeder (1991), who start with the assumption that the (C+O)/He ratio is a monotonic function of spectral subclass, with earlier (higher-excitation) subtypes being more enriched. They then argue that the connection between metallicity and WC subtype can be explained rather simply by the fact that a massive star can strip off its outer layers and be revealed as a WC star only in a more 'enriched' state at lower metallicity. While this explains the lack of late-type WCs in lower metallicity systems, it does not explain the lack of early-type WCs in higher metallicity systems. As time goes on we would expect that WCLs evolve to WCEs if this interpretation were correct. Where, then, are the early WCs in M 31?

2.4. Playing the game with O-type stars

Data on the field *population in the LMC and SMC suggest that stars more massive than 30 $\mathcal{M}_\odot$ evolve to WR stars in the LMC, while the mass limit is perhaps 50 $\mathcal{M}_\odot$ in the SMC.*

I emphasized in the introduction that with the advent of 8-m class telescopes and multi-object spectrographs it may prove possible to answer the 'number of O stars' question in the Local Group galaxies beyond the Magellanic Clouds. In the meanwhile, we have some data on this from the SMC and the LMC, although I caution that even here we have made significant corrections for incompleteness (Massey *et al.* 1995b). What do we find? If we assume that the relative lifetimes of the main-sequence phase, and of the WR phase, is about 1:10, then the mass limit for becoming a WR star is about 30 $\mathcal{M}_\odot$ in the LMC, and possibly higher (50 $\mathcal{M}_\odot$) in the SMC. See Massey *et al.* (1995b) for discussion.

3. Coeval populations

Hillenbrand *et al.* (1993) studied star formation in the 'Eagle Nebula' (M 16, NGC 6611), and concluded that their data were consistent with all of its massive stars 'having been born on a particular Tuesday'. In any event, the time over which the massive stars form in Galactic clusters and associations appear to

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be < 1–2 Myr (Massey *et al.* 1995a). Given this, it should be possible to look at clusters and OB associations containing WR and other evolved stars, and determine the (initial) masses of the stars still on the H-burning main-sequence. If coevality strictly holds, then we know that *(a)* the progenitors of these WR stars started out with masses greater than this amount; and that *(b)* we can estimate the bolometric corrections for WR stars by comparing their absolute visual luminosities with the bolometric luminosities of the main-sequence stars. I'll note that when I tried this once before (Humphreys, Nichols, & Massey 1985), Peter Conti shook his head and assured me this was absolutely crazy, but I am hoping the data are a little better these days and maybe I can convince him, and the rest of you, that this isn't entirely nuts. I'll note that previous efforts to do this (Lundstrom & Stenholm 1984; Schild & Maeder 1984; Humphreys *et al.* 1985; Smith, Meynet & Mermilliod 1994) were severely hampered by lack of good spectroscopy in the clusters being discussed.

4. Conclusions

This work is still in very much preliminary form, and I report here on our results for the first time. My collaborators Kathy Eastwood, Liz Waterhouse, and I are analyzing new photometry and spectroscopy on SMC, LMC, and Galactic OB associations, and combining this with the associations that are well studied from the literature. As of this writing, only the LMC data have been partially analyzed, but here is what we judge we can safely conclude from this:

- WNE stars come from a wide range of initial masses (30–100 $\mathcal{M}_\odot$), and have BCs that are consistently large (negative): −6 to −8 mag.
- The Ofpe/WN9 stars seem to come from stars with masses of 20–30 $\mathcal{M}_\odot$; this is consistent with the reports of St-Louis *et al.* (1998). The BCs are far more modest (−1 to −3 mag).
- The WC stars consistently come from stars with higher masses (>60–70 $\mathcal{M}_\odot$). Their BCs are similarly uniform (−3 to −4 mag).
- The 'B2I+WN3' systems are invariably found in clusters with very high turn-off masses (>70–90 $\mathcal{M}_\odot$).
- The LBV S Dor began life with a mass > 90 $\mathcal{M}_\odot$, just as Massey & Johnson (1993) found for η Carinae.

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Discussion

Moffat: In your plot of WC/WN number-ratio *versus* metallicity Z you do not give error bars. For example with only 1 WC and 8 WN in the SMC, it may be fortuitous that its value of WC/WN lies on the overal trend. In the case of IC 10, even with ~ 20 stars, you have small numbers, so I would not exaggerate the apparently large deviation of this galaxy from the trend.

Massey: In the published version I've enclosed the error bars corresponding to $\sqrt{N}$-statistics. IC 10 has a very anomalous WC/WN ratio given its metallicity. As you note, galaxies with far fewer WR stars fit the relationship very well, just as you expect given the size of the error bars. I have, however, left IC 1613 out of this diagram as it has exactly one known WR star — and there I agree that we do have to worry about small number statistics. Nicole Homeler has reminded me of two other factors that could lower

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the WC/WN ratio is IC 10. First, the extinction in IC 10 is somewhat clumpy. While I think our survey for IC 10 is complete for weak-lined WNs, maybe it's not. That's potentially a much more serious issue than having only 20-odd stars in our sample. Also there are still a few WR candidates in IC 10 that could turn out to be WN stars, which would lower the number ratio down to something like 1.5, but that would still be highly anomalous.

Crowther: The use of OB associations to obtain bolometric corrections for WR stars is clearly a powerful technique, as demonstrated in our Galaxy by Smith & Maeder. After a lot of effort, WR analyses now approach their results (~ -4.5 mag). So, if the WNE BCs in the LMC are indeed –8 mag, their huge EUV flux should easily be seen, *e.g.*, in a highly ionized nebula.

Massey: This is a really good point and needs to be checked, of course, there can be cases where the OB association has gotten rid of its gas. We are also working on re-doing the data on Galactic clusters, obtaining new data in most cases.

Shara: There are still no WC9s known in M 31; do you expect them to exist, and would you perhaps hazard a guess at their total number?

Massey: Well, some of the late WCs we've found in M 31 could be WC9s, and we just don't know it yet — we need spectra in the yellow-red to really tell. But even if they're not, only a small region of M 31 has been deeply surveyed, and we know that WC9s have modest line-fluxes ($EW \simeq 30$–100Å).

Alfaro: (1) I miss the Y-axis error bars in your WC/WN ratio *vs.* abundance plot. In some cases the number of WR stars in a single galaxy is lower than 10, which could yield to error bars larger than 1. (2) I also miss some reference to our poster where we show that the WC/WN ratio changes for different galactic regions, going from values lower than 0.5–1.8 for the Sagittarius star complexes.

Massey: In the published version I've included error bars corresponding to $\sqrt{N}$-statistics. As I stated in my answer to Tony Moffat this has no effect on the correlation. As for your poster, unfortunately your 'WC/WN ratio' has little meaning unless you are averaging on many star-forming regions, so that you are dealing with a mixed-age population. And, how many stars are there in your 'anomalous' regions...?

Langer: You are very definite in saying that WR stars form through mass loss. How can you distinguish whether perhaps the role of mixing for WR star formation is not the dominant one? The recent models with rotation, also from the Geneva group (see G. Meynet, these Proceedings), seem to imply that rotational mixing may also be relevant.

Massey: I think what I've said is that the data are in fact consistent with the predictions made by the Conti-scenario. Of course, you are right that this doesn't 'prove' the Conti-scenario! But the way science is done is that you have a hypothesis which has certain observational implications, and it then behooves you to go out and check to see if those predictions are in fact met. If they were not, then it's back to the drawing board! Surely you're not now suggesting that with rotation we can forget all about the effects of mass-loss? I mean, the observed mass-loss rates will lead to a very massive star shedding about 1/3–1/2 of its mass during the core-H burning life-time, and that is likely to play some role in all this! Also, let me remind you that we know that the old Geneva evolution models do predict the observed distribution of stars in the HR diagram for stars in the Magellanic Clouds (Massey *et al.* 1995b). I don't believe that any critical observational tests of your new rotation models — nor, those of the Geneva group — has yet been carried out.

Schmutz: The large BC you showed imply that those objects are very hot and that there must be a considerable fraction of radiation that emerges at $\lambda < 228$Å. This has as a consequence that He in the nebulae should be completely ionized and therefore, you should find nebular He II 4686. Is this prediction correct?

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Massey: I don't know. It's a little hard for me to understand, though, why this method should give 'reasonable' (expected) BCs for some spectral types (slash stars, WCs) but not for others (WNEs) — particularly for the cases when they're located in the same associations.

Massey: A question that I expected from Nolan or Peter was: at what mass range do we run out of RSGs but get WRs instead. Let me answer it anyway. In M 31 we run out of RSGs at a mass roughly corresponding to $15\,M_\odot$, so at that (relatively high) metallicity, say $2 \times$ solar, I think that even $5\,M_\odot$ can 'do it'. In NGC 6822 ($1/3 \times$ solar) we see RSGs in large numbers down to about $30\,M_\odot$. For M 31 there's a sharp cut-off, so maybe at higher metallicity you form either WRs or RSGs. Maybe the same is true for the Milky Way. But at lower metallicity the number of RSGs just dribbles off to higher luminosity (masses), so the massive stars may go through both a RSG and a WR phase.

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