Wolf-Rayet Stars
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Finding Wolf-Rayet Stars in the Local Group

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We summarize past and current surveys for WRs among the Local Group galaxies, emphasizing both the why and how. Such studies are invaluable for helping us learn about massive star evolution, and for providing sensitive tests of the stellar evolution models. But for such surveys to be useful, the completeness limits must be well understood. We illustrate that point by following the "evolution" of the observed WC/WN ratio in nearby galaxies. We end by examining our new survey for WR stars in the Magellanic Clouds, which has revealed a new type of WN star, never before seen.

1 Introduction

The motivation for WR surveys should be to improve our understanding of massive star evolution, and not just for the sake of adding a few more WRs to our lists. Stellar evolutionary modeling is hard, and there are numerous simplifications that our theoretician colleagues have had to adopt. How good are these approximations? Until we compare observations with the model predictions, we don't know. But, to succeed at this our surveys must be complete enough to be useful.

The basic premise of the "Conti scenario" (Conti 1975) is that a massive star strips off its H-rich outer layers through stellar winds, first revealing He and N, the products of the CNO cycle. If there is sufficient additional mass loss, then the star peels down far enough for us to see C and O, the productions of triple-α He burning. Today we would argue that this process is occasionally aided by Roche-lobe overflow in close binaries and/or episodic mass loss during the LBV stage (Smith & Owocki 2006), although whether these processes are important for most massive stars or not remains an open question.

These stellar winds are driven by radiation pressure in highly ionized metal lines, and hence the mass-loss rates are metallicity dependent. Since the nearby star-forming galaxies cover a range of 20× in metallicity (Massey 2003), these galaxies make ideal laboratories for studying massive star evolution as a function of metallicity.

We show in Fig. 1 an example of what we can learn from such studies. We have plotted the log of the relative number of RSGs and WRs against the metal abundance, measured from the oxygen content of H II regions, for four Local Group galaxies for which we believe the numbers are relatively complete. Note that this quantity changes by an order of magnitude over a similar change in metallicity. Maeder et al. (1980) was the first to suggest that this number ratio should be very sensitive to the (initial) metallicity of the stars, and that a comparison with observations would be a good test of the models.

If our surveys for WRs and other evolved stars are to be useful in learning about massive star evolution, we must be careful that they are complete, or at least that their limitations are well understood. To be useful, WR surveys must be sensitive enough to detect the weakest-lined WRs at the faintest magnitude limits one expects to find them, and be volume-limited, and not magnitude-limited.

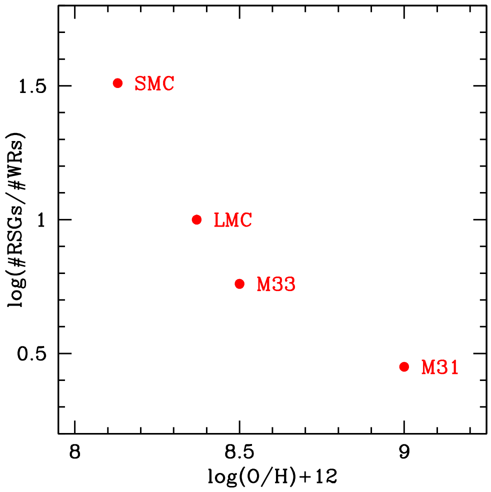

Fig. 1: We have counted the number of RSGs more luminous than $M_V \sim -5$ with $T_{\rm eff} < 4000$ and compared that to the number of WRs as a function of metallicity.

An advantage of using WRs in an external galaxy for such studies is that the stars all lie at essentially the same distances; thus the second criterion (being volume-limited) is automatically met. Sadly, studies of the WR content of the Milky Way do not share this, as distances are highly uncertain, greatly magnifying the problems with other selection effects. Nor is it clear what we learn by detecting a few WCs in more distant galaxies, so this review will be restricted to the WRs in Local Group.

2 Past Surveys for WRs

One of the testable predictions of massive star evolutionary models is the relative number of WC- and

WN-type WRs as a function of metallicity. In a completely mixed-age population (such as what we observe by averaging over many star-forming regions in a galaxy) we would naively expect this ratio to increase with metallicity according to the Conti Scenario, as at high metallicity we expect stars of somewhat lower masses will suffer sufficient mass-loss to become WC stars. At lower metallicities the mass limit for evolving to the WC stage should be higher. And indeed, when the first author was a graduate student, this was known to be the case, with the WC to WN ratio changing from about 1:7 in the low metallicity SMC and 1:1 in the Milky Way, while the LMC, at intermediate metallicity, had an intermediate ratio (1:4.5) (see e.g. Vanbeveren & Conti 1980). Shortly after that, Massey & Conti (1983a) confirmed that there was a galactrocentric gradient in the WC to WN ratio in M33, consistent, perhaps, with its metallicity gradient. And, our good colleagues (Moffat & Shara 1983, 1987) were busy discovering WRs in M31, almost all of WC type, again consistent (one might imagine) with M31's supersolar metallicity (Zaritsky et al. 1994).

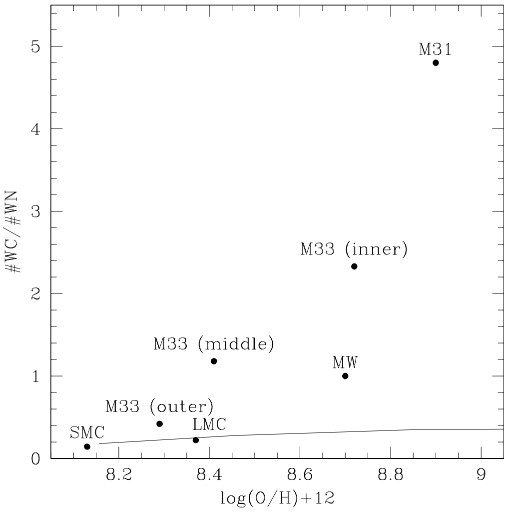

Fig. 2: The relative number of WC and WN stars as a function of metallicity as we knew from photographic studies, compared to the predictions of the Geneva evolutionary models from Meynet & Maeder (2005).

The problem came when one attempted to compare the actual numbers with the predictions of the stellar evolutionary models. Recall that the predicted ratio isn't simply due to the lowering of the mass limits with increased metallicities: the relative lifetimes of the WC and the WN stage also play a critical role. And when these are folded in with the mass limits, one finds a rather disturbing disagreement between the data (such as we knew it in the early 1980s) and the models, as Fig. 2 shows dramatically. (For convenience, we have adopted the predictions from the rotating models of Meynet & Maeder 2005, although we had nothing so advanced at the time.) We find that there is a factor of 13 difference between what the observations and models predict for the WC to WN ratio in M31! Clearly something was very wrong. Interpreted naively, this would suggest a horrendous problem with the model mass limits and/or WR lifetimes.

However, there was another possibility. The strongest optical emission line (C III λ4650) in WC-type WRs is, on average, much stronger than that of the strongest emission line (He II λ4686) in WN-type WRs (see, e.g., Massey et al. 1987; Conti & Massey 1989). What, then, if the surveys of the galaxies beyond the Magellanic Clouds were just very biased towards WCs? In all honesty, this thought did occur to us at the time; Massey & Conti (1983a) discuss this as a possibility, but conclude that the amount of incompleteness would have to be too great to explain the discrepancy even between the outer regions of M33 and the SMC/LMC.

2.1 A Brief Journey Through Time

To understand why the WC/WN ratios of the higher metallicities systems agreed so poorly with the models let us consider what we are calling the three eras of Local Group WR surveys.

The First Era: Photographic. The data in Fig. 2 came photographic surveys. These began with the Henry Draper Catalogue (1918–1924) and its extension (1925–1936), both general objective prism surveys which found many of the bright Galactic and LMC WRs. These were followed by general objective prism surveys of the Magellanic Clouds, (Sanduleak 1970; Azzopardi et al. 1975), which found not only OB stars but also a wealth of WRs. There followed the first searches specifically for WRs, namely Azzopardi & Breysacher (1979a,b, 1980). They did a very clever thing: they took photographic objective prism images of fields in the Magellanic Clouds, but added a 120Å wide filter that centered at 4650Å in order to isolate only objects with C III λ4650 and/or He II λ4686 emission. This had the advantage of cutting down on crowding, and also greatly reduced the sky contribution, allowing them to go much deeper than would otherwise have been possible. The photographic era ended with WR surveys being extended to the more distant members of the Local Group, M33 and M31. Wray & Corso (1972) used an on-band He II/C III filter and a continuum filter to take images of two fields in M33, identifying the first WRs beyond the Magellanic Clouds. The same technique was used by Massey & Conti (1983a) for a more extensive survey of M33, and by Moffat & Shara (1983, 1987) for two fields in M31.

The Second Era: Optimal filters and Small CCD fields. With the advent of CCDs, it was no longer necessary to blink on-band and off-band photographic plates trying to spot the change in brightness that would demark the presence of a WR star. Instead, quantitative photometry could be used to measure the brightness of all the objects on a CCD frame, and the magnitude differences compared to the photometric errors to find statistically significant candidates. Armandroff & Massey (1985) were the first to apply this technique, searching for WR stars in the nearby irregular galaxies NGC 6822 and IC 1613, as well as two test fields in M33. For this work they designed a new filter system, consisting of 50Å-wide bandpasses centered on C III λ4650, He II λ4686, and neighboring continuum at 4750Å. This system was designed to be optimized for the detection of WRs, using the extensive spectrophotometry of the normal (non-WR) stars from Jacoby et al. (1984) and WRs from Massey (1984) and Massey & Conti (1983b). They discovered three more WNs in NGC 6822 (Massey et al. 1987) in addition to the one previously known (Westerlund et al. 1983), but more importantly their study identified five new WN stars in a M33 field previously known only to contain six WCs and two WNs. (Compare Table 5 in Armandroff & Massey1985 to Table 2 in Massey et al. 1987.) Thus, in this one field the WC/WN ratio changed from 3.0 to 0.9. The significance of this was not immediately apparent, but further studies hammered home the point that the photographic studies had been woefully incomplete for WNs. In particular, Massey et al. (1986) surveyed eight small fields in M31 for WRs, identifying new WR candidates, many of which were subsequently spectroscopically confirmed as WRs (Massey et al. 1987; Armandroff & Massey 1991). Massey & Johnson (1998) extended these studies to include additional fields in M33, provided catalogs of all WRs beyond the Magellanic Clouds, and extensively discussed the selection biases against WNs. Their conclusion was that the photographic studies had been 50% incomplete for WNs, a number we might consider now to have been conservative. These studies also demonstrated the need for spectroscopic confirmation of any photometrically-detected WR candidates: none of the new IC 1613 WR candidates found by Armandroff & Massey (1985) turned out to be real. Similarly, Royer et al. (1998) designed their own photometric system aimed at identifying WRs, and used this to announce the discovery of the first WC9 stars detected in another galaxy (Royer et al. 2001). When observed spectroscopically, none of the WC9 candidates proved to be WRs (Crowther et al. 2003).

The Third Era: Large CCDs and Image Subtraction Techniques. Although CCDs were much more sensitive than photographic plates, and allowed quantitative assessment of the candidates, the early chips were *tiny* compared to plates, and the areal coverages about large enough to include a single OB association in one of these galaxies. The introduction of larger chips and mosaic cameras provided the means to finally complete surveys for WRs in M33 (Neugent & Massey 2011) and even M31 (Neugent et al. 2012a). Furthermore, our supernovae colleagues had spent years developing powerful image subtraction techniques. Combined with photometry, these greatly reduced the number of false positives we had typically experienced by just using photometry. (When one is considering 10,000 stars, a 3σ criterion will lead to 15 spurious detections!) With these deeper surveys what has happened to the large discrepancy with the models shown in Fig. 2? The improved data are shown in Fig. 3.

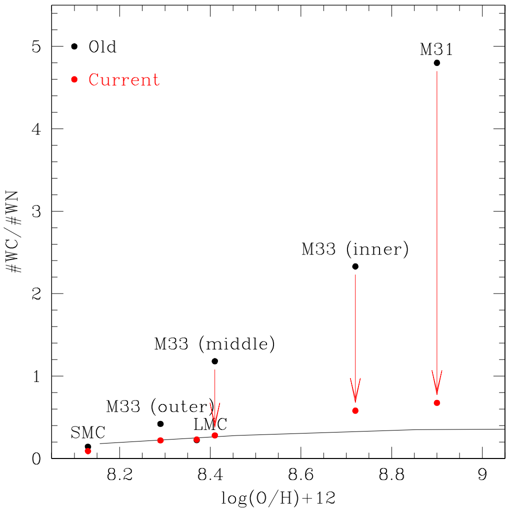

Fig. 3: The relative number of WC and WN stars as a function of metallicity as we know today (red) compared to the older data shown in Fig. 2. The agreement with the models is significantly improved!

What haven't we included in Fig. 3? First, we have ignored NGC 6822 and IC 1613 due to their very small number statistics: NGC 6822 has four WNs confirmed (Massey et al. 1987, and references therein). There is one WR star known in IC 1613; this is of WO-type. We have also not included any numbers for the Milky Way, as we suspect that these are still incomplete, and defining a volume-limited sample from the distances derived from spectral types to contain too many biases.

The galaxy most conspicuous by its absence is IC 10. IC 10 is a metal-poor (log O/H+12 ~8.3) irregular Local Group galaxy, chracterized as a starburst due to the surprising discovery of 15 WRs by Massey et al. (1992) and Massey & Armandroff (1995). This meant that IC 10 had ~ 5× the surface density of WRs as the SMC, comparable to that found in the most active OB associations (Massey & Holmes 2002). Even more surprising was that the WC/WN ratio in IC 10 was very high, ∼2, despite the fact that the metallicity was low; one would expect a value about 0.2. Although it seemed unlikely that the answer was that there were a very large number of WNs unaccounted for, nine of the additional candidates found by Royer et al. (2001) were spectroscopically confirmed by Crowther et al. (2003), demonstrating the incompleteness of the Massey et al. (1992) survey. Using deeper images, Massey & Holmes (2002) in fact found a large number of additional candidates, suggesting that the total WR population of IC 10 might be as large as 100! The WC/WN ratio to now down to 1.2, and many dozens of candidates still await spectroscopy.

What else have we learned from the study of WRs in nearby galaxies? For one thing, the relative number of early and late WNs change with metallicity, as does the the relative number of early and late WCs (Table 1). For the WCs we think we understand this purely as a metallicity effect on the spectral appearance (Crowther et al. 2002), but for the WNs, something more complicated is going on.

Tab. 1: Early and Late-Type WRs

Galaxy	log O/H +12	WNE/ WNL	WCE/ WCL
SMC	8.1	4.5	∞
M33out	8.3	4.4	∞
LMC	8.4	1.6	12
M33mid	8.4	1.2	1.8
M33in	8.7	0.9:	1.3
M31	8.9	1.2	0.4

3 A Modern Survey for WRs in the Magellanic Clouds

During the 2013 Rhodes meeting the three authors decided that we had to conduct a modern search for WRs in the Magellanic Clouds. Although the prevailing wisdom was that the WR content of the Clouds was mostly known, 7 new LMC WRs had been found accidentally since the Breysacher et al. (1999) catalog. All but one of these were WNs, suggesting that the WC/WN ratio might be biased even in the Magellanic Clouds. The seventh star was found by ourselves, and was a very strong-lined WO-type star, only the second known in the LMC (Neugent et al. 2012b). So, it seemed as if we still had some work to do. We designed a multi-year project, in which we would apply the same successful techniques used in M33 and M31 by Neugent & Massey (2011) and Neugent et al. (2012a), with the imaging done on the Las Campanas Swope, and the followup spectroscopy with Magellan.

We have now finished the second year of the survey; our results are described by Massey et al. (2014) and Massey et al. (2015). With 60% of the survey complete, we have discovered 13 new WRs in the LMC, plus a variety of other previously unknown interesting emission-line objects. However, the most interesting finding is that 8 of these 13 WRs are of a type never before recognized, stars that would naively be classified as WN3+O3 V. These stars are, however, too faint (by several magnitudes) to harbor an O3 V star, and our modeling has shown that we can reproduce both the emission and absorption lines with a single set of physical parameters (Massey et al. 2014). In this conference, Neugent et al. (2015) discuss these stars in detail. Here we would like to comment on a simple question: why haven't we found these stars elsewhere?

Surveys such as ours are not just flux-limited. As emphasized by Massey & Johnson (1998), what matters is the magnitude *difference* Δm between the on-band filter and the off-band filter. Thus, even though an Of-type star has a great deal of flux in the He II λ4686 emission line, they are relatively difficult to detect because they are also bright in the continuum. In other words, the detection limit is sensitive to the equivalent width of the line as a function of continuum flux. In Fig. 4 (left) we see the WRs and Of-stars we successfully detected in our survey, along with our 3σ and 5σ detection limits.

Fig. 4 (left) shows that our survey goes several magnitudes deeper than the faintest WN3/O3s we find, and so there aren't even fainter ones that we are missing. Note too that one or two of the SMC WNs are in a similar region of the diagram. All but one of the SMC WRs show absorption lines, and for many years there has been speculation that all of these stars are binaries, yet only four have orbit solutions. Hainich et al. (2015) has now shown that the absorption and emission can be modeled with a single set of physical parameters. The SMC WNs are more luminous visually than our WN3/O3s, and thus are not the same thing, but likely are related.

Why haven't WN3/O3s been found elsewhere in the Local Group? They probably don't form at high metallicities as no Milky Way ones are known, so it's not surprising that we haven't found them in M31. But what about M33? Earlier we've said that surveys need to be "sensitive enough to detect the weakest-lined WRs at the faintest magnitude limits one expects to find them." But what if we don't know how faint that is? The LMC WN3/O3s are quite faint, with $M_V\sim-2.5$ to -3.0. Do we go sufficiently deep in the M33 survey to find them? As Fig. 4 (right) shows, the answer is "no." We should have found most of the other M33 WRs, but to find WN3/O3s will require a bit more work, and we are planning deeper imaging to find such stars.

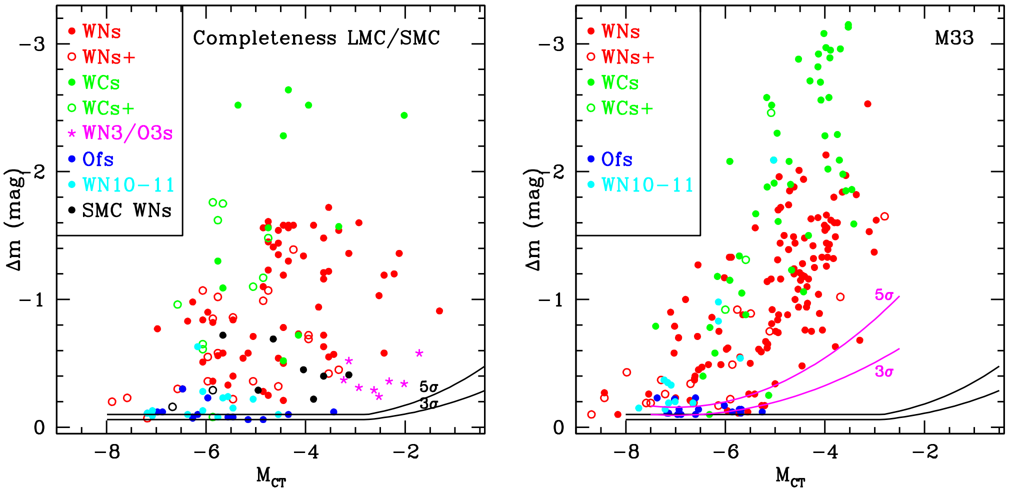

Fig. 4: The magnitude difference Δ m is plotted against the absolute magnitude $M_{\rm CT}$ for WRs in the LMC/SMC (left) and in M33 (right). The 5σ and 3σ detection limits are shown.

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References

Armandroff, T. E. & Massey, P. 1985, ApJ, 291, 685
Armandroff, T. E. & Massey, P. 1991, AJ, 102, 927
Azzopardi, M. & Breysacher, J. 1979a, A&A, 75, 120
Azzopardi, M. & Breysacher, J. 1979b, A&A, 75, 243
Azzopardi, M. & Breysacher, J. 1980, A&AS, 39, 19
Azzopardi, M., Vigneau, J., & Macquet, M. 1975, A&AS, 22, 285
Breysacher, J., Azzopardi, M., & Testor, G. 1999, A&AS, 137, 117
Conti, P. S. 1975, Memoires of the Societe Royale des Sciences de Liege, 9, 193
Conti, P. S. & Massey, P. 1989, ApJ, 337, 251
Crowther, P. A., Dessart, L., Hillier, D. J., Abbott, J. B., & Fullerton, A. W. 2002, A&A, 392, 653
Crowther, P. A., Drissen, L., Abbott, J. B., Royer, P., & Smartt, S. J. 2003, A&A, 404, 483
Hainich, R., Pasemann, D., Todt, H., et al. 2015, A&A, in press
Jacoby, G. H., Hunter, D. A., & Christian, C. A. 1984, ApJS, 56, 257
Maeder, A., Lequeux, J., & Azzopardi, M. 1980, A&A, 90, L17
Massey, P. 1984, ApJ, 281, 789
Massey, P. 2003, ARA&A, 41, 15
Massey, P. & Armandroff, T. E. 1995, AJ, 109, 2470
Massey, P., Armandroff, T. E., & Conti, P. S. 1986, AJ, 92, 1303
Massey, P., Armandroff, T. E., & Conti, P. S. 1992, AJ, 103, 1159
Massey, P. & Conti, P. S. 1983a, ApJ, 273, 576
Massey, P. & Conti, P. S. 1983b, ApJ, 264, 126
Massey, P., Conti, P. S., & Armandroff, T. E. 1987, AJ, 94, 1538
Massey, P. & Holmes, S. 2002, ApJ, 580, L35
Massey, P. & Johnson, O. 1998, ApJ, 505, 793
Massey, P., Neugent, K. F., & Morrell, N. 2015, ApJ, 807, 81
Massey, P., Neugent, K. F., Morrell, N., & Hillier, D. J. 2014, ApJ, 788, 83
Meynet, G. & Maeder, A. 2005, A&A, 429, 581
Moffat, A. F. J. & Shara, M. M. 1983, ApJ, 273, 544
Moffat, A. F. J. & Shara, M. M. 1987, ApJ, 320, 266
Neugent, K. F. & Massey, P. 2011, ApJ, 733, 123
Neugent, K. F., Massey, P., & Georgy, C. 2012a, ApJ, 759, 11
Neugent, K. F., Massey, P., Hillier, D. J., & Morrell, N. 2015, in Wolf-Rayet Star Workshop, ed. W. Hamann, A. Sander, & H. Todt
Neugent, K. F., Massey, P., & Morrell, N. 2012b, AJ, 144, 162
Royer, P., Smartt, S. J., Manfroid, J., & Vreux, J.-M. 2001, A&A, 366, L1
Royer, P., Vreux, J.-M., & Manfroid, J. 1998, A&AS, 130, 407
Sanduleak, N. 1970, Contributions from the Cerro Tololo Inter-American Observatory, 89
Smith, N. & Owocki, S. P. 2006, ApJ, 645, L45
Vanbeveren, D. & Conti, P. S. 1980, A&A, 88, 230
Westerlund, B. E., Azzopardi, M., Breysacher, J., & Lequeux, J. 1983, A&A, 123, 159
Wray, J. D. & Corso, G. J. 1972, ApJ, 172, 577
Zaritsky, D., Kennicutt, Jr., R. C., & Huchra, J. P. 1994, ApJ, 420, 87

Anthony (Tony) Moffat: (1) The absorption lines you refer to in these weak-line WN stars are not truly photospheric; they have negative RVs relative to the star and are formed in the wind (albeit near the base), not in the stellar photosphere.

(2) In Foellmi et al. (2003) we assigned spectral types of WNha or WNh to many SMC and some LMC WNE stars, which is an alternative that precedes your designation as WN + O or WN/O. As Paul Crowther stated the next day of this meeting to K. Neugent, “You don’t need to invent yet another designation”.

Philip Massey: (1) Actually according to our CMFGEN modeling, these absorption lines ARE photospheric: the winds are thin enough that we would call the formation region for the absorption photospheric. (2) There are a number of problem with your nomenclature (see Conti 1999, New Astronomy, 4, 489) but one of the most obvious ones in this case is that the “WNa” doesn’t really give any description of what the absorption spectrum is like. Does it contain He I and He II? Does it show hydrogen absorption? Is it purely He II? So, that is why we have been using our current designation. The absorption we see is both stronger and of earlier type than that found in the “WN3+O3-4” stars that Massey & Duffy (2001, ApJ, 550, 713) Massey et al (2003, PASP, 115, 1265) discovered in the SMC plus the ones that were already known, as as SMC WR-1. Our LMC WN3/O3s are nothing like HD 9974 (aka WR3) and spectrally not like the SMC WNs, other than in the sense of being “WN3+abs”.

Wolf-Rainer Hamann: In some of your statistics you were distinguishing between WNE and WNL stars. I am not sure if this categories do tell the same about their evolutionary stage when considering different metallicity environments. In the Galaxy, the early and late types generally coincide with the absence and presence of hydrogen, respectively. In contrast, the WNE stars in the SMC use to display hydrogen in their spectra (see talk by Rainer Hainich).

Philip Massey: Conti, Garmany, & Massey (1989, ApJ, 341, 113) discussed this, and we suggested that because the wind density might be lower in the SMC WNs that one way of looking at the situation was that the low metallicity resulted in “animals spectral classifications”: if the SMC WNs were WNLs rather than WNEs, then their weak lines and the presence of hydrogen would be expected.

Wolf-Rainer Hamann: Comparing the relative number of WNE to WNL stars as a function of metallicity may not be relevant.

Philip Massey: I agree that the comparison of the number of early- and late-WN stars is hiding a lot of the physics. Still, this is the sort of thing that it would be great we could reproduce well with evolutionary models.

Richard Ignace: It appears that there may be a relatively high ratio of WO/WR [in the LMC]. Could you comment?

Philip Massey: We’ve found two new WOs in the LMC, bringing the total number of WOs known to 3, out of 152. Is that a lot? I don’t know; its 2%. In IC 1613, one out of 1 WRs is a WO, so that’s a much higher ratio (100%). In the SMC, 1 out of 12 WRs is a WO (8%). So, I don’t know how to separate small number statistics from metallicity effects. In the MW, there are four (?) WOs know, out of nominally 600 WRs according to Paul. Is that a metallicity effect, or does it say how poorly we understand the WRs content of the MW?

Christopher Rosslowe: I agree that there are problems with the distances to Galactic WR stars, but I think we’re improving things gradually. An advantage of the Galaxy is we can spatially resolve nearby WR stars in clusters – closely spaced WR stars of similar spectral types would presumably appear as single WRs at extra-galactic distances. How much of a problem do you think this is in your surveys?

Philip Massey: This is a potential problem, but it’s rare to have two WRs that close to each other. This sort of question always arises in studying stars in nearby galaxies; Rolf Kudritzki notes though that usually there are spectral anomalies that show if one is dealing with one star or two. So, to me if you can fit the spectrum of a star with a single set of physical properties, you are likely (but not certain) to be dealing with a single object. The Potsdam group has done such a nice job fitting the WNs in the LMC with PoWR models (Hainich et al. 2014, A&A, 565, 27), and I think we know which ones have companions.

Dominik Bomans: Going to low metallicity implies lower absolute numbers. Do you see a limit for you WC/WN analysis. I notice you did not mention IC 10 and IC 1613.

Philip Massey: Well, of course it’s not just the metallicity; it’s also the star formation rates that affect the absolute numbers. For instance, Massey & Holmes (2002, ApJ, 580, L35) claims that IC 10 may have as many as 100 WRs, despite its low metallicity (log O/H + 12 = 8.25, intermediate between that of the SMC and LMC). I didn’t use IC 10 because we are still working on confirming candidates spectroscopically. IC 1613 has a much lower metallicity but it only has one WR star, a WO. Dany has been preaching the importance of binaries in massive star evolution for decades, and I think that IC 1613 WR is an example of where binary evolution really does actually matter.

Anthony (Tony) Moffat: An afterthought (submitted after the conference) to the answer of Phil Massey on my first question:

(1) HD 193077 = WR138 was found to be a long-period binary by Annuk (1990), albeit with fairly noisy RVs especially for the O component. More recently in 2014 (N. Richardson et al., in prep.) we have obtained CHARA snapshot data for this system and find that it is indeed a wide binary (separation 3 milli-arcsec) with NIR magnitudes for both stars that correspond quite well with the spectral types. Parallel CHARA observations show that the other Cygnus long-period binary WR137 = HD 192641 (Lefevre et al. 2005) also has two components separated by 4 milli-arcsec.

(2) Smith et al. (2000, New Astronomy, 5, 423) have dispensed with Conti's (1999) critiques of the otherwise generally well-received Smith et al. (1996) 3D classification system for WN stars. In particular the WN3ha type fits very well for the Galactic WR star WR3, as well as similar types for many weak-line WN stars in both Magellanic Clouds. "h" refers to the presence of hydrogen from the alternating Pickering decrement, while the "a" refers to the presence of hydrogen and other absorption lines intrinsic to the WR star.

Philip Massey: (1) It's funny how two of my thesis stars, HD 193077 and HD 9974, keep being mentioned at this conference! As far as HD 193077 is concerned, I think the jury is still out. Massey obtained many high dispersion spectra of reasonable S/N over three years, finding no evidence of radial velocity variations. We demonstrated that using the centroid of the intensity cubed produced much smaller scatter in the radial velocities than using the simple centroid. Annuk took much poorer quality data, and then tried to combine this with the lower accuracy measurements to decide this star had a 1500 day period. I suspect his result had more to do with the sampling of the measurements than with any actual velocity measurements. The result of the 3mas separation is quite interesting, and I look forward to seeing this as a published result rather than simply reported as "in prep." But, I have to ask then, that companion must be quite an unusual object—our fourier analysis showed that the absorption component was broadened *by rotation* by 500 km/s, higher than that of any known O star. I guess we just did something fundamentally wrong? Still, I'm curious how you can have it both way: a 1500 day period of a 30 $M_{\odot}$+30 $M_{\odot}$ star would have an orbital separation of about 10 AU by Kepler's 3rd law, wouldn't it? If HD 193077 is a member of Cyg OB1, its distance is about 2 kpc. So, that would imply a separation of about 5 mas. I suppose it could be the same punitive companion, but if not, it's a very crowded system. I do think it will be interesting to see if we can reproduce the spectrum of HD 193077 with a single set of physical parameters; I'll send you a preprint once we have this sorted out.

(2) The Smith et al classification scheme has never really caught on, and I think for good reasons. Other than you and your co-authors, and Paul Crowther's group, this system is seldom used. One of my principle objections is that it buries the nature of the absorption spectrum: if you see a WNE+abs spectrum with the "abs" containing lots of He I, well, it's pretty unlikely that the absorption comes is intrinsic. On the other hand, if it's "WNE+abs" with the "abs" dominated by He II with little or no He I, you have to work at it to figure out if the "abs" is intrinsic or from a early-type companion. Despite a few advantages to this scheme, it was not adopted by van der Hucht in his VIIth catalog, by BAT99 in their catalog of LMC WRs, or by Neugent in their classification of hundreds of WRs in M31 and M33. So, I guess you haven't really convinced the rest of us of the usefulness of the third parameter. Besides, the notation is, frankly, awkward.

Anthony (Tony) Moffat (Email, still continuing the after-workshop discussion): (1) Regardless of which spectroscopic data set one believes for WR 138 (HD 193077), the newly discovered, clear presence from CHARA of a resolved companion with appropriate brightness and separation says it all, subject to being published of course. Our observed snapshot projected separation of 3 mas would seem entirely compatible with your estimate of $a = 5$ mas. Also, at this meeting Dany Vanbeveren stressed that O stars in WR+O binaries could have spun-up rotations after RLOF ranging up to some 700 km/s, entirely compatible with the width of 500 km/s for the O star in WR 138.

(2) Actually the Smith et al. (1996) 3D classification system (ionization, hydrogen and line width being the 3 prime dimensions, as had been suspected for some time before this, but never before systematically incorporated into a unique classification system like this one) enjoys a lot of use beyond the world of Peter Conti, yourself and collaborators. In particular, the well-used on-line Galactic WR Catalogue of P. Crowther now numbers over 640 entries and uses the Smith et al. system, along with a variety of references for it. The Smith et al. classification system is clearly laid out and summarized in Table 4 on page 169 of Smith et al. (1996). As a result, the designations are quite simple and straightforward to apply, not to mention their obvious utility. For example, the absorption-line criterion "+abs" means that the absorption lines are of unknown origin. However, if one knows from other evidence that the absorption lines come from the WR star (e.g. from orbital motion or convincing lack thereof) and there is H present in emission, then one simply adds the suffix "ha" to mean that the absorption lines are indeed intrinsic to the WR star. If on the other hand, the star is an SB2 or there are H-absorption line without evidence of H emission, then one can convert "+abs" to "+OB", with "OB" assigned to a more specific subtype as appropriate. There are plenty of WNE+abs stars which

have now been converted to WNEha, especially in the Magellanic Clouds (Foellmi et al. 2003a,b), but also among Galactic stars such as WR3 = HD 9974, WN3ha, which Marchenko et al. (2004) showed convincingly that it is indeed single.