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A GLOBAL ASSESSMENT OF WOLF-RAYET BINARIES IN THE MAGELLANIC CLOUDS

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RESUMEN

Los estudios empíricos extensos de la evolución avanzada de estrellas masivas a través de la fase de Wolf-Rayet se han complicado por las enormes disparidades en el brillo aparente y la extinción atmosférica, así como por las incertidumbres en las distancias. Estos problemas desaparecen en las Nubes de Magallanes (NMs), donde se pueden explorar sistemáticamente los efectos de menor metalicidad inicial (Z). Desde hace dos décadas yo inicié, en parte en colaboración con Virpi Niemela, un amplio programa espectroscópico para examinar la binaridad de todas las estrellas WR conocidas en la NMM (en ese entonces, cerca de 100) y extraer información sobre propiedades generales de las estrellas WR. Ahora en 2006 el último paso de este proyecto está a punto de ser concluido por el tercer estudiante de doctorado [Olivier Schnurr quien ha trabajado en las estrellas WNL después de Peter Bartzakos (WC) en 1998 y Cédric Foellmi (WNE) en 2002]. El programa incluye las 144 estrellas WR conocidas en las NM, definidas por los catálogos de Breysacher et al. para la Nube Mayor, y de Massey et al. para la Nube Menor. Aquí resumimos los puntos sobresalientes de este trabajo. Éstos incluyen (1) una frecuencia binaria WR normal en ambas nubes y en la Galaxia, (2) una mayor presencia de H en las estrellas WNE, aún en las binarias, a menor Z, (3) vientos en colisión, y (4) estrellas muy masivas WNLha. Terminaré con algunas sugerencias para trabajo futuro.

ABSTRACT

In the Galaxy, comprehensive empirical studies of advanced massive-star evolution via Wolf-Rayet (WR) stars have been hampered by huge disparities in apparent brightness and interstellar extinction, and by uncertainties in the distances. These problems all but disappear in the Magellanic Clouds (MCs), where one can also systematically probe the effects of lower initial metallicity (Z). Over two decades ago I began, partly involving Virpi Niemela, a vast optical spectroscopic program to examine all of the (then about 100) known MC WR stars for binarity and use them to extract information on general properties of WR stars. Now in 2006 the last step of this project is being wrapped up by the third doctoral student [Olivier Schnurr working on the WNL stars, after Peter Bartzakos (WC) in 1998 and Cédric Foellmi (WNE) in 2002] to embark on this project, now including the 144 known MC WR stars, as defined by the catalogues of Breysacher et al. for the LMC and Massey et al. for the SMC. Here we will summarize the highlights of this work. These include (1) a normal binary WR frequency in both MCs as in the Galaxy, (2) the increased presence of H in WNE stars, even binaries, as one goes to lower Z, (3) colliding winds, and (4) very massive WNLha stars. I will end with some suggestions for future work.

Key Words: binaries: general — stars: fundamental parameters — stars: Wolf-Rayet

1. INTRODUCTION

Wolf-Rayet (WR) stars are like the canary in the mine (no parallel intentionally sought between explosive coal dust in a mine and carbon/oxygen in WC/WO stars!). Being the last stage (especially WC/WO) before a presumed core-collapse supernova explosion, their properties reflect in a very sensitive way the initial conditions, mostly with respect to the ambient metallicity (Z) of the ISM that formed them. This is no better reflected than in the relative numbers of different WR subtypes as a function of Galactocentric distance (e.g. van der Hucht 2001), which in turn depends on the metallicity, going from about twice solar in the central regions to subsolar in the outer extremity of the Galactic star-forming disk, close to R = 16 kpc. This is probably why the mix of WR subtypes in the LMC is quite similar to that of the outer Galaxy, i.e. dominated by WN stars; WC stars dominated by WCE and lacking WCL; and increased numbers of WNE stars. In the SMC, the effect is even more pronounced, although small numbers prevail there.

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The main goal of this project, conceived during the early 1980's, was to test the metallicity dependence of WR binary properties in the Magellanic Clouds (MCs), compared to the Galaxy. In particular, the WR binary frequency based on stellar interior models before ∼1995, was expected to increase considerably in regions of lower Z, where mass-loss rates of single massive stars are reduced compared to Z-rich regions, allowing only the most luminous and hence massive stars to reach the WR stage (Maeder & Meynet 1994). At the same time, it was believed that binary evolution would be independent of Z, hence the binary *fraction* would increase at lower Z. In this way, it was expected that, while the observed WR + O frequency in the Galaxy was ∼40%, essentially all the WR stars in the SMC should be binary. This seemed to be played out, since essentially all the WR stars in the SMC seemed to have ∼undisplaced absorption lines that were assumed to arise in O companions (e.g. Azzopardi & Breysacher 1979).

However, after 1995, rotation was (finally) included in stellar models (Meynet & Maeder 1997, 2003), which seemed to resolve a number of apparent previous inconsistencies in the relative numbers of WR/O, WC/WN and RSG/BSG stars as a function of Z. It also predicted that the binary frequency need not be so strongly dependent on Z, since both higher initial and sustained rotation at lower Z would maintain the observed mass-loss rates of WR stars. The introduction of realistic magnetic fields is another factor, which may play against the effects of rotation (Maeder & Meynet 2005). However, the jury is still out in this difficult regime of modelling.

As of ∼2005, another important factor has arisen: The mass-loss rates of WR-progenitor O-stars appear to have been seriously over-estimated systematically by factors possibly ranging up to a factor ten and more (Bouret et al. 2005; Fullerton et al. 2006), due to clumping. If confirmed, this may be even more serious than for WR stars, for which previous work (e.g. St-Louis et al. 1988) revealed an overestimate of a factor 2–5 due to clumping in their easier-to-observe, strong stellar winds. If O stars reveal a factor of 10+, stellar models will once again have to be rerun, with uncertain outcome. Actually, in the latest models, a factor ∼3 is already included (Maeder & Meynet 2008).

2. OBSERVATIONS

The original concept of this project stemmed from an extension of Virpi's and my current projects around 1980 to examine more systematically many of the 108 WR stars then known in the MCs (Breysacher 1981; Azzopardi & Breysacher 1979). We first started to examine all 21 of the then known WC/WO stars in the MCs. I fondly recall enjoying with Virpi the last run in the CTIO 1 m dome during the first year that CCDs had been introduced there at the spectrograph. In any case, it was clear that only 3 of the WC/WO stars in the LMC and the sole WC/WO star in the SMC, were in fact bona fide WR + O binaries of relatively short period. The results of that run appeared in Moffat, Niemela, & Marraco (1990; MNM).

This was followed by a more extended and complete spectroscopic study for binarity among all the 23 subsequently known WC/WO stars in the LMC and the sole WO star in the SMC in the PhD thesis of Peter Bartzakos, completed in 1998 (Bartzakos et al. 2001a,b). A new fainter (due to heavier IS extinction and its likely being single) LMC WC member was found by Testor, Schild, & Lortet (1993), now known as BAT99-69, which had little effect on the already clear results of the Bartzakos study (see below).

During the 1990's more WR stars were discovered in the LMC, leading to a fairly complete catalogue of 134 WR stars (Breysacher, Azzopardi, & Testor 1999, referred to as BAT99), although another WR star was discovered since then (Massey et al. 2001), although disputed by Foellmi et al. (2003b). Most of these were of weaker-lined and fainter WN type, although a now erroneously claimed WC9 star BAT99-4 should be removed (Moffat 1991), as should BAT99-6, now found to be an O3f*-star in a multiple system (Niemela et al. 2001). This led to a grand total in BAT99 of 24 real WC/WO stars (23 WCE, 1 WO); 61 WNE stars (WN1-5, excluding H-rich WN5h stars); and 47 WNL stars (WN6 and later, including WN5h and all stars in BAT99 of generic types denoted Of/WNL or WNL/Of).

As for the SMC, a recent updated compilation of the massive WR population was made by Massey & Duffey (2001), indicating 11 (mostly weak-line) WN stars and still the sole WO binary, all of which we denote SMC/WR1, 2, ..., 11. Then another WN star was found in the SMC by Massey, Olsen, & Parker (2003), labelled WR12 by Foellmi (2004).

After the Bartzakos study, the WN "pie" in the MCs was divided into two further PhD theses: 72 WNE stars, completed by Foellmi in 2002 (Foellmi et al. 2003a,b; Foellmi 2004) and 47 WNL, all in the LMC, completed by Schnurr in 2006 (Schnurr et al.,

TABLE 1

OVERALL BINARY FREQUENCY

Group	Gal($Z_\odot$)	LMC ($Z_\odot/2$)	SMC ($Z_\odot/5$)
WN	9/31 = 0.29	16/102 = 0.15	4/11 = 0.36
WC/O	6/36 = 0.17	3/24 = 0.13	(1/1 = 1.00)
WR	15/67 = 0.22	19/126 = 0.15	5/12 = 0.42
WN8,9	0/4 = 0.00	0/8 = 0.00	not present

in prep.). The rest of this paper will summarize the findings in these 3 studies.

Overall, a total of 144 WR stars were observed spectroscopically at mostly moderate resolution (R ∼1000) and S/N ∼80 in the optical, 20–30 times each over various timescales ranging from a day to 2–3 years. Two-metre class telescopes were used in the Southern Hemisphere: CASLEO in Argentina, CTIO and LCO in Chile, SAAO in South Africa, and MSO and SSO in Australia, except for the 6 WNL stars in the dense core R136 of 30 Dor in the LMC, which were observed using SINFONI/AO in NIR spectral mode at the VLT (ESO, Chile) over an interval of 22 days.

3. RESULTS

The most important finding of this study related to the original goals is the binary frequency. Assuming BAT99-69 to be single, and including Galactic WR stars out to d=4 kpc and in R(kpc)=6.5 ... 9.5 for R_o = 8.0 kpc from van der Hucht (2001), we compare the results (without the 6 WNL stars in R136) in Table 1. We restrict the comparison to orbital periods below P=200d, beyond which the detection becomes difficult. Here we see no compelling trends in WR binary frequency with ambient metallicity. Thus, it would appear that *whether a massive star becomes a WR star does not depend on whether it is in a binary system or not, regardless of Z.* This is contrary to previous ideas, especially involving tidal effects and Roche-lobe overflow (e.g. Vanbeveren et al. 1998).

3.1. *WC/WO Stars*

Taken as a group, it is quite remarkable that among the 24 WC/WO stars in the LMC, 23 are of type WC4 with one WO3. Previous work showed one star with WC5 and another of WC6 type. However, these have now been reclassified using our more homogeneous data, including allowance for wind-wind collision (WWC) effects, as in Br 22, which has gone from WC6 to WC4, due to strong WWC-produced CIII 5696 emission. The reason for this high degree of uniformity in spectral type is due to the lower Z, which reduces the opacity and allows one to always see the hottest deep layers of the wind (Crowther 2007). If some of these WC stars were in the inner Galaxy, they would have higher Z, stronger winds and we would only see cooler outer layers. The SMC contains only one WC/WO star of type WO4, which is compatible with this trend.

Despite the homogeneity in spectral subtypes, there is a large variation in line width among the MC WC/WO stars, ranging for CIV5808 from FWHM = 2000 to 5000 km/s. Curiously, stars with the *fastest* winds tend to have systemic RVs closer to that of the mother galaxy. This may be due to slower winds having larger photospheres ($\tau = 1$ in the wind) leading to stronger P Cygni absorption edges and RVs shifted significantly more to the red.

Among the 4 WC/WO binaries, they all tend to be brighter than, and have diluted emission-lines, compared to their single counterparts, yet do not show any obvious spectral differences (e.g. in FWHM). This again implies that the presence of a companion has little effect on the overall spectrum. The binary periods are all relatively short, with P = 1.9, 3.0, 14.9 d for the 3 LMC systems and 16.6d for the SMC system. Systems with periods up to ∼200d could normally have been easily detected. Although the numbers are small, this implies reduction of initial periods probably during rapid mass-loss in the intermediate LBV phase via a common-envelope mechanism. This is especially necessary in the 1.9 and 3.0 d systems, the shortest known for any WC + O binaries.

Unfortunately, all three WC binaries in the LMC have close visual companions, that could not be excluded in the analysis, thus rendering the mass estimates unreliable, even before dealing with estimating the orbital inclination. However, the SMC WO + O binary does not appear to be obviously affected in this way, even if it is located within the open cluster NGC 602c. Thus its mass ratio M(WO4)/M(O4V) = 0.27 is probably reliable and low, as expected for a system in which the original primary has evolved as far as WO via extreme mass loss. However, this (non-eclipsing) system still needs an estimate for its orbital inclination. This has been attempted with moderate success from WWC by St-Louis et al. (2005). Another attempt using broadband polarimetry is in preparation and will be published elsewhere, both for this star and two of the WC4 binaries (Br 22 and Br 32; Br 31 was omitted, because it is dominated by the light from a bright blue supergiant not involved in its short-period orbit).

All 4 WC/WO binaries show moderately strong, phase-dependent WWC effects in some of their optical emission lines (e.g. CIV 5802/12), as well as FUV lines for the 3 binaries, Sand 1, Br 22 and Br 32, observed with FUSE (St-Louis et al. 2005; Boisvert et al., in prep.). However, of particular interest is the behaviour of Br 22 in the CIII 5696 line, which is ∼80% dominated by strongly phase-dependent WWC emission. None of the other two WC4 binaries shows enhanced CIII 5696, probably a result of their shorter period (and thus orbital separation) with P = 1.9 and 3.0d for Br 32 and Br 31, compared to P = 14.9d for Br 22. (In the Galaxy, the (also reclassified) WC4 + O7 P = 14.3d binary WR9 shows similar behaviour to Br 22.) In the former, the winds collide at lower speeds when they are hotter, yielding lower compressions at higher temperatures, which probably disfavours the formation of CIII 5696 downstream in the shock-cone flow. Unfortunately, while the WWC model of Lührs (1997) for the CIII 5696 emission excess in Br 22 did fit the data well, it was degenerate in (thus providing no information on the) orbital inclination, although Falceta-Gonçalves et al. (2006) did claim otherwise in their attempt to extract its WWC parameters.

3.2. *WNE Stars*

Among the 11 WN stars in the SMC, 9 are WNE (WN3-5) and two have WN6 types, based on the Smith et al. (1996) system. We refer to all as WNE anyway, as they were in previous catalogues. All the single stars and even two of the four binaries, SMC/WR3 and WR5, contain H in their spectra. Blending by the supergiant O companion was too strong to be certain of H content in the WN components of the other two binaries (SMC/WR6 and WR7), although they, too, may very well contain significant H.

As for the WC stars in both MCs, the orbital periods of the SMC WNE stars are all below 20d, and easily detectable. These systems are all significantly brighter than their single counterparts, which form a similar-slope sequence in M_V as (although somewhat brighter zero-point than) their Galactic counterparts, going from $M_V = -4$ for WN3 to -6 for WN6. Of special interest is the binary SMC/WR5 = HD 5980, which is discussed in more detail by Koenigsberger & Moreno (2008). It consists of an Of/WNLh primary, which underwent an LBV-like eruption in 1994, and a WNE companion in a 19.3d orbit with e = 0.3 and deep double eclipses. It also shows strong WWC effects, although the stellar masses are still poorly constrained.

Only three SMC WR stars have positive detections in X-rays with Chandra, all binary (WR5, 6, 7). Not surprisingly, WR5 is the most luminous (L_X = 1.2 10^{34} erg/s) and hardest.

As for the LMC, our uniform spectral survey shows the WNE sample to be a mixed bag, with a smaller fraction than those in the SMC showing intrinsic H in their spectra, but a larger fraction than in the Galaxy. In contrast with the SMC, many of the LMC WNE stars have broad lines, much like their Galactic counterparts. Nine binaries, varying from certain to suspicious, were found, all with periods below 40d.

Among the 9 binaries, four are eclipsing, all discovered for the first time on the basis of MACHO and OGLE data combined with our spectral data: BAT99-19 (WN4b+O5:, P = 18.0d), BAT99-64 (WN4o+O9:, P = 37.6d), BAT99-71 (WN4+O8:, P = 2.33d) and BAT99-129 (WN3(h)a + O5V, P = 2.77d). The last of these has the deepest eclipses and was the subject of a recent detailed study (Foellmi et al. 2006; Antokhin & Cherepashchuk 2007). In fact, BAT99-129 is an extragalctic counterpart of the well-known Galactic eclipsing binary V444 Cyg (WN5 + O6, P = 4.2d). With i = 78 ± 2°, the masses in BAT99-129 turn out to be 15 ± 2 $M_\odot$ for the WR star and 25 ± 2 $M_\odot$ for the O star (compared to 9.3 ± 0.5 & 27.9 ± 1.1 $M_\odot$ in V444 Cyg, WN5 + O6III-V: Marchenko et al. 1994). The O-star mass in BAT99-129 seems low compared to recent models. Both stars in this system probably evolved from progenitors in the range 20–40 $M_\odot$, after significant mass-loss and angular-momentum loss from the system to reduce the orbital period to its present low value. Spectroscopic observations at secondary eclipse (O star in front) are being used to probe the sizes of the WR line-emitting regions in absolute units (see Foellmi et al. 2006).

Several of the apparently single LMC WNE stars show rather strange light curves. The most intriguing is for BAT99-26 (WN4b) with semi-regular (∼200 d) 0.1 mag outbursts of unknown origin.

From the MC work on the WNE stars, Foellmi et al. (2003a,b) proposed a new evolutionary definition of massive stars, guided in large part by the presence of hydrogen in the WR winds. These include, in order of time: eO (in core H-burning CHB: O, Of, WN6, WN7), eOW (in shell H-burning SHB: RSG, LBV, WN9-11), eWNL (beginning CHeB: WN8, WHEh) and 2WNE (CHeB: WNEb). This scheme allows one to understand how the SMC WNE stars can contain significant H, unlike their Galactic cousins.

3.3. *WNL Stars*

These are generally the most luminous of WR stars, in many cases because WNL stars are still in the CHB phase, sometimes even on or near the Main Sequence. In the latter case, it is their extremely high luminosities that drive the strong winds that yield the WR signature of broad emission lines in the optical.

Among the 41 WNL stars studied spectroscopically in the LMC using traditional techniques at 2 m telescopes, eight were found to be certain binaries, with 6 systems having periods in the range 2–5d, and two systems with P = 92.2d (BAT99-99, WN5h:a) and 158.8d (BAT99-119 = R145, WN6(h)). One system, BAT99-92 has been returned to the WNE category, while two other stars fall in the "possible binary" category. Note that, as for all the WNE stars, we have reclassified all the non WN10-11 WNL (or WNL-like) stars from the BAT99 catalogue in the Smith et al. (1996) system without any difficulty. This was important in order to gain a homogeneous overview and reveal the presence or not of significant H in the winds.

Among the six certain binaries, all are evenly distributed within the WN5-7 types, while no binaries were found within the WN8-11 sample. This appears to be quite significant, as noted in a preliminary way by Moffat (1989), since the narrower strong emission lines of the latter subgroup should easily allow their detection as binaries, if there were any. Curiously, the binary frequency among WNE stars is also very low (only one known) among the 10 hottest (WN2-3) subtypes. This would imply that WN binaries occur most frequently among WN4-7 subtypes. The binaries are also generally brighter than the single counterparts at all subclasses, although some individual single stars can outshine some binaries.

From our AO/IR spectroscopic results for R136, we find that none of the 6 WNL stars (R136 a1, a2, a3, a5, b, c) there shows evidence for short-period binarity, nor runaway properties. Especially for the most central WN5h stars R136 a1, a2, a3, a5, this is in stark contrast with the core of the Galactic clone object NGC 3603, in which 2 of the 3 WN6ha stars, all central, are short-period binaries.

In contrast with the MC WC stars, the LMC WN stars (WNE combined with WNL) show that HeII 4686 RVs approach the LMC value for the narrowest lines, with all broader-line systems (FWHM $>$ 1000 km/s) showing a $\sim$60 km/s redshift (with large significant scatter), probably as a result of the line formation process in an accelerating wind. Two LMC WN stars appear to have relatively high (runaway?) RVs: BAT99-12 (the stronger case with RV $\sim$650 km/s cf. 280 km/s for the LMC) and BAT99-55 (RV $\sim$140 km/s).

Still comparing all the LMC WN stars, hotter, more compact WN stars tend to have faster winds on average, with FWHM (HeII 4686) ranging on average from $\sim$400 km/s for WN9-11 stars through $\sim$1200 km/s for WN5-6 stars, to $\sim$2400 km/s (with considerable scatter) for WN2-4 stars. Binary WN stars show no significant difference in FWHM from their single couterparts. Finally, hotter WN stars have stronger lines on average, although the scatter in EW is very large.

Among detected LMC WN stars, L_X appears to be higher on average for WNE stars than WNL stars, with little if any excess due to binary presence. With L_X $\sim$$10^{35}$ erg/s, the two apparently single stars BAT99-116 and -101/102 (but probably only one of these blended stars) clearly stand out. These stars may be close binaries with accreting, compact companions.

Two bright WNL stars stand out, both in 30 Dor, although far from the central dense cluster R136: R144 = BAT99-118 (WN6h), the brightest known WR star anywhere, and R145 = BAT99-119 (WN6(h)), only $\sim$0.5 mag fainter intrinsically. Based on our current RV data combined with those of Moffat (1989) and previously unpublished broadband polarization data, we find that R145 is a long-period (158.8d), elliptical (e = 0.7) binary, while R144 may also be a binary but currently lacks repeatibility to prove this. For R145 we were unable to convincingly see the companion on any given spectrum, so we devised a technique of shift-and-add of the individual spectra into the expected frame of the companion, most likely an O-type star, moving in anti-phase with the known primary orbit, as a function of RV amplitude K(O). We found a clear best K(O) value at maximum line-depth after shift-and-add, that led to minimum masses M $\sin^3$ i = 126 $\pm$ 32 and 55 $\pm$ 21 $M_\odot$. This makes the WR star in R145 the most massive star weighed, surpassing either WN6ha component in the Galactic binary WR20a with 83 $\pm$ 5 and 82 $\pm$ 5 $M_\odot$, or the primary WN6ha component in NGC 3603/A1 with 114 $\pm$ 30 $M_\odot$. However, with $\sin^3$ i = 0.25 in R145, the masses become even much higher. We are currently in the process of verifying this result. R145 also shows strong WWC excess in HeII 4686, increasing in strength around periastron passage somewhat more steeply than with 1/r (r is the orbital separation), as expected from adiabatic WWC theory (Usov 1992). Both of these stars have L_X $\sim$ 1–2 10^{33}

erg/s, which is not especially high, although could be phase dependent, increasing at periastron. We note that the polarization data for R145 lead to a mass-loss rate of 3 10^{-4} $M_{\odot}$/yr for the brighter WR component. This value is comparable to the value 1.5 10^{-4} $M_{\odot}$/yr derived by Crowther & Dessart (1998) from spectral fits for R144, where they did not allow for its possible binary nature, nor the increased values of T* and L for the WR star due to clumping and blanketing.

4. SUMMARY OF HIGHLIGHTS

The most important findings of this study can be summarized as follows:

- The binary frequency of WR stars does not appear to vary with ambient metallicity, implying that RLOF is not important in most WR stars and that the presence of a massive star in a binary does not enhance its probability of becoming a WR star.
- Very short period, evolved (i.e. post-LBV) WR+O systems were probably formed via CE evolution involving rapid expansion during the LBV phase, with significant mass-loss from the system.
- Wind-wind collision effects are strongest in WR+O binaries with periods in the range 2-3 weeks.
- Significant amounts of H are seen in WNE stars at lower Z; this may be related to such stars having lost less of their initial angular momentum and having weaker winds than their cousins at higher Z.
- WN5-7ha stars are little evolved off the H-burning Main Sequence and are likely the most massive stars.

5. FUTURE

Of particular importance in my view would be the following follow-up studies:

- Detailed studies of eclipsing WR systems to provide absolute geometric constraints.
- Detection and quantification of the (mostly so-far neglected) companions in the binary systems.
- Improved orbits.
- More work on the brightest stars in R136.

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DISCUSSION

G. Rauw - Concerning the debate about WNLha stars or O2–O3 stars being the most massive MS stars, I would like to emphasize that the distinction between these two categories is quite difficult to make from their spectra in binary sytems. In WR20a, for instance, some of the emission lines that lead to the WN6ha classification actually forms in the wind-wind collision zone rather than in the winds of the individual components.
A. Moffat - Sure, but you have to take the lines that are least (or not at all) susceptible to wind-wind collision effects. In WN6ha stars, lines of NIV 4058 and NV 4603/19 fall on this category and they are sensitive to spectral type as well.
M. Corcoran - The short period binaries must be co-rotating. Do you see any evidence of rotational variability in the line profiles?
A. Moffat - The quality of our "discovery spectra" preclude any refined study like that.
A. Maeder - Tony, if you reduce the mass loss rates by a factor of 10 and in addition you say that the Roche lobe overflow is unimportant, how do you form the WR stars? In addition, the LBV scenario has no confirmed dependence on Z.
A. Moffat - Well, André, you tell me! The fact that the LBVs seem to occur at all Z suggests that they might be the ideal stages to do the lion's share in removing H-rich outer layers so that an O star can pass to a (classical) He-burning WR star.
N. Smith - The very high masses of 80–120 $M_{\odot}$ that Tony showed for these WNL stars shouldn't be taken lightly. There are many clues that these stars are intermediate between O stars and LBVs – probably mid or late stages of core H-burning. Yet they all seem to have very high masses. These are giving us another clue that the most massive stars reach the end of the main sequence without shedding much of their mass in line-driven winds. By the way I have a hardtime believing that NGC 3603 and R136 are only 1 Myr old.
A. Moffat - I am not sure that all these WNL stars (actually WN5-7ha) are at the end of the main sequence. Sometimes (e.g. in NGC 3603 in the Galaxy) the WNLha stars are stright up from the brightest cluster O2-3 stars, i.e at similar $T_{\rm eff}$ and significantly brighter (by 1 mag in the case of NGC 3603). The 1 Myr age refers only to NGC 3603, based on pre-main sequence fitting (Brandl et al. 1999) and the size of the central cavity pushed back by the combined winds of the central hot stars in the cluster.
P. Massey - Back to these very high mass Wolf-Rayet stars – in the R136 cluster there are stars that were called WR stars but these were hydrogen rich and not necessarily N rich. We called these "Of stars on steroids" – just very luminous stars whose wind characteristics make them look a bit like WR stars.
A. Moffat - We reclassified some of these extreme Of stars using the WN system of Smith et al. (justified when stars have emission lines that are stronger than the strongest absorption lines – that was always the distinction between Of and WN) and found them to fit well in the WN system. Whatever they are called, they have emission lines that are stronger than normal Of stars and owe their WN-like emission to extreme luminosity, which drives a strong wind.
H. Zinnecker - I am impressed that your VLT/Sinfoni data do not reveal any new short period massive binaries in the R136 core, while there are a few tight massive eclipsing binaries further out (Massey et al 2004). Any clue why is this so?
A. Moffat - This may be due to small numbers.
N. Walborn - I agree with Nathan. There are 100 $M_{\odot}$ O2-3 stars, and I believe that the similarly massive WNLs are more evolved descendants of such, still H core burning but more highly mixed. 30 Dor, NGC 3603 and Trumpler 16 that contain such stars are $\sim$ 2 Myr old. LH10, the core of NGC 346, Tr14 and Pismis 24 that do not, are $\sim$ 1 Myr old.
A. Moffat - Be careful with small number statistics! Anyway, the most luminous WNLha stars are probably more massive than the most luminous O2-3 star (on average) i.e. in the the 100–150 $M_{\odot}$ range.
G. Koenigsberger - We proposed that periastron passages should be associated with increasing line emission; it appears like your excentric system is another example of this phenomenon.
A. Moffat - The observed behaviour of the excess emission in HeII 4686 in R145 (30 Dor 158 days binary) seems compatible with colliding winds theory for the adiabatic case. It does not appear to require any additional energy input such as tidal effects, if we accept the model.
N. Walborn - CIII 5696 is a selective emission line in O-type spectra, so the possible contribution of narrow feature (antiphase for binary companions, stationary for visual) in the variable profile should be considered (perhaps weaker than the wind or colliding wind contribution, of course).
A. Moffat - If the feature was there, we should have seen it at constant RV in the frame of the O star, but we didn't in Br 22 or WR 9 (in the Galaxy). This is probably compatible with the O stars being main sequence or (sub)giants.