MASSES OF MAGELLANIC WOLF-RAYET STARS: MASS LOSS AND EVIDENCE FOR A WR SUBCLASS VS. MASS RELATION

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Abstract: New spectroscopic observations in the LMC/SMC combined with published data on Galactic WR stars lead to a correlation between mass ratio, M_{WR}/M_O, and WR subclass. As a consequence of this and their high mass loss rates, WR stars probably evolve from cool to hot ionization class in a way which depends on the metallicity.

Observed mass loss rates for WR stars are so high ($2\text{-}6 \times 10^{-5}\ M_\odot\ y^{-1}$ for all subclasses: Barlow et al.1981) that these stars will lose about half of their original mass during the entire WR phase ($\sim 3 \times 10^5$y), most of which is assumed to represent the core He-burning stage in the advanced evolution of massive stars (cf.model calculations of Vanbeveren 1981). The actual fraction of mass lost is expected to increase slightly with the initial metallicity and so be somewhat larger in the Galaxy than in the Magellanic Clouds. It is thus of great importance to obtain masses of a large number of WR stars in order to put constraints on the influence of different metallicity and extreme mass loss on the late evolutionary stages of massive stars.

Among the WR stars in the Galaxy, only about a dozen double-line spectroscopic orbits are known (Niemela 1981), leading to mass estimates within the usual factor $\sin^3 i$. I have attempted to extend this sample by searching for orbits among the 20 brightest LMC/SMC WR-stars besides the bright central core of 30 Dor. Over 300 image tube spectra at 45 Å mm^{-1} obtained recently at CTIO, Chile, lead to the following results (details to be published elsewhere).

Ten of the stars observed, all in the SMC, are of the luminous subclasses WN6-8 ≡WNL. Of these, 60±30% are (mainly single-line) spectroscopic binaries, compatible with the binary frequency of Galactic WNL stars (Moffat and Seggewiss 1979) and O stars (Garmany et al.1981). Thus, mass transfer in a binary system is confirmed to be of minor importance compared to the strong stellar wind in forming the bright WNL stars. Among the other ten WR stars, all of lower luminosity (WN3-5 ≡ WNE and WC), double-line orbits were obtained for five in the LMC and all three in the SMC.

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 301–305.

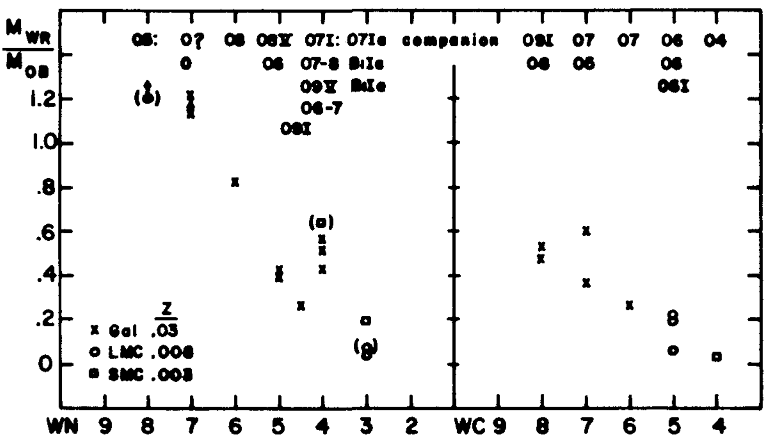
One could now proceed by estimating the absolute masses of the WR components as was done for the Galactic SB2's by Massey (1981) who found typical masses of $\sim 15 M_{\odot}$ for WNE, WC stars and more for WNL. But such values are plagued by uncertainties in the orbital inclination and/or assumptions regarding the mass of the OB companion. An alternative is to consider the mass ratios, $Q \equiv M_{WR}/M_{O}$, which are independent of these factors and offer the additional advantage that, to a first approximation, they can be expected to reflect the relative total mass loss of the WR stars during the WR-phase, regardless of the original (large) absolute masses. The reasons for this are primarily that (a) the mass ratio just before the WR phase (binary O-star) was probably not too far from unity (Garmany et al.1981; de Loore 1981) and (b) the mass loss of the presently observed O companion will be very small compared to that of the WR star.

A plot of the observed Q-values for all known WR SB2's versus spectral subclass is shown in the Figure. Two striking features are evident:(1) the LMC/SMC mass ratios are significantly lower than those in the Galaxy, but at the same time they refer to hotter subclasses. This cannot be due to differences in metal content since one would expect lower mass loss rates and thus higher Q values in the LMC and especially the SMC, on the average, contrary to the observations; also, Hellings and Vanbeveren (1981) show from model calculations that massive SMC stars differ only little from Galactic stars prior to the WR phase. Nor can it be due to tidal effects on the emission lines since no correlation is evident between the mass ratios and the period. (2) Lumping all the data together we thus see a clear correlation of mass ratio with spectral subclass for either WN or WC, such that the hotter subclasses tend to have significantly lower mass ratios. Note that WNL stars resemble most the O and Of binaries (cf.Garmany et al.1981) in this respect, not surprisingly since Of-stars are likely their immediate progenitors (Conti 1976).

Coupled with the large observed mass loss rates for WR stars, the fairly tight trends in the Figure force one to conclude that WR stars evolve along the sequence WN8 → WN3 and WC8 → WC4. Although the overall starting point is not clear from the Figure, it seems likely to be among the more massive WNL stars. One can speculate that how far a WR star proceeds along the sequence and at what point a WN star becomes WC depend on two factors primarily: the mass loss rate and, not independently the metallicity Z. In the Galaxy, where the mean Z is higher, the ratio of the number of WC stars to WN stars is close to unity compared to much lower values in the LMC/SMC where the slightly lower mass loss rates retard the peeling-off process, and where the central He-burning cores are probably smaller and denser, by analogy with H-burning stars (Hellings and Vanbeveren 1981). This may lead to delayed exposure of the inner C- enriched layers in LMC/SMC WR stars causing the transition WN → WC to occur at lower mass and, thus explaining the complete absence of the more massive WC stars (WC7,8,(9?)), which abound in the Galaxy. In fact, the SMC contains only one very hot WC star of very low mass. On the other hand, a relatively large number of WN stars may reach the frequently encountered WN3 stage in the LMC/SMC (rare in the Galaxy) before going over to very low mass WC stars, if they succeed in doing so at all, before the WR phase ends.

It is noted that the masses of the hottest WR subclasses (WN3,WC4, 5) are very low, ~ 4 $M_\odot$, assuming a typical O-companion mass of 40 $M_\odot$ (Massey 1981). This is near the minimum for a He-star to evolve into a collapsed object (cf. van den Heuvel 1976). If the WR phase and its high mass loss rate continue, WR stars could conceivably terminate in some cases as white dwarfs. Furthermore, it is very unlikely that these low mass ratios ($\lesssim$0.2) can be produced in a massive binary just after Roche lobe overflow (de Loore 1981); they require the very large wind mass loss rates observed during the WR phase.

In summary, the WR subclass-mass relation noted here is consistent with the peeling-off process in which we are probably seeing a progressively denser and hydrogen poorer, hotter wind as the dense, hot core is approached. The residual scatter in the observed relation may be due to imperfections in the classification of the WR subclasses and some degree of spread in initial mass ratios or absolute masses. It will be interesting to see whether more accurate determinations of the intrinsic luminosity reveal a similar trend with subclass beyond the only fairly secure fact that the WNL stars are more luminous than the others.



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DISCUSSION

CONTI: I'm a little worried about the very small mass ratios you find (those less than 0.1). Doesn't this lead to uncomfortably small WR masses?

MOFFAT: This occurs in three cases, one of which is based on an incomplete orbit (AB 8). In the others, the OB companion is a supergiant and may be very massive ($\lesssim$ 100 $M_\odot$?). With a ratio $M_{WR}/M_{OB} \simeq 0.05$, this gives $M_{WR} \lesssim 5 M_\odot$, which is in line with the theoretical He-star masses left after considerable mass loss (cf. Vanbeveren, this volume) based on observed mass loss rates for WR stars (cf. Barlow, Smith and Willis this volume). This also supports the idea that the hotter WR stars could have evolved by large mass loss from the more massive, cooler WR stars.

SAHADE: Your conclusions are based on a set scenario that today is considered by many as an established fact, something that it is far from true. I would feel happier if other alternatives were considered. There are quite a number of facts that are there and that we should take into account in building up possible scenarios for the evolution of the WR stars.

MOFFAT: The scenario with evolution from one WR subclass to another is quite new and is considered as the most likely one with the present data.

LORTET: We will present a poster tomorrow on the localization of different subtypes of Wolf-Rayet stars in the Galaxy. This study and a similar one for the Large Magellanic Cloud would certainly put constraints on possible evolutive scenarios: it well be interesting to check that the proposed scenarios are compatible with these observational data.

MOFFAT: Certainly factors like the initial mass, age and metallicity which vary from place to place in the Galaxy and LMC/SMC will determine in what part of my diagram, M_{WR}/M_O versus WR-subclass, a WR-star enters. But wherever it starts, it must evolve in the way I indicated, provided the mass loss rates are sufficiently large and that my one-to-one relation between M_{WR}/M_O and subclass is universally valid.

SERRANO: Have you also seen this difference in M_{WR}/M_O between stars in the directions of the galactic center and anticenter?

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MOFFAT: No, I have not been able to do it yet. It is a very time consumming job.

MAEDER: People frequently refer only to one unique evolutionary scenario for forming WR stars. But we may suspect that there are multiple evolutionary paths for making such objects: the post red supergiant evolution would be one of the possibilities in addition to the nice scenario proposed by Peter Conti some years ago.

MOFFAT: If more data on mass ratios in WR+OB binaries confirms the suggested relation between M_{WR}/M_O and spectral subclass, the high mass loss rates observed from WR stars will force us to accept an evolution from one subclass to another such as I have indicated. I was not concerned here with how WR stars are formed, merely how they evolve once formed, except for the case of the linear WN7 subclasses which probably evolve from luminous Of stars (both show similar spectral properties, despite difference in degree of emission-line strenght).

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