WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS: SPECTROSCOPIC BINARIES AND MASSES

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ABSTRACT. Repeated spectra to V-mag 13.0 (13.5) have been obtained since 1978 for the 25 (5) brightest WR stars in the LMC (SMC). More than half of these are orbiting spectroscopic binaries, mainly SB1 for the luminous subclasses WN6-9, and SB2 for the rest. Together with galactic data, the Cloud SB2's lead to a correlation between mass ratio WR/OB and WR spectral subclass for each of the WN and WC sequences. This correlation is interpreted as an evolutionary sequence in which the peeling-off process of the strong stellar wind exposes successively hotter regions and eventually converts WN to WC at a point in time which appears to depend on the ambient metal abundance.

I. INTRODUCTION

The Magellanic Clouds are ideal laboratories of known, not too large distance for the study of WR stars. The Clouds have been surveyed to relatively faint magnitudes and we can be fairly certain of completeness (Azzopardi and Breysacher 1979, 1980): the LMC contains 101, the SMC 8 WR stars.

Since spectral subclasses have been obtained for all these stars (Breysacher 1981, Azzopardi and Breysacher 1980), one of the next logical steps is to look for duplicity in a complete sample and subsequently estimate the masses of those stars that reveal orbits. Since 1978 I have collected 355 blue optical spectra of the 25 brightest WR stars in the LMC and the 5 brightest in the SMC, using the Carnegie image tube spectrograph at 45 Å mm^{-1} attached to the Yale 1-m telescope at CTIO. ,These stars comprise a broad sampling in spectral subclass and position in the two galaxies. In the LMC the sample contains 13 of type WNL = WN6-9 (10 in the 30 Dor region, including the bright core itself of this giant HII complex), 7 of type WNE = WN3-5 (2 in 30 Dor) and 5 of type WC (none in 30 Dor). In the SMC, the sample contains 4 WNE stars and one WC4 (actually WO; cf. Barlow and Hummer 1982). The only

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obvious selection effect involves the magnitude cutoff ($M_V \lesssim -6$) which favours WNE and WC binaries with bright OB companions. The intrinsically brighter WNL stars are much less affected.

Although this study is still underway, all the present spectra have been analysed and allow a useful evaluation, following a previous one (Moffat 1981). Detailed results are in press for two stars (Moffat 1982a; Breysacher et al. 1982); the rest will be published soon.

II. SAMPLE OBSERVATIONS

For lack of space I will briefly describe only three stars, one each from the sequences WNE, WC and WNL, for which reliable orbits have been obtained: (a) For the WN3 + O7I binary AB6 = R31 in the SMC (Moffat 1982a), the only measurable emission feature is due to HeII 4685; other WR lines are drowned out by the bright O-component. Its radial velocity varies in close antiphase with the mean absorption line velocity. For a circular orbit of period 6.861 days, the masses are $M_{WR} \sin^3 i = 6.4 \pm 1.7\ M_\odot$ and $M_O \sin^3 i = 37 \pm 13\ M_\odot$. While the minimum O-star mass is reasonable, the mass ratio $Q \equiv M_{WR}/M_O = 0.17 \pm 0.03$ is low compared to galactic WNE + OB binaries (Massey 1981). (b) The LMC binary FD21 = R90, WC5 + O6, yields an orbit with e = 0, P = 12.29 days and masses $M_{WR} \sin^3 i = 4.8\ M_\odot$ (based on CIV 4650) and $M_O \sin^3 i = 20.7\ M_\odot$. Again, the mass ratio $Q = 0.23 \pm 0.07$ is small. (c) The single-line WN7 binary FD 24 = HD 36063 gives e = 0, P = 1.9075 d and a mass function $f(m) = 2.5 \pm 0.3\ M_\odot$, much like the galactic WN7 binary CQ Cep with e = 0, P = 1.641245 d, $f(m) = 5.1 \pm 0.3\ M_\odot$ and an invisible O-companion (Leung et al. 1982). However, FD 24 has a continuum light curve with only one shallow minimum per cycle compared to CQ Cep's two nearly equal, deep minima. In this respect, FD 24 resembles more the galactic runaway WN7 binary HD 197406 with a suspected compact but moderately massive companion (Moffat and Seggewiss 1979, 1980). FD 24 is situated on the outer fringe of the LMC.

Four stars deserve particular attention. In the SMC, the WN4 + O7I eclipsing binary HD 5980 = AB5 shows strong phase-dependent emission-profile variations (Breysacher et al. 1982), while the intense OVI 3811/34 emission feature in the WO + O4 binary (or possibly triple: Barlow and Hummer 1982) AB8 = Sk 188 shows bizarre behaviour: the WO-orbit is based on CIV 4650. In the LMC, the WN6 + WC binary FD 68 = R 140 reveals an orbit for the WN component (C-lines are not evident on the present spectrograms); if this is a genuine WR pair (it has a 1" visual companion), the mass function implies a mass ratio WN/WC ∿ 5. Finally, the WN6 component of the 30 Dor core shows periodic velocity modulations (cf. Moffat 1982b). This implies either a single luminous WR-component in orbit about some unresolved star, or radial pulsation of a single supermassive star (cf. Cassinelli et al. 1982).

III. BINARY STATISTICS

The Table gives a résumé of the preliminary results of the binary frequency and mass ratios. Note that somewhat over half the WNL stars may be binary, much like the situation in the galaxy (Moffat and Seggewiss 1979). Presumably the high-luminosity WNL stars have strong enough winds to evolve without the aid of a binary companion. On the other

Table: Observed numbers and mass ratios ($Q \equiv M_{WR}/M_O$)

	WNL		WNE		WC	
Binary nature	No.	Q	No.	Q	No.	Q
Constant RV	4^+	-	0^+	-	0^+	-
WR + OB	$4^{(a)}$	1-2	6^+	.03-.22	5^+	.04-.30
WR + c	$5^{\pm(b)}$	5-15	5^-	2-10	1^-	7

Notes: c = low-mass (compact?) companion; + (-) implies lower (upper) limit; (a) OB-component visible in only one case; (b) includes FD68, WN6 + WC.

hand, virtually all the lower-luminosity WNE, WC stars observed show binary characteristics. In order to check whether this is due to magnitude selection (see above), I intend to study fainter stars during the next MC season.

IV. MASSES

The determination of masses of WR stars in double-line binaries is plagued by two factors: (a) uncertainties in the orbital inclination i and (b) errors in the velocity semi-amplitude, both of which become amplified by high powers in the expression

$$M_{WR} = k\ (1-e^2)^{3/2}\ P\ K_O(K_{WR} + K_O)^2/\sin^3 i, \text{ where } k = \text{a const.}$$

The mass ratio $Q \equiv M_{WR}/M_O = K_O/K_{WR}$, on the other hand, is independent of i and less sensitive to errors in the K's.

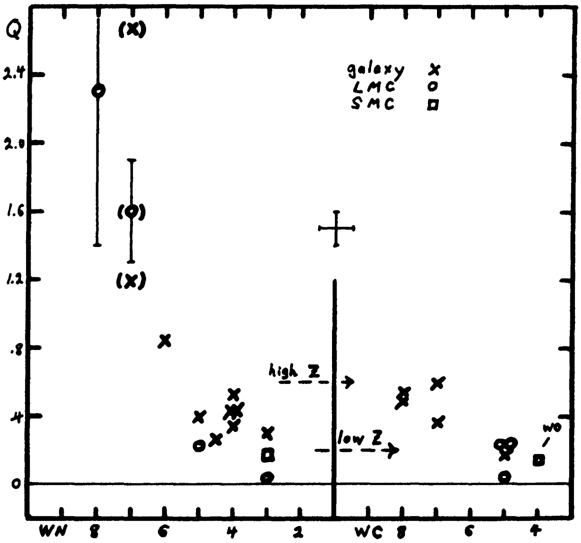

Figure: Mass ratio $Q = M_{WR}/M_O$ versus WR-subclass for all known well-studied SB2's. The error cross is a typical 2σ estimate for WNE, WC.

In the Figure, we look for a dependence of Q on spectral subclass (∿ ionization temperature) for reliable binaries in each of the WN and WC sequences. Galactic data are added from van der Hucht et al. (1981) except for the complex quadruple system GP Cep which is omitted, CV Ser for which a more recent Q is available (Massey and Niemela 1981), and two recently studied binaries HD 320102 and HD 63099 (Niemela 1982), which are added. Points for the WN7 binaries CQ Cep and HD 92740 are in parentheses since the detection of the O-component is uncertain. Also, the mean Q for 3 single-line WN7 binaries in the LMC is added in parentheses, after assuming $M_{WR} = 40\ M_\odot$ and $i = 60^o$. We note the following:

(1) Within the limits of the errors in either axis, there appears a fairly clear trend of Q with spectral subclass for each of WN and WC, in the sense that Q decreases for the hotter subclasses. A similar plot with the estimated masses M_{WR} (cf. Massey 1981) instead of Q shows a hint of a similar trend with a large amount of scatter (see above).

(2) The trend for WC is less noisy, possibly related to the fact that WC stars appear to form a more homogeneous sequence (Leep 1982).

(3) Despite limited overlap, and differences of up to 10x in the metallicity, the MC's and the galaxy together show the same overall trend.

(4) There exist some (espec. hotter) WC stars whose mass ratios are inferior to those of some (espec. cooler) WN stars.

(5) There is no apparent trend of Q with the luminosity or mass of the O-component.

(6) The trend in the Figure is not likely the spurious result of a decrease in K_O by the presence of a close ($\lesssim 1''$), second O-star in the spectrograph slit. From the 30 MC stars, 4 such cases are omitted from discussion; this fraction is like that expected on the basis of observed galactic visual binaries projected to the MC distances.

(7) The trend is also not likely to be caused by an increase of K_{WR} by streaming effects in the WR wind: a plot of Q vs. orbital separation (or P) for the WNE, WC stars reveals no correlation.

The correlation of Q with subclass could represent a fixed sequence in which the present Q is determined uniquely by the initial masses of the WR star and its O-companion. However, it then becomes difficult to understand what makes a star become WC instead of WN.

In view of the extremely high mass-loss rates ($\dot{M} \sim 3 \pm 1 \times 10^{-5} M_\odot y^{-1}$ for all WR-subclasses: Abbott et al. 1982), a more appealing interpretation is that of an evolutionary sequence. Presumably these $\dot{M}$'s persist during the whole WR phase ($\sim 3 \times 10^5$y as a massive He-star: Vanbeveren 1981), binary or single, and the star can lose a total of ~9 ± 3 $M_\odot$. This is a significant fraction of the mean mass of galactic WR stars ($\sim 20\ M_\odot$: Massey 1981). Therefore, with a mass ratio at the beginning of the WR phase, $Q_o \gtrsim 1$, as for WNL stars (see Figure) or similar to evolved O-stars in binaries (de Loore 1981), the mass of the WR star will decrease with time, carrying the WR star down the Q-spectral sequence for WN stars. The O-star mass will change very little in this time scale. Eventually, when triple-α products are brought to the surface, a WC star emerges. Indeed, abundances in WR envelopes are compatible with removal of outer layers and exposure of nuclear processed material (Willis 1982).

Apparently, if the (rapid) transition from WN → WC does take place at all, it tends to occur at a higher Q-value in the galaxy than in the

MC's, possibly due to differences in metallicity. Schematically we suggest the following trend:

galaxy: WNL → WN5 → WC 9,8 → hotter WC?

MC: WNL → WN5 → WN 4,3 → WC5.

This would explain the relative paucity of WN3,4 stars in the (inner) galaxy, where Z is largest and where WC8,9 stars abound. Conversely, in the MC's more time is spent in the WN stage, often reaching WN3 before transfer to the common WC5 subclass, with a lack of WC 7-9. This also accounts for the lower WC/WN number ratio in the MC's than in the galaxy.

However, the physical reason for the metallicity effect is not obvious. If $\dot{M}$ is lower for lower Z (Abbott 1982), one might expect WN stars in the MC's to pass more slowly to lower masses, perhaps never reaching them, either as WN or WC. It is doubtful that the internal structure plays a role according to the models of Hellings & Vanbeveren (1981). Observations of $\dot{M}$ for MC WR-stars are urgently needed.

The evolutionary trend presented here also predicts an age progression increasing from WNL through WNE to WC. Assuming that the ejection of observed ring nebulae is related to the formation of the WR phase, just such a trend is found in the nebular expansion ages for galactic WR stars (Chu 1981).

It is not clear how much of the scatter in the Q or M_{WR} versus subclass diagrams is intrinsic. Possibly Q is more appropriate than M_{WR} because it reflects the relative mass lost from the WR component, which depends on the degree of peeling down to hotter layers. Thus, while there might be large spread in M_{WR} for a given subclass, the mass ratio appears to be more confined, even at the beginning of the WR phase.

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DISCUSSION FOLLOWING MOFFAT

Turner: Is it not possible that part of the dependence of mass ratio on WR spectral type might be due to the fact that the early-type WR stars are less luminous than the late-types? With your magnitude limited observations for Magellanic Cloud objects, it may be that you can only detect the early-type WR stars if they have a massive, luminous O type companion to make them accessible to spectroscopic observations.

Moffat: Yes, this may be true; I have observations and will be getting more of the fainter WNE stars. However, there is no apparent correlation of m(WR)/m(O) with the spectral class (and in some cases luminosity) of the O companion for any of the observed double-line binaries.

Massey: Are you worried about pair blending problems in the absorption line curves for your LMC and SMC stars? For instance, I seem to recall that Walborn saw double absorption lines in his spectrum of AB6 (=SK108). I think you have to check the spectral luminosity indicators of the O stars to see if they are consistent with the observed M_V to be sure how many stars you have on the slit. You also may be able to sort this out from the emission-line mass functions, at least statistically.

Moffat: Taking the Galaxy as an example and moving its known WR stars and their close visual companions to 55 Kpc leads on to expect about 8% close visual binaries ($\leq$ 1") in the LMC. Four of 30 WR stars (13%) observed here are such visual binaries and are deleted from the discussion. Of course, there may remain individual cases of undeterminable nature. In AB6, Walborn claimed a shadowing of the absorption lines, possibly due to a third absorption-line star. I have checked for consistency in the M_V's but unfortunately blending and drowning effects often prevent an accurate luminosity classification in the O companion.

Underhill: You have leaped to the conclusion that mass and rate of energy generation (= stage of evolution) will result in a unique spectral type. This is not so, and once again I emphasize that a WR spectrum comes from superficial conditions in the star. At present we do not have a theory relating these conditions to the stage of evolution of a star of any mass.

Moffat: My conclusions concerning the evolutionary consequence of the empirically observed mass ratio - subclass relation are based on the presently observed mass loss rates for WR stars, i.e. if we accept the shown (fairly tight) relation between m(WR)/m(O) and subclass, and the mass loss rates, we are forced to conclude that WR stars evolve from one subclass to another as indicated.

Smith: Mike Dopita and I have also been observing HD 164270. We confirm that it is variable in light (by about 0.1 mag) and in line profile. But we are seeing a period of 8 or 9 days, and not 1.7 days.