PROPERTIES OF WOLF-RAYET BINARIES: THE KEY TO UNDERSTANDING WOLF-RAYET STARS

ANTHONY F.J. MOFFAT
Département de physique and Observatoire du mont Mégantic, Université de Montréal, C.P. 6128, Succ. Centre Ville, Montréal, QC, H3C 3J7, Canada

Abstract. It is argued that, with few exceptions, WR stars in binaries are essentially indistinguishable from single WR stars of the same subtype. In particular, mass transfer from one star to the other can be neglected, being completely dominated by the winds and their interaction. Empirical masses and mass-loss rates derived for WR stars in binaries are then examined as typifying WR stars in general; they are used to derive a plausible scenario for the evolution of WR stars.

Key words: stars: hot – Wolf-Rayet – binaries

1. Basic WR parameters and binaries

It is useful to consider WR parameters in two regimes: the core and the wind. The cores can be mainly characterized by the mass M, luminosity L, core radius R_*, and age. The winds can be mainly characterized by the mass-loss rate $\dot{M}$, velocity-distance law $v(r)$, temperature stratification $T(r)$, and chemical composition, although other factors such as clumping, rotation and magnetic fields may play a significant role.

Clearly, without binaries, the mass would be a difficult parameter to obtain. However, many of the other parameters and laws listed above can also be estimated from binaries *with a minimum of assumptions.* The reason for this is two-fold: (a) the orbit is a yardstick and (b) the companion star acts as a probe, illuminating various parts of the wind in its orbit. A good example is the surprisingly shallow $v(r)$ law found on the basis of UV spectroscopic studies of WR stars in binaries (Koenigsberger 1990).

In this review I will concentrate on the masses and mass-loss rates of WR stars, obtained from WR+O binaries. This will be followed by a discussion of the evolutionary consequences.

2. Complications

2.1 Spectral line distortions

The very emission lines that are used to obtain radial velocity (RV) orbits, and hence masses of WR stars in binaries, are susceptible to various perturbations, which are generally stronger in closer systems. These perturbations, *e.g.,* all of which can be seen *together* in the He II 4686Å line of the famous eclipsing WN5+O6 binary V444 Cygni (see Marchenko, these proceedings),

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include: (1) excess emission from the shock cone interaction zone of the two colliding winds; (2) selective atmospheric eclipses; (3) geometric wind eclipses; (4) photospheric OB lines, superposed on WR emission lines; (5) effects due to tidal influence, heating and reflection: these are generally of minor importance *cf.* (1) - (4).

In order to minimize the impact of these effects on the RV orbits, and hence the masses, one should as much as possible: (a) use line flanks to determine the RVs; (b) avoid spectra around phases 0.0 and 0.5; (c) use lines that are: weak, subordinate, symmetric, non-variable, of high ionization, have no OB absorption counterpart and are in good RV antiphase with OB absorption lines. There are no 100% ideal lines, but a line like N IV 4058Å is probably a good choice compared to He II 4686Å for WNL stars (as in the 1.6-day WR+O binary CQ Cep: *cf.* Leung *et al.* 1983).

2.2 Mass transfer *vs.* colliding winds

A crucial question regarding the relevance of binary studies is whether WR stars in binaries behave like single WR stars of the same subtype. The answer to this question depends largely on whether Roche lobe overflow can occur, leading to rapid mass transfer from one star to the other. Among lower mass stars in binaries with negligible winds, this does seem plausible, as the existence of post-transfer, Algol-like systems would testify. However, among the massive stars (that form WR stars), one must allow for the fact that they have *strong winds.* In massive binaries, the observed mass ratios are generally not drastically different from unity (Garmany *et al.* 1980), so that both stars *always* have appreciable winds. During the long-lived main-sequence stage, and once a WR star appears in a massive binary, neither star normally fills its classical Roche lobe; the winds collide mutually to produce a general flow of matter out of the system: there is no (or at least negligible, *e.g.*, even when one wind crashes down on the other star) mass transfer from one star to the other.

When the initially more massive star evolves and leaves the main-sequence, it will tend to fill its Roche lobe. To first approximation (*i.e.*, neglecting hydrodynamical pressure effects in the plasma wind), radiation pressure will distort the equipotential surfaces, such that one no longer has the familiar contact surfaces of the classical Roche potential. Rather, "mass leaving the Roche-lobe filling star can reach a much larger volume surrounding the binary, even for very low initial [wind] velocities" (Kondo & McCluskey 1976; *cf.* also Schuerman 1972, with some criticisms by Vanbeveren 1978). Although many details are still lacking, and in particular one awaits a more rigorous, full hydrodynamical calculation of this problem, it does seem likely for now that mass transfer *per se* in massive binaries does not take place, even when one star formally fills its *classical* Roche lobe. Nevertheless, one should look for empirical evidence one way or the other. In the theoretical community, I already note a lack of consensus, as exemplified by the two following works: Sybesma (1986) notes that "mass transfer in binaries is not important for the formation of WR stars that have a precursor mass in the range $M \geq 35\ M_\odot$, supported by the existence of high orbital eccentricities in long-period WR binary orbits". On the other hand, Vanbeveren (1991) notes that if the spectral type of the OB companion is earlier than about O7, then RLOF and accretion onto this companion *must* have played an important role.

3. Observational data base

I have gleaned from the literature all WR+OB systems (SB2 or SB1h) for which (a) reliable RV orbits exist and (b) mass-loss rates and orbital inclinations are available from light curve and/or polarization analyses. These are supplemented by some of my own (+ collaborators') unpublished work, especially in the Magellanic Clouds. The total sample includes some 25 systems, of varying quality. Details will be presented in separate journal publications.

From the SB2 RV orbits, one normally can extract the masses multiplied by the usual $sin^3 i$ factor. In the case of SB1h, one gets only the mass function; nevertheless, as in the case of single-line WNL SB1 systems, one can still make meaningful statistical estimates of the mass ratio and stellar masses. From the light-curves or polarization curves (*e.g.,* Moffat *et al.* 1990b), one can get i and $\dot{M}$; when combined with $M sin^3 i$, this leads to an estimate of M. Another potentially interesting way to obtain i in some wind-interacting binaries is to study the phase-dependent line profile variations (Lührs 1991), although this has only been applied so far to two systems (see Bartzakos *et al.* these proceedings). Note that the mass ratio in SB2's is impervious to the orbital inclination.

A good example of extracting i and $\dot{M}$ is for the WC7+O7V binary HD 97152 using its light-curve (Lamontagne *et al.* , in preparation) and polarization orbital curve (St-Louis *et al.* 1987). Both techniques yield similar values of i for this star (44^o), and a larger sample of stars for which both methods can be applied yield general agreement with standard errors in each method of typically 5^o.

It is worth noting that another independent method of determining $\dot{M}$ and i from polarization *eclipses* has been applied to V444 Cygni (Robert *et al.* 1990; St-Louis *et al.* 1993). This technique yields similar values to the polarization orbital method.

4. Results

4.1 Masses

Using WR spectral subclass as independent variable, I plot in Fig. 1 (a) the WR to O mass ratio, (b) the WR mass, and (c) the spectral class of the

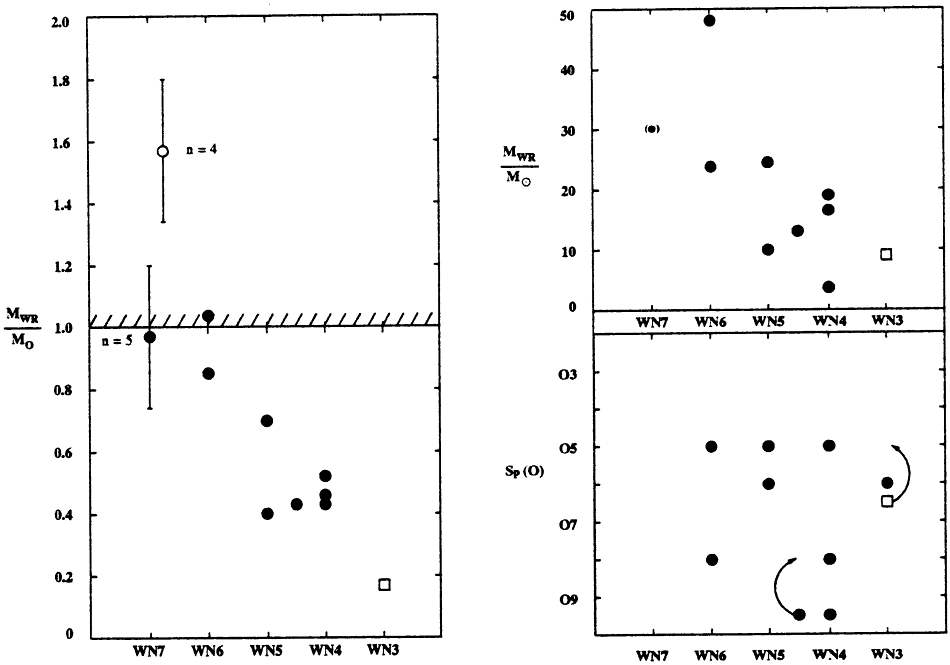

Fig. 1. WR to O-star mass ratio, WR mass and O-star spectral type versus WR spectral subclass for WN members of WR+O binaries. WN7-star mass ratios are based on mass functions and assuming a mean inclination of 60° for an ensemble of stars. The rms errors of this ratio are typically 0.1. Filled circles refer to Galactic stars, open circles to LMC and open boxes to SMC.

O-companion for all studied WN binaries. (Similar plots for WC stars are given by Moffat *et al.* 1990a.) These plots, along with a plot of absolute visual magnitude (which for a given bolometric correction, yields a correlation between mass and luminosity for WR stars, as expected: *e.g.*, Smith & Maeder 1989) *vs.* WR subtype (see van der Hucht *et al.* 1988; single LMC stars are entirely compatible with the Galactic stars, within the scatter), show the following: (a) The spectral type (or the mass) of the O-companion is *independent* of the spectral subclass of the WR star; (b) The mass ratio $Q \equiv M_{WR}/M_O$ (or M_{WR}, with considerably more noise, possibly caused by errors in i) and the luminosity M_V are monotonic functions of the WR subtype, decreasing dramatically towards earlier subtypes of each sequence; and (c) Q and M_V are independent of metallicity (*i.e.*, galactic environment, whether in our Galaxy at $Z_\odot$ on average, the LMC at $Z_\odot/3$ or the SMC at $Z_\odot/10$). The interpretation is as follows: *If* mass transfer to the secondary *did* take place, with accretion by the original secondary, one would expect an *anticorrelation* between the mass of the WR star and the mass of the O star in WR+O binaries. For example, if we started with a WNL+O

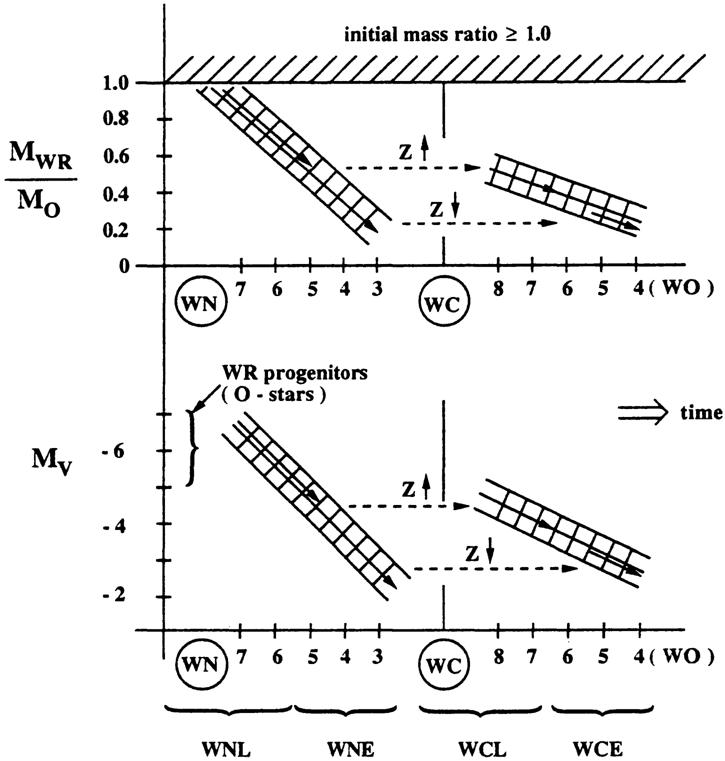

Fig. 2. Diagram showing WR to O-star mass ratios and absolute visual luminosities *vs.* subclass for each WR sequence. These are interpreted as time sequences, starting with mass ratio above unity and high luminosity (like their O-star progenitors), and proceeding continuously to successively lower values, with transition from WN to WC occurring as a function of metallicity.

system with typical masses of 40+30 $M_\odot$, *i.e.*, WNL+O7, we would later see a WNE system with masses of say 10+60 $M_\odot$, *i.e.*, WNE+O3. Such an anticorrelation is excluded by the data. Rather, I claim (*cf.* Moffat 1981, 1982), based only on masses and their continuity with time, that *Q and M_V decrease due to the WR mass-loss peeling-off process* (see Fig.2). Thus, in a sense, Q is a normalized quantity that is a good measure of the *relative evolution* due to mass-loss, going deeper and deeper into the WR stage, no matter what the actual initial mass was. This being the case, a number of important consequences follow, whether for WR stars in binaries or single WR stars:

(i) All WR stars start as WNL, the WR stage which resembles most their Of progenitors. (These may be on average somewhat more massive and luminous in low-Z environments, where the opacity driving is reduced and therefore must be compensated by higher driving luminosity. This would explain why there are relatively fewer WR stars in low-Z environments.)

(ii) After WNL, evolution occurs along the WR sequences towards earlier subtypes.

(iii) The transition from WN to WC subclass occurs at a WN subtype that depends on the initial metallicity: for higher Z_{init} (as in the inner Galaxy, as opposed to the outer Galaxy, the LMC, or especially the SMC), the stellar envelope is removed by radiation-driven mass-loss more quickly, at a later WN subtype. This explains the fact that WNE stars are less abundant, while WCL stars are more frequent in the inner Galaxy, and *vice versa* in the outer Galaxy or the Magellanic Clouds.

(iv) A mean mass-loss rate can be calculated, assuming that a typical WR star passes from WNL to WCE: $<\dot{M}_{WR}>=<M_O>[(Q_i - Q_f)]/\delta t(WR)$. With a mean O-star mass $<M_O>= 30$ M$_\odot$, initial and final mass ratios $Q_i = 1.0, Q_f = 0.2$ and mean lifetimes of WR stars $\delta t = 5 \times 10^5$ y, one finds $<\dot{M}_{WR}>= 5 \times 10^{-5}$ M$_\odot$/y, which appears to be quite reasonable.

4.2 Mass-loss rates

How reliable are current estimates of mass-loss rates for WR stars? While photometric and polarimetric mass-loss rates agree quite well with each other in the mean, the radio rates (neglecting the extremely close system CQ Cep, where the polarization model may break down) appear to be too high by a factor that ranges up to an order of magnitude (Moffat *et al.* in preparation)! It is suspected that this difference may be due to the fact that the free-free emission radio (and IR) values, which depend on the square of the density, will be overestimated in a clumpy wind, whereas the polarization and photometry values, which depend linearly in the density, are impervious to clumping. There is now ample evidence for clumping in WR winds (Moffat *et al.* 1988; Robert 1992; Moffat *et al.* 1994a); however, the problem is to be able to estimate quantitatively how this affects the radio emission.

Fortunately, one has at one's disposal an ideal test object: V444 Cygni. Not only are radio/IR and polarization mass-loss rates available, but also dynamic values, based on the well-observed period increase of this important eclipsing system (see Table 1 and St-Louis *et al.* 1993). It is clear that those methods that are independent of clumping (polarization, period-change) yield a mean value of $\dot{M}(WR) = 0.7 \times 10^{-5}$ M$_\odot$/y, while the radio/IR line methods lead to a rate above 2×10^{-5} M$_\odot$/y, *i.e.*, at least three times larger. Taken at face value, this probably means that indeed, the radio/IR values are overestimated, due to clumping, which appears to continue to occur as far out as the radio emission region of the winds (at some 1000 R_*). Adopting a mean of the polarimetric and photometric mass-loss rates for Galactic WR binaries, I find a correlation $\dot{M}(WR) \sim M(WR)^\alpha$, where α is close to *unity*. This correlation is qualitatively similar to that expected from theory, but differs from the theoretical slope $\alpha = 2.5$ (Langer 1989). Note that later type WR subtypes tend to have higher mass-loss rates, as well as

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TABLE I
Comparison of $\dot{M}$ ($10^{-5}M_{\odot}/y$) from different techniques for the WR star in V444 Cygni.

	indep. of clumping	
period increase (2 sources)	0.4	1.0
polarization (2 methods)	0.6	0.75
	dep. on clumping	
radio	2.4	
IR lines	2-5	

higher masses.

Unfortunately, the data for extragalactic systems are too sparse at present to make any meaningful comparisons of $\dot{M}$ for different metallicities. Nevertheless, there is no *obvious* correlation of $\dot{M}$ with Z so far.

4.3 Binary frequency

From theory, mass-loss rates of O-stars should scale as $\dot{M}_O \sim Z^{1/2}$ (Kudritzki *et al.* 1987). The same dependence on the initial metallicity should then also apply to WN stars for equilibrium CNO-cycle H-burning (*i.e.*, C + N + O = constant): $\dot{M}_{WR} \sim Z^{1/2}$. However, once the WC phase is reached, there should be only negligeable dependence on Z, since the increased C + O comes from the primary fusion process of He. Therefore, it was proposed some time ago (Maeder 1982) that a new channel was necessary to produce WR stars from the low-mass range of O-star progenitors in environments of low Z. That channel was binaries, for which it was assumed that the presence of a companion could enhance the WR mass-loss rate, in compensation for the lower opacity wind driving force at lower Z. Thus, one expected to find an increased binary frequency of WR+O binaries in the LMC and especially the SMC, especially among the lower mass stars. The observations were thought to bear this out (Hidayat *et al.* 1984). However, the binary frequency was based primarily on the *spectroscopic* presence of a companion. Since optical doubles could be more frequent especially in the more distant Magellanic Clouds, it is clearly more appropriate to look at the WR+O binary frequency based on *orbital RV variations.* Table 2 shows a summary of the current situation, in limited samples of WR stars, neglecting WR+c binaries, potential or otherwise. The global Galactic frequency is based on Moffat *et al.* (1986), revised with new statistics to b = 12 mag for LMC WNE and WC; the SMC on Moffat (1988); the Galactic and LMC WNL stars on Moffat (1989); the WC population in the MCs on a preliminary but

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TABLE II
Binary frequency (WR+OB)/(all WR) in different galaxies.

galaxy	all subtypes	WNL	WNE	WC
Galaxy	17/42=42%	11/25=44%	7/15=47%	10/27=37%
LMC	?	5/12=42%	?	<50%
SMC	5/8=62%	(0/2)	(4/5)	(1/1)

complete study by Bartzakos *et al.* (these proceedings).

From Table 2, I note that there is no convincing evidence of a correlation of the binary frequency with metallicity, *i.e.*, galaxy. A critical case is of course the SMC ($Z = Z_\odot/10$); however, the numbers for it are too small to be statistically meaningful. This lack of any obvious correlation supports the previous suspicion that the binary channel is probably incidental for the development (but crucial for the study!) of WR stars, in the sense that binary mass transfer is unimportant. However, it is important to note that the WR/O-star number ratio *is* a decreasing function of Z, independent of the binary frequency.

Finally, it is worth pointing out that the binary frequency among WN6/7 stars in the Galaxy and LMC is 58% and 56%, respectively, with a mean of 16/28 = 57%. This is in stark contrast to the combined binary frequency in both galaxies among the WN8/9 (mostly WN8) stars: 0/9 = 0%. Together with the high frequency of runaways, avoidance of clusters and high degree of variability among WN8/9 stars, this lends support to the possibility that WN8/9 stars may be the result of some kind of spiral-in effect in a WR+c binary (*e.g.*, Cherepashchuk & Moffat 1994).

5. Summary conclusions

Armed primarily with masses and mass-loss rates for WR stars in massive binaries, it is possible to provide several far-reaching constraints regarding the evolution of WR stars in general:

(1) With few exceptions, WR stars in WR+OB binaries show no significant differences from single WR stars of the same spectral subclass.

(2) There is no convincing evidence that either masses or mass-loss rates of WR stars depend on the initial metallicity, although the number ratio of WR to O-stars does depend on Z_{init}. It is surprising for WN stars that $\dot{M}$ does not depend on Z, although perhaps the dependence is weak and below the threshold of detectability.

(3) On the other hand, there is a ($\sim$ linear) correlation between $\dot{M}$ and

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M for WR stars. This is less steep than the power law ($\dot{M} \sim M^{2.5}$) from theory.

(4) All WR stars start as WNL, where the mass ratios are close to unity, after which the mass ratios decrease dramatically as WR stars lose mass rapidly via a wind and evolve from cool subtypes to hotter subtypes in either sequence.

(5) The transition from WN to WC occurs at a WN subtype that depends on the initial metallicity. In the inner Galaxy, where Z_{init} is high, one finds WNL → WCL before a likely supernova explosion. In the outer Galaxy (or the LMC), where Z_{init} is intermediate, one has WNL → WNE → WCE before a SN. Between these two extremes, the change is gradual. In the SMC, the statistics are poor, although the situation may be more similar to that in the LMC.

(6) The final masses of WR stars before a potential SN are probably those of the lowest observed: in the range 5–10 $M_\odot$. This may fit well into the scenario for producing Type Ib supernovae (Population I, H-poor).

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References

Cherepashchuk, A.M., Moffat, A.F.J. 1994, *ApJ (Letters)* **424**, L53
Garmany, C.D., Conti, P.S., Massey, P. 1980, *ApJ* **242**, 1063
Hidayat, B., Admiranto, A.G., van der Hucht, K.A. 1984, *Ap Space Sci.* **99**, 175
Koenigsberger, G. 1990, *ASP Conf. Series* **7**, 139
Kondo,Y., McCluskey, G.E. 1976, *IAU Symp.* **73**, 277
Kudritzki, R.P., Pauldrach, A., Puls, J. 1987, *A&A* **173**, 293
Langer, N. 1989, *A&A* **220**, 135
Leung, K.C., Moffat, A.F.J., Seggewiss, W. 1983, *ApJ* **265**, 961
Lührs, S. 1991, Dissertation, University of Münster; and these proceedings
Maeder, A. 1982, in: C.W.H. de Loore & A.J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, *Proc. IAU Symp. No. 99* (Dordrecht: Reidel), p. 405
Moffat, A.F.J. 1981, in: C. Chiosi, R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, *Proc. IAU Coll. No. 59* (Dordrecht: Reidel), p. 301
Moffat, A.F.J. 1982, in: C.W.H. de Loore & A.J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, *Proc. IAU Symp. No. 99* (Dordrecht: Reidel), p. 515
Moffat, A.F.J., Lamontagne, R., Shara, M.M., McAlister, H.A. 1986, *AJ* **91**, 1392
Moffat, A.F.J. 1988, *ApJ* **330**, 766
Moffat, A.F.J., Drissen, L., Lamontagne, R., Robert, C. 1988, *ApJ* **334**, 1038
Moffat, A.F.J. 1989, *ApJ* **347**, 373
Moffat, A.F.J., Niemela, V.S., Marraco, H. 1990a, *ApJ* **348**, 232
Moffat, A.F.J., Drissen, L., Robert, C., Lamontagne, R., Coziol, R., Mousseau, N., Niemela, V.S., Cerruti, M.A., Seggewiss, W., van Weeren, N. 1990b, *ApJ* **350**, 767
Moffat, A.F.J., Lépine,S., Henriksen,R.N., Robert,C. 1994a, *Ap Space Sci.* **105**, 11
Robert, C., Moffat, A.F.J., Bastien, P., St-Louis, N., Drissen, L. 1990, *ApJ* **359**, 211
Robert, C. 1992, PhD thesis, Université. de Montréal
St-Louis, N., Drissen, L., Moffat, A.F.J., Bastien, P. 1987, *ApJ* **322**, 870

St-Louis, N., Moffat, A.F.J., Lapointe, L., Efimov, Yu.S., Shakhovskoy, N.M., Fox, G.K., Piirola, V. 1993, *ApJ* **410**, 342
Schuerman, D.W. 1972, *Ap Space Sci.* **19**, 351
Smith, L.F., Maeder, A. 1989, *A&A* **211**, 71
Sybesma, C.H.B. 1986, *A&A* **168**, 147
Vanbeveren, D. 1978, *Ap Space Sci.* **57**, 41
Vanbeveren, D. 1991, *A&A* **252**, 159
van der Hucht, K.A., Hidayat, B., Admiranto, A.G., Supelli, K.R., Doom, C. 1988, *A&A* **199**, 217

DISCUSSION:

Nussbaumer: When treating mass transfer it is important to know whether the donor fills the Roche lobe. What is the situation in the WR-binaries during the different stages of evolution?
Moffat: In the case of O + O, WR + O or even WR + WR binaries, the Roche lobe has little significance, in view of the strong winds. Rather, the collision of this wind tends to carry matter out of the system.
van Kerkwijk: 1. It is important to realise that when a star becomes observable as a WR star in a binary, most of the envelope has already transferred, in a very short timescale. The timescale can become longer when the mass ratio has inverted. Could this be related to the fact that you observe mass ratios M_{WR}/M_O of 1 and smaller?
2. How can one get rid of 10^{-3} M⊙ yr^{-1} by a radiation-pressure driven wind (given that a much lower rate is already so difficult)?
Moffat: 1. Yes, this may happen, although I still think that the WR phase in a binary *begins* with WNL + O and evolves *later* via wind mass-loss gradually down the sequence through WNE → WC, etc. But mass accretion even on a RLOF primary still has to be demonstrated via self-consistent hydro calculations.
2. The 10^{-3} M⊙ yr^{-1} I mentioned is not a true wind mass-loss rate; it is the effective rate at which matter will flow through L_1 when the primary is evolving quickly from the ZAMS to the red in the H-R diagram.
Conti: An additional argument against the importance of RLOF for production of W-R binaries is the existence of short period eccentric orbits (e.g. HD 5980 with period ~ 19 days).
Moffat: Yes, I briefly mentioned this in my talk, although when the eccentricity is large ($e \geq 0.3$), no-one can really estimate the circularization time with any certainty, since the perturbation equation breaks down in that case (Tassoul, priv.comm.).
Gies: We know of some O binaries with extreme mass ratios (cf. Gies et al. 1994, ApJ, 422, 823); will we ever find the descendants of these systems at WR + B (with q = M(WR)/M(B) > 1)?
Moffat: Some WR-star masses are generally on the low side compared to O-stars, we should see WR + B systems fairly easily in the RVs of the emission lines. The only system that comes to my mind like this is HD 197406 (WN7, SB1, P ~ 4d), which we (Drissen et al. 1986) have claimed may harbour a black hole companion rather than an early B companion.