THE EVOLUTION OF MASSIVE CLOSE BINARY SYSTEMS : ESTIMATES OF THE PARAMETERS GOVERNING MASS AND ANGULAR MOMENTUM LOSS

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It becomes more and more evident that for close binary evolution during Roche lobe overflow as well mass transfer as mass loss occurs. When a mass element ΔM is expelled from the primary during this phase, a fraction β is transferred to the secondary; the remaining part leaves the system. Moreover, angular momentum leaves the system, and also this fraction has to be specified; this fraction is related to a parameter α (Vanbeveren et al., 1979). For the computation of the evolution of massive close binaries also mass loss due to stellar wind of both components, prior to the Roche lobe overflow has to be taken into account. The mass loss rate $\dot{M}$ due to radiation driven stellar winds can be expressed as

$$\dot{M} = -N \frac{L}{c^2}$$

An estimate of the N-value for single O-stars has been made by Lamers, Paerels and de Loore (1979); they found that N is of the order 100 to 200. The N-value for binaries could be higher, due to the gravitational forces exerted by the secondary. We have tried to specify the values of N, β and α, using various methods, relating computed evolutionary models with observations. These methods are :

1. comparison of the position of O-type stars sufficiently well known with mass-luminosity curves derived from evolutionary sequences computed with N=0, 100, 300. This leads to a lower limit for N.
2. An analysis of the magnitude differences between primary and secondary in binaries gives an estimate for N.
3. Constraints on α and β.

Evolutionary models were constructed for a number of systems (see section 1) and constraints on α and β were determined using the following criteria :

a) Vanbeveren and Packet (1979) determined upper and lower limits for the amount of mass that still has to be removed after RLOF in order to obtain an early WN star or a WC star.

M. J. Plavec, D. M. Popper and R. K. Ulrich (eds.), Close Binary Stars: Observations and Interpretation, 115–121.

Using the observed masses of WR systems we can use these results to point out that in massive systems the mass ratio $(\frac{\text{secondary}}{\text{primary}})$ just after RLOF is less than 2.

b) The mass ratio of the system (secondary to primary) will increase during core hydrogen burning due to stellar wind mass loss, and come nearer to 1. The results of Garmany (1979) and the computations of Vanbeveren et al. (1979) reveal that we can expect an overabundance of systems just before Roche lobe overflow with a mass ratio larger than 0.7.

c) A large majority of massive close binaries evolves through a case B of mass exchange. An analysis of the observed periods for systems after the mass exchange and the minimum periods before RLOF in order to have a case B system reveals that the period ratio (after to before) should be of the order 1 or smaller.

1. SUFFICIENTLY WELL DEFINED SYSTEMS EVOLVED OR NOT

We considered a system as evolved, if the mass of the secondary exceeds that of the primary, hence the system is in its post mass exchange stage (PRLOF). The parameters of these systems are shown in Table 1 (evolved systems) and in Table 2 (non evolved systems). Table 1 contains the OB components of 6 X-ray binaries, with well defined parameters (mass, luminosity).

Table 1. Observed parameters for evolved systems.

System	q	$M_1\sin^3 i$	$M_2\sin^3 i$	i	P(d)	$-M_{bol_1}$	$-M_{bol_2}$	Spectral types 1	Spectral types 2	References
HD90657	2.01	6.8	13.6		6.5			WN5	O6	(3)
HD152270	2.68	1.8	4.9		8.9			WC7	O5	(5)
HD168206	4.35	8.1	35.2	≥60°	29.7			WC8	O	(6)
HD186943	2.38	3.36	7.94		9.6			WN4	B	(7)
HD190918	3.70	0.21	0.78		85		9.8 (CA) 10.1 (W)	WN4	O9I	(7)
HD193576	2.32	8.4	19.5		4.2			WN5	O6	(2)
HD211853	2.87	11.5	33	≥60°	6.7		10 (CA) 10.7 (W)	WN6	O6I	(1)
γ Velorum	1.88	17	32		78.5		9.8 (CA) 10.1 (W)	WC8	O9I	(4)
HD1337	1.37	19	26	~90°	3.5	8.6	8.6	O9III	O9III	(11)
HD57060	1.21	24	29	~90°	4.4	9.6 (CA) 10.3 (W)		O7f	O7	(11)
		23	30			9.7 (CA) 10.15 (W)		O8Ia	O7	(12)
HD149404	1.68	1.6	2.7			9.65	8.77	O8.5I	O7III(f)	(13)
HD163181	1.74	12.5	21.8	~73°1	12.01	8.8	6.5	BO.5Ia	B	(10)
HD166734	1.07	29	31		34.54	9.6 (CA) 10.7	9.6 (CA) 10.3	O7f	O7f	(16) (W+16)

Table 1 (continued)

System	q	$M_1 \sin^3 i$	$M_2 \sin^3 i$	i	P(d)	$-M_{bol_1}$	$-M_{bol_2}$	Spectral types 1	Spectral types 2	References
HD190967	1.28	17.5	22.4	~90°	6.5		7.2(CA 7.0(W)	B1Ib	O9.5V	(5)
HDE228766	1.48	23	34		10.74	10.3		O5.5f	O7.5	(9)
BD+40°4220	3.44	9	31	≥60°	6.6	10.8	10.5	O6f	O7f	(8)(9)
HD153919	20.69	1.31	27.1	~90°	3.41		10.2		O6f	(14)
Cen X-3	12.11	1.42	17.2	~80°	2.09		9.0		O6.5III	(14)
HDE226868	1.61	1.48	2.39	~29°	5.60		8.7		O9.7Iab	(14)
SMC X-1	15.86	0.79	12.53	~70°	3.89		8.1		BOI	(14)
HD77581	15.01	1.42	21.32	~74°	8.97		9.6		BO.5Iab	(14)
LMC X-4	9.00	2.5	22.53	~75°	1.41		8.4		O7	(15)

(1) Stempien (1970)
(2) Ganesh et al. (1967)
(3) Niemela (1976)
(4) Niemela and Sahade (1979)
(5) Seggewiss (1974)
(6) Cowley et al. (1971)
(7) Bracher (1967)
(8) Bohannan and Conti (1976)
(9) Massey and Conti (1977)
(10) Woodward and Koch (1975)
(11) Stothers (1972)
(12) Hutchings (1977)
(13) Massey and Conti (1979)
(14) Conti (1978)
(15) Hutchings et al. (1978)
(16) Conti,P.S.,Ebbets,D.,Massey,P.,Niemela,V.,1979,private communic.

Table 2. Observed parameters for non evolved systems

System	q	$M_1 \sin^3 i$	$M_2 \sin^3 i$	i	P(d)	$-M_{bol_1}$	$-M_{bol_2}$	Spectral types 1	Spectral types 2	References
HD19820	0.48	18.9	9.2		3.4			O8	O8	(3)
HD34333	1	19.7	19.7	~64°	4.1	5.8	5.3	B3III	B3III	(3),(4),(5)
HD36486	0.36	28	10	~67°	5.7	9.1	5.5	O9.5	B	(3),(4),(5)
HD57060	0.83	23	19	~90°	4.4	9.57(CA) 10.27(W)		O7f	O7	(1)
HD93205	0.38	39	15	<50°	6.08	10.0 10.5	7.4	O3	O8	(11)
HD190967	1.00	23	22.4	~90°	6.5		7.2(CA)	B1Ib	O9.5V	(5)
HD191201	1	13.9	12.9		8.3	8.5(CA)	8.5(CA)	O9.5III	O9.5III	(3)
HD152218	0.80	13.4	10.7		5.4	8.5(CA) 7.9(W)		O9.5III		(9)
HD152248	0.92	24.4	22.5		5.97	9.6(CA) 10.3(W)		O7f		(9)
HD159176	0.96	11.4 14.7	10.8 14.1	<50°	3.4	8.5-9.1	8.5-9.1	O7	O7	(6) (7)
HD165052	0.87	2.5	2.2	<25°	6.1	8.6(CA)	8.6(CA)	O6.5	O6.5	(10)
HD167771	0.87	2.7	2.3	<28	3.97	9.4(CA)	8.4(CA)	O7 ((f))	O9	(10)
HD206267	0.33	18.7	6.5	<55°	3.7			O6	O9	(8)
HD228854	0.89	37	33	~90°	1.9			O7	O8	(2)

(1) McCluskey and Kondo (1972
(2) Batten (1968)
(3) Batten (1967)
(4) Koch et al. (1970)
(5) Stothers (1972)
(6) Conti et al. (1975)
(7) Evans (1979)
(8) Crampton & Redman (1975)
(9) Hille et al. (1974)

2. ESTIMATES FOR N DURING CORE HYDROGEN BURNING DERIVED FROM THE OVERLUMINOSITY OF O TYPE COMPONENTS IN BINARIES

a) Comparison of the O star in Figure 1 with the mass-luminosity curves computed for N=0,100,300 gives a lower limit for N. Indeed, the considered systems have not necessarily finished core hydrogen burning. In order to explain the observed overluminosities for O components in binaries, large N-values have to be involved. For the indicated supergiant components in X-ray binaries, which are most probably at the end of the core H-burning, a comparison with the theoretical curves allows a real estimate for N. From the figure may be derived that N~400.

https://doi.org/10.1017/S007418090006469X Published online by Cambridge University Press

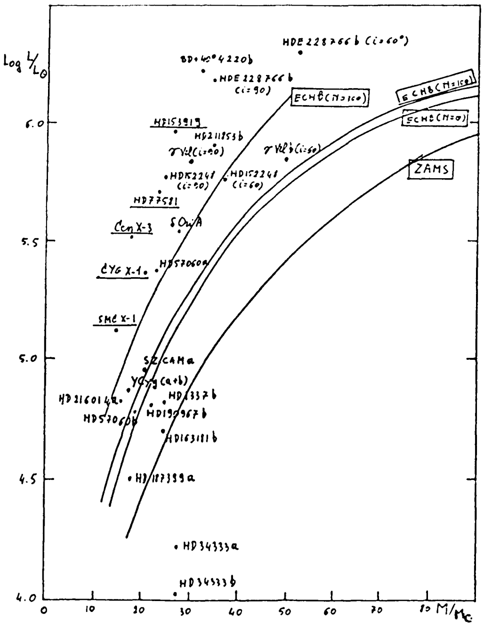

Figure 1. Comparison between the theoretical M-L relations at the end of core hydrogen burning for different N-values with observed luminosities of binary components.

b) We consider now the systems with sufficiently accurate determined spectral type. Using the evolutionary sequences of de Loore et al. (1977,1978) with the inclusion of mass losses and selecting these models with effective temperature corresponding with these spectral types, we can plot the luminosity of these O components as a function of their mass

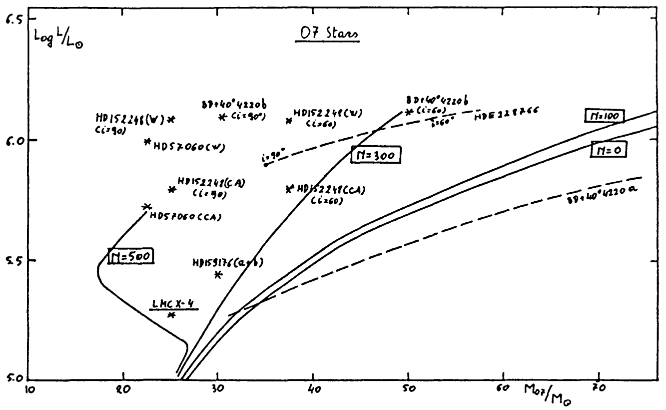

Figure 2. The M-L relations for O7 stars for different N-values: the positions of observed O7 stars, members of close binaries are indicated.

https://doi.org/10.1017/S007418090006469X Published online by Cambridge University Press

for N=0,100,300,500. The observed position of the O6, O7 and O9 stars in this diagram corresponds with large stellar wind mass loss rates (N≥300)(as an example we have chosen the O7 spectral type in Figure 2; the conclusion for N holds for O6 and O9 as well).
Conclusion :

$$300 \leq N < 500$$

3. CONSTRAINTS ON α AND β

For evolved systems it is possible to calculate their original parameters at the ZAMS, for different assumptions on α, β and N. This was done for evolved O and Of stars by using interpollation formulas derived by Vanbeveren and De Grève (1979) for N=0 and 300, α=1,2 and 3 and β=0, 0.5, 0.8 and 1. For unevolved binaries the future of these systems can be evaluated by calculating evolutionary sequences, including stellar wind mass loss (N=300) for the same values of α and β as before. Inspection of the mass ratios and the periods (or period ratios, final to initial) and comparison with the constraints,concerning N and the mass ratio, determined in the previous sections lead to a large mass and angular momentum loss from the system during RLOF, i.e. at least 50% of the mass lost by the primary should leave the system taking with typically some 50% of the orbital angular momentum.

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DISCUSSION FOLLOWING VANBEVEREN AND DE LOORE

Sugimoto: Is the separation between the components decreasing or increasing during the mass loss before filling their Roche lobes?

de Loore: For the orbital period variation, the equation for isotropic mass loss of Hadjidemetriou (Advan. Astron. Astroph. 5, 131 1967), was used

$$P/P_o = \left(\frac{M_1^o + M_2^o}{M_1 + M_2}\right)^2 \quad \text{(subscript o refers to initial situation)}$$

Hence the period, and also the separation between the components during the phase before RLOF is increasing.

Massey: How are the luminosities plotted in your slides derived? Several of these stars are not known to be members of clusters (HDE 228766, HD 211853 for example). If the luminosities come from the spectral types and not from distance moduli, aren't they highly uncertain for the evolved stars? How did you correct for the continuum contribution of the WR star in the WR + OB systems?

de Loore: The luminosities are partly determined from the distance of the systems. If spectral type and luminosity class are sufficiently well known the bolometric magnitude is found from the studies of absolute magnitude of Conti and Altschuler (Ap. J., 170, 325, 1971) and Walborn

(Astron. J., 77, 392, 1972). Bolometric corrections are from Morton (Ap. J., 158, 629, 1968).

I agree that uncertainties remain due to the continuum contribution of the WR star in WR systems.

DISCUSSION FOLLOWING VAN DER LINDEN

Sugimoto: Are you planning to compute the evolution of the mass-accreting companion?

van der Linden: Until now we limited ourselves to evolution of the loser. But we are certainly planning to calculate also the mass-gaining star. Work on this is in progress.