THE INFLUENCE OF MASS LOSS ON THE EVOLUTION OF BINARIES

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1. INTRODUCTION

Mass loss can affect the evolution of binaries in various ways, during different stages of the evolution.

1. For massive stars stellar wind mass loss will change the masses of the components during their main sequence evolution.
2. During the Roche lobe overflow phase (or tidal interaction phase) matter can leave the system.
3. For low mass stars matter can leave the system during the mass exchange phase and can be stored in envelopes, disks or rings.
4. Sufficiently massive stars(>8-$15M_{\odot}$) undergo at the end of their life a supernova explosion, where most of the matter is blown away and a compact object, a neutron star or a black hole can be left.
5. For intermediate stars one of the components can evolve into a degenerate He or CO dwarf; a reverse mass transfer can dump matter on this degenerate dwarf. If the conditions are favorable the white dwarf can explode with loss of matter, and a neutron star can be the result.
6. The chemical abundances in the outer layers change.

2. MASS LOSS IN NOT EVOLVED BINARIES (i.e. before mass exchange)

For the computation of evolving stellar models as well for single stars as for binaries the mass loss rates are needed. The mass loss rates are only known to a factor 10 (Gathier & Lamers, 1981), for a restricted number of stars. Moreover the stellar wind mechanism is still unclear. Hence it is not very convenient to try to include a complicated mass loss formalism into the computations. Different groups have computed evolutionary sequences taking into account mass losses, using different stellar parameters for the derivation of the mass loss rates $\dot{M}$:

$$\dot{M} = \frac{-L}{cv_{th}} \frac{\alpha}{T} \left(\frac{1-\alpha}{1-\Gamma}\right)^{\frac{1-\alpha}{\alpha}} (K)^{1/\alpha} \qquad \text{(Chiosi et al., 1978)}$$

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 405–430.

$$\dot{M} = -N \frac{L}{c^2} \qquad \text{(de Loore et al., 1977,1978a,b)}$$

$$\dot{M} = -k \frac{LR}{M} \qquad \text{(Stothers \& Chin (1980)}$$

The general features of the evolution as a consequence of the mass losses are

1. the luminosity is lower than for conservative evolution;
2. the effective temperature is lower;

hence as a consequence of (1) and (2) the star moves to the lower right corner of the HRD;

3. the mass of the convective core is lower;
4. the hydrogen burning lifetime is larger.

These points are common in all computations. Moreover some general features of the evolving stars during various parts of their evolution can be explained more or less satisfactorily by mass loss including computations. The $\dot{M}$~L relation as used in the computations of Chiosi et al. (1978) and de Loore et al. (1978) was criticized by Conti and Garmany (1981). However, this is probably a consequence of the small sample. If we consider the mass loss rates determined for some 100 O and B stars we see a correlation, with a large spread, but let us remember that also the $\dot{M}$ are not so accurately determined (see Figure 1).
From all collected mass loss rates a mass loss-luminosity relation for O stars may be derived :

$$\log \dot{M} = -14 + 1.5 \log L \qquad (1)$$

($\dot{M}$ in solar masses per year, L expressed in solar units).

According to Lamers (this colloquium)

$$\log \dot{M} = -14.1 + 1.42 \log L - 0.99 \log M/30 + 0.6 \log R \qquad (2)$$

(with L, M and R expressed in solar units).

Adopting for O stars a mass range from 30 $M_\odot$ to 90 $M_\odot$ the third term of the righthand side varies between 0.47 and 0.99; from the computations of de Loore et al. (1978) the radii of these stars during core hydrogen burning range between 6 and 36, so the fourth term of the righthand side varies between 0.46 and 0.92. Hence the 3^{d} and 4th term cancel each other and the equation reduces to

$$\log \dot{M} = -14.1 + 1.42 \log L \qquad (3)$$

The luminosity ranges between 10^5 and 10^6 $L_\odot$, hence the difference between equations (1) and (3) is 0.5 à 0.6, smaller than the observational errors. We can also estimate the contribution of the M and R-terms for different evolutionary stages for a 100 $M_\odot$ and a 40 $M_\odot$ star, calculated with mass loss (N=100)(see Table 1).

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Table 1.

M/M_O	R/R_O	value -M term	value R term	sum
100	13	0.49	0.67	0.18
90	16	0.45	0.72	0.27
78	35	0.39	0.93	0.54
40	8	0.12	0.54	0.42
36	12	0.07	0.58	0.51
33	20	0.06	0.78	0.74

Even for the most unfavourable situation the difference is not larger than 0.75, and for $\dot{M}$ the ratio is not larger than a factor 5. Hence a straightforward relation between mass loss rate and luminosity for O stars and Of stars is suitable to calculate evolutionary sequences. An advantage of a formalism like $\dot{M} = -N\,L/c^2$ is that different values for N can be used and that even N can be changed during the evolution. Comparison between evolutionary tracks of Chiosi et al. (1978) and de Loore et al. (1978) shows a fair agreement.

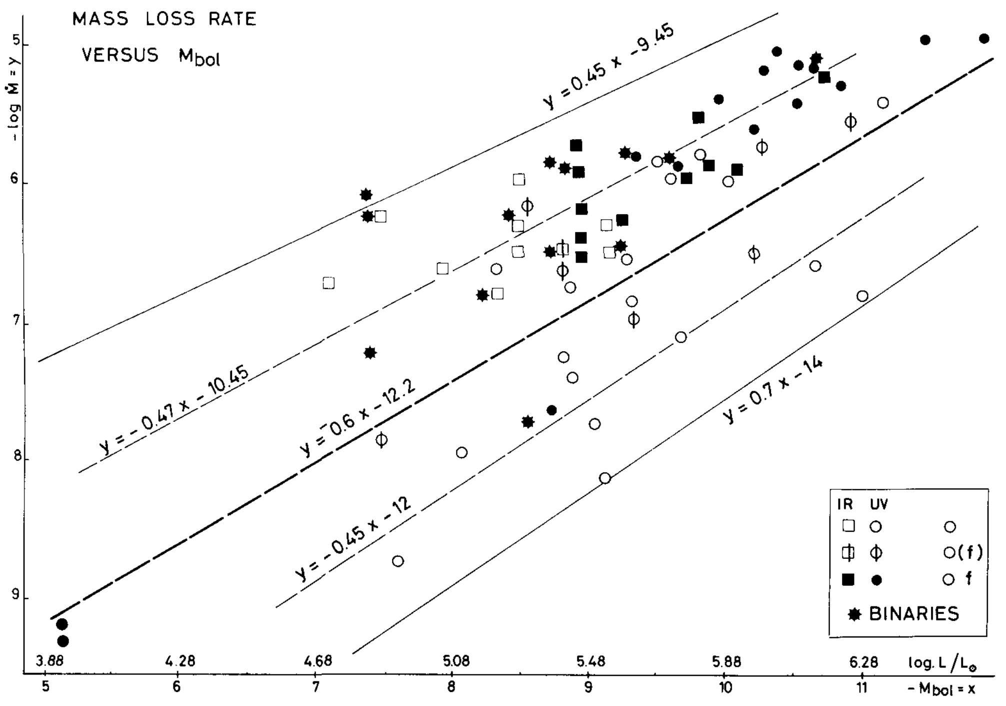

Figure 1. Mass loss rates versus M_{bol}.

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3. STELLAR WIND MASS LOSS RATES FOR BINARIES

Computations of binary evolutions are more complicated than for single stars, since all the difficulties which are involved in the evolution of single stars appear also in close binary evolution plus the typical difficulties related to binaries: Roche lobe overflow and how to treat it, the case of convective outer layers, mass transfer and mass loss, the fraction of the matter expelled by the primary which is leaving the system, and what fraction is accreted, the effect of accretion.
Massive stars can lose a large fraction of their mass by stellar wind, and this is also the case for the components of massive binary systems. An important question is to know if close binaries have higher mass loss rates than single stars. Hutchings (1976) suggested that this is really the case, Conti and Garmany (1981) on the contrary find no difference between single stars and binaries. Mass loss rates for binaries determined from infrared and ultraviolet observations are shown in Table 2.

Table 2. Mass loss rates in binaries

Object	$-M_{bol}$	log T_{eff}	log $\dot{M}$	Sp. type
a) IR determinations (Tanzi et al., 1980)				
HD 47129	8.8	4.54	-5.8	08f
HD 57061	9.8	4.49	-5.85	09Ib
HD 37043	8.56	4.52	-6.40	09III
HD 135240	8.06	4.58	-6.60	09V
HD 77581	9.3	4.45	-5.8	B0Ia
HD 144217	6.06	4.41	-6.7	B0.5V
HD 35411	6.06	4.41	-6.7	B0.5V
HD 37041	7.3	4.52	-6.15	09.5Vep
HD 153919	10.56	4.65	-5.03	05f
HD 159176	8.3	4.58	-6.35	07
HD 167771	9.70	4.54	-5.80	08I(f)
HD 36486	8.56	4.49	-5.78	09.5I
b) UV determinations (Conti and Garmany, 1981)				
HD 37041	7.3	4.52	-7.25	09V
HD 48099	8.95	4.57	-7.70	06V

However the overluminosity observed in the primaries of non evolved massive binaries is a strong argument in favor of large mass loss rates in binaries. In Figure 2 is depicted the luminosity as a function of the stellar mass at the end of core hydrogen burning for various mass loss rates (N=0,100,300)(Vanbeveren and de Loore, 1980; Conti, 1979; de Loore et al., 1978). The positions of primaries of some normal binaries and X-ray binaries are indicated. The O type stars considered here have not necessarily finished their core hydrogen burning, hence the mass can still decrease during further evolution, so the N-values are lower limits. One could think of mass accretion by the mass gaining component to explain the observed overluminosities of the X-ray binaries (the mass accretion will cause large T_{eff} and eventually large luminosities).

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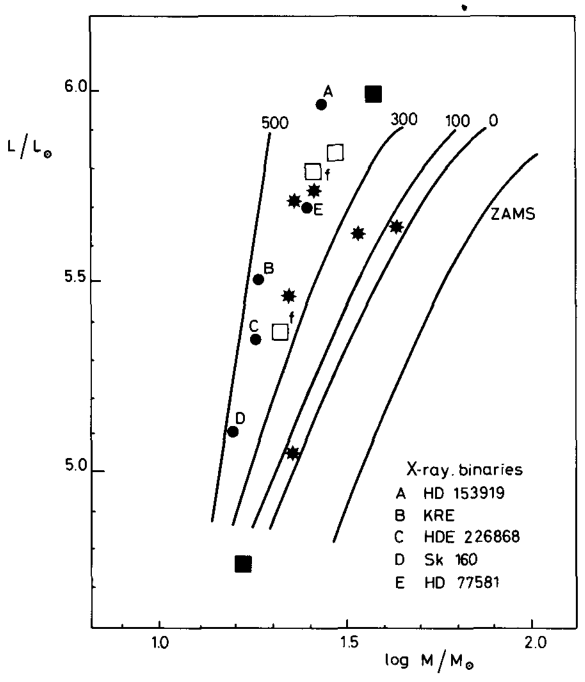

Figure 2. Luminosity as a function of the stellar mass at the end of core hydrogen burning (TAMS). The TAMS for different N are labeled with their N-values. The positions of the primaries for X-ray binaries are indicated (A,B,C,D and E), and also the position of primaries for some evolved (filled squares) and non-evolved (open squares) binaries. The symbol f indicates that the O star is of the type f. The asterisks refer to single stars.

However this process alone cannot be responsible for the overluminosity. If we look now at the position of the single stars and of the O type component of the neutron star in the X-ray binaries, we see that the value of N for the latter sources is higher than for single O stars. However a number of these stars is also of the f-type or of luminosity class I, where the mass loss rates are already higher (Lamers et al., 1980). The same authors compared the location of single O and Of type stars in the HR diagram with equal mass curves derived from evolutionary tracks with mass loss with different N-values. The observations agree best with the case N = 100 (Figure 3, a and b). If we apply a similar method to binaries (Figure 3, c and d) we must conclude that here again the case N = 100 matches the observations. However for lower masses ($M<40M_{\odot}$) also the case N = 300 agrees. For larger masses possibly the border of the main sequence has to be shifted to the right. According to Appenzeller (1970) massive stars are vibrationally unstable. In pulsating stars mechanical energy is generated in the core.

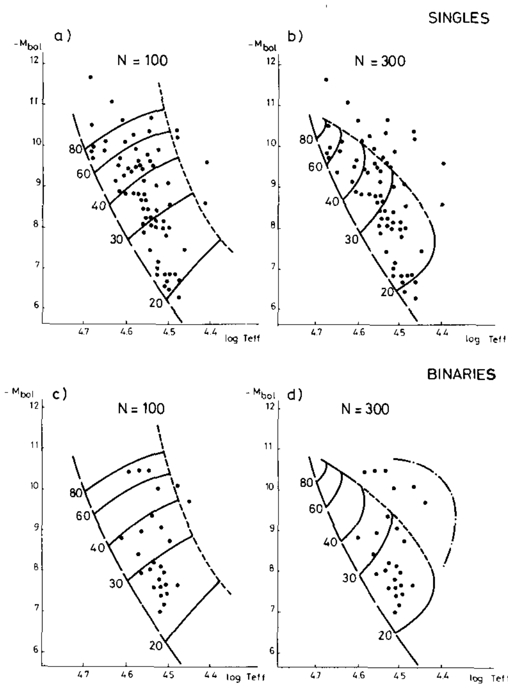

Figure 3. The location of O type stars in the HR diagram is compared with equal mass curves (full lines) derived from evolutionary tracks with mass loss calculated with N=100 (a and c) and N=300 (b and d). The Figures a and b refer to single stars, c and d to the primary in binary systems. The ZAMS is indicated by a dashed curve, the TAMS by a dotted line. The numbers at the equal mass curves are stellar masses. The dash-dotted curve in d refers to the displaced TAMS, when the increase in stellar radii according to vibrational instabilities (Appenzeller, 1970) is taken into account.

In normal main sequence stars the gain of mechanical energy in the core ($\Delta E_{mech,core}$) equals the loss of mechanical energy in the outer layers ($\Delta E_{mech,env}$). When the stellar mass exceeds a certain limit however

$$\Delta E_{mech,core} > \Delta E_{mech,env} \quad \text{(Ledoux,1941; Schwarzschild \& Harm, 1959)}$$

According to Appenzeller this limit is ~60 $M_{\odot}$. The result of this netto gain in mechanical energy is a decrease of the effective gravity g_{eff}:

$$g_{eff} = \frac{GM}{R^2} + \frac{\partial^2 r}{\partial t^2}$$

and consequently an expansion of the outer layers; pulses are generated and mass is ejected. The mass ejected by one pulse is

$$M \lesssim \frac{2}{v_e{}^2} \Delta E$$

where v_e is the escape velocity and E the netto gain in mechanical energy. The effective radius R_e (radius at optical depth $\tau = 2/3$) cannot be determined by evolutionary computations after the expanding shell is formed but can be estimated from the condition that at the depth corresponding with R_e, the increase of the optical depth τ due to the outstreaming mass equals the decrease of τ due to the atmospheric expansion. According to Appenzeller the effective radius R_e for a 130 M_0 star, some time after the star has left the ZAMS, is about four times larger than the normal radius. If we take this into account the TAMS for large mass stars should shift to lower effective temperatures, over a distance corresponding with $\Delta \log T_{eff} \sim 0.3$. A picture of the evolutionary tracksin the HR diagram for initial masses of 100, 60 and 30 M_0, expanded according to this mechanism, is shown in Figure 4. The changed position of the end of the main sequence (TAMS') is indicated and also the masses.

The binaries in the mass loss rate-luminosity diagram (Figure 1)occupy the upper part of the figure. This also points to high mass loss rates

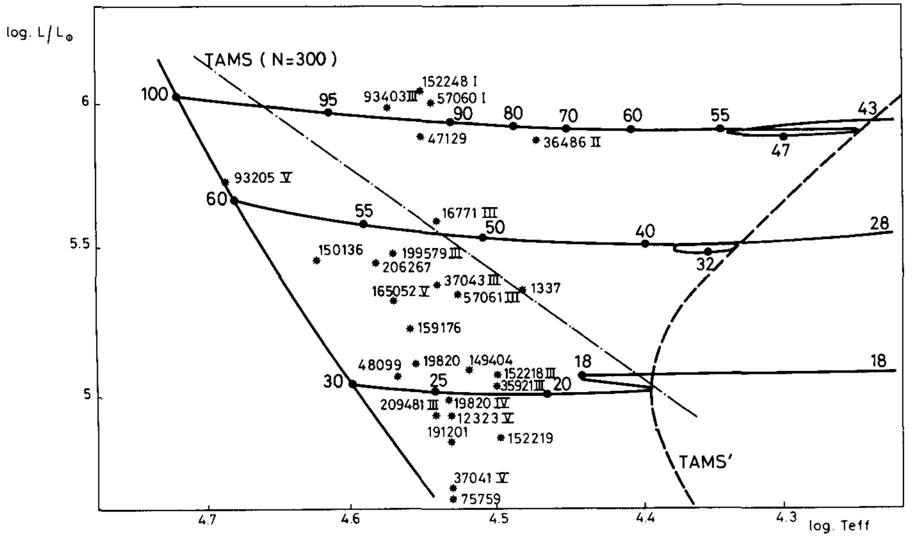

Figure 4. The evolutionary tracks calculated with N=300 expanded to take into account the effect of vibrational instabilities which force the star to increase its radius with a factor 4. TAMS' is the new position of the right border of the main sequence. The position of a number of O type binaries is indicated (with HD number and luminosity class) by asterisks. The decreasing mass at the evolutionary tracks is indicated by dots, and given in solar masses.

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for binaries. However, a number of primaries of the binaries in this figure is of the type Of or OI, hence it is not easy to decide if it is the binary character or the f or I type that positions these stars in the upper case.
We can proceed in another indirect way to decide upon the mass loss rates in binaries, as was done by Vanbeveren and de Loore (1980). We consider those systems for which we know accurately the spectral type of the non evolved main sequence component. Using the evolutionary tracks with stellar wind mass loss of de Loore et al. (1978) with different N, and considering the models with effective temperature related to the involved spectral type, the luminosity of the O type component can be plotted as a function of mass for different N-values. As an example the mass-luminosity relation for O7 stars is shown in Figure 5. The figure shows clearly that the position of observed O7 stars, indicated in the figure, can only be explained if N ranges between 300 and 500.

Final conclusions

1. From comparison between the location of the O-stars in the HRD and evolutionary tracks with mass loss we find that the width of the core H-burning phase matches the predictions for $50 \lesssim N \lesssim 200$ ($N=\dot{M}c^2/L$) - in agreement with the observed $\dot{M}$.
2. Of stars lose matter at a rate about 4 times larger than O stars.
3. For binaries: N ~ 300.
4. The observed overluminosity for X-ray binaries can be explained by evolutionary tracks computed with N=300.

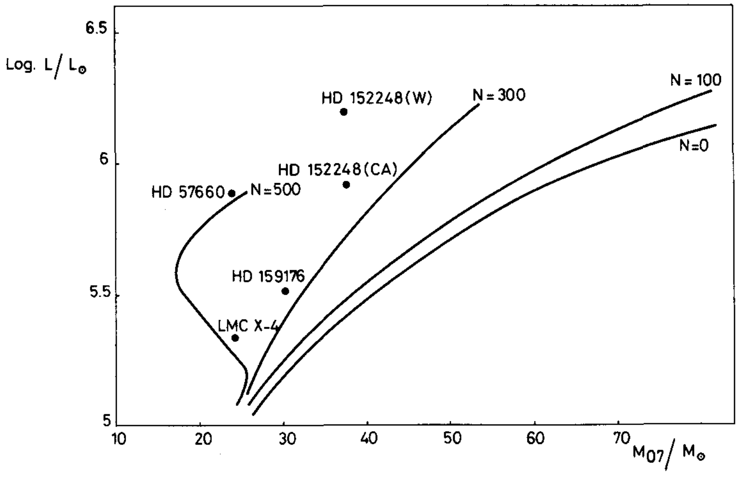

Figure 5. Mass-luminosity relation for O7 stars. The position of O7 type primaries of massive close binaries is compared with the evolutionary positions in a mass-luminosity diagram for N=0,100,300,500. W refers to the Walborn classification, CA to the classification of Conti and Alschuler.

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4. THE MASS TRANSFER PHASE

The Roche lobe model is a very handsome tool for the solution of the problem of the internal structure of the two components in a binary system. Instead of two real stars two mass points are considered. The centrifugal force is calculated for the case of synchronous rotation. The picture of the total potential can be represented by two wells separated by a saddle point L_1, the first Lagrangian point (Kuiper, 1941; Kopal, 1959). Along the straight line joining the two mass centers two more saddle points exist, the Lagrangian points L_2 and L_3. The easiest way to describe the mass exchange phase, when the primary satisfies the condition of losing mass, is to assume that all the mass leaving the primary is accreted by the secondary, hence the total mass remains constant, and also the total orbital momentum does not change. These conditions are conservative assumptions. The observed presence of disks, rings and clouds in binary systems shows that these assumptions are not justified and the treatment of close binary evolution in the conservative way is not exact. The solution of the hydrodynamical problems arising when the conservative hypothesis is dropped has not yet been found.

One can consider different cases of mass transfer , A, B and C depending on whether the mass transfer starts during hydrogen burning before H exhaustion, before the start of He burning, or after He exhaustion.

A new case is introduced, the case BB, denoting the start of mass transfer of a He star, after or before He ignition, following a case B, leaving a He remnant.

Another way to describe various cases of mass transfer is based on different mass exchange modes (Webbink, 1979; de Loore, 1981).

a) contact interaction
b) mass loss from radiative envelopes
c) mass loss from convective envelopes

Important in this respect is to know if helium burning occurs in a degenerate helium core or not, in other words if helium burning starts in a thermally instable way, with a flash, or if on the contrary it starts quietly. Iben (1967) found that the helium flash occurs for masses lower than 2.25 $M_{\odot}$. The central temperature, radius and luminosity are determined by the mass of the degenerate core. As a consequence, for medium mass stars helium burning starts in the red giant region, while for more massive stars helium ignition occurs in the blue region of the HR diagram (Barbaro et al., 1972; Chiosi and Summa, 1970).

5. MASS AND/OR ANGULAR MOMENTUM LOSS FROM BINARY SYSTEMS

The case B has been studied more extensively than the cases A and C, for two reasons: firstly it is expected that case B occurs more frequently than the other cases, and secondly because the other cases are more difficult to compute: the semidetached phase in the conservative case A probably leads to a contact configuration and very complex evolutionary consequences arise. Case C is difficult to treat because it is very hard to keep the mass giving star within its Roche lobe. In all cases it is not just the mass giving star which causes troubles but also the companion. Already ten years ago it became clear that the mass gainer has to radiate a surplus of energy (Benson, 1970). The amount of energy gained as a consequence of the gravitational deposit of matter has been calculated by Ulrich and Burger (1976), Kippenhahn and Meyer-Hofmeister (1977), Neo, Miyaji, Nomoto and Sugimoto (1977), Webbink (1976,1977a,b); they all conclude that the high mass loss rates during the rapid phase can lead to contact systems. Kippenhahn and Meyer-Hofmeister (1977) define critical periods, i.e. the smallest periods in order to avoid contact, for conservative systems, for masses of 10, 15 and 20 $M_\odot$. A review of mass and angular momentum losses is published by Thomas (1977).

6. BINARY EVOLUTIONARY COMPUTATIONS WITH MASS AND/OR ANGULAR MOMENTUM LOSS

Yungelson (1973) calculated mass transfer according to case B for a system consisting of a 1.5 $M_\odot$ primary and a 1.3 $M_\odot$ secondary, assuming that a quarter of the matter expelled by the primary, carrying with it a given amount of angular momentum, leaves the system. The result for the computed case is that the final period is smaller than in the conservative case.
Plavec et al. (1973) calculated the mass transfer for a 7 $M_\odot$ star with a convective envelope, assuming that a fraction f of the matter lost by the mass loser leaves the system, carrying with it a fraction g of the specific angular momentum. The value of the conservative evolution and the influence of the various parameters on the final state was examined by De Grêve et al. (1978). In order to explain some remarkable features due to the conservative assumption (the fact that for the production of WR systems and X-ray binaries extreme mass ratios are necessary), the group Vanbeveren, De Grêve, van Dessel and de Loore calculated the evolution of massive close binaries including stellar wind mass loss before the filling of the Roche lobe and the mass exchange phase, adopting parameters β (fraction of the matter lost by the primary and accreted by the secondary) and α (a measure for the lost angular momentum).

7. MASS LOSS AND THE PRODUCTION OF WR STARS

Early WN stars show almost pure He at their surfaces, hence from an evolutionary viewpointit is obvious that such stars are in a post-core H burning and a post-shell H burning phase, since all H has to be processed into He in order to have He at the surface. For WC stars we see 3α products in the atmosphere, so they are still more evolved and deeper layers appear at the surface. Stellar wind mass loss is not sufficient to produce these WR stars. A still higher mass loss rate will not help since then the convective core shrinks at a faster rate. The highest He rate one can get in that case is that of the material of the convective core in an earlier H core burning stage, but then the H content was not yet zero. Hence in this way it is not possible to create pure He layers at the surface. Since the stellar wind is not sufficient to pro-

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duce early WN or WC stars, we have to involve some other mechanism. The evolutionary stages following core H burning are shorter, so if we want that during these stages the mass should be reduced, we need much larger mass loss rates, e.g. during the red giant stage as is claimed by Chiosi et al. (1978). For the case of late WN stars however stellar wind mass loss could be sufficient. The case of binaries offers an easy and straightforward scenario for the production of WR stars. We know that many WR stars are formed through binary evolution (~25%, according to Massey et al., 1981). During the mass transfer phase the star loses a large fraction of its matter, and layers with enhanced nitrogen appear at the surface with N(H)/N(He)~1. In the overflow phase (case B evolution) a rapid mass loss phase ($\dot{M} \sim 10^{-2}\ M_{\odot}\ yr^{-1}$) is followed by a slow phase ($\dot{M} \sim 10^{-4}\ M_{\odot}\ yr^{-1}$). After the Roche lobe overflow phase the H abundance by weight in the atmosphere is ~0.2. According to Vanbeveren and Conti (1980) this corresponds with the WN 7/8/9 phase. These authors conclude that further mass loss reduces the H content of the atmosphere until pure He-layers appear; then an early WN star is formed.

8. NON-CONSERVATIVE EVOLUTION

The 6th Catalogue of Galactic Wolf-Rayet Stars (van der Hucht et al., 1981) contains 158 galactic Wolf-Rayet stars and 18 among them are known binaries with solutions for the orbit. A study of these systems by Massey (1981) reveals that the average mass of a WR star is ~20 $M_{\odot}$, ranging from 10 to 50 $M_{\odot}$; the period range of these systems is similar to that of their O type progenitors. From a comparison of the projected orbital separations and eccentricities of O type binaries and WR binaries Massey concludes that only the most massive O systems evolve into WR systems, which agrees with the conclusion of Vanbeveren and de Loore (1980) that early WN and WC systems result from ZAMS masses exceeding 50 $M_{\odot}$.

Vanbeveren, De Grève, van Dessel and de Loore (1979) have performed non conservative evolutionary computations including

a) stellar wind mass loss in the phase prior to RLOF (core H burning and H shell burning before RLOF; case B)

b) mass loss and angular momentum loss during the RLOF phase, with as value for the parameters β=0.5 (50% of the mass expelled by the primary leaves the system), and different values for the angular momentum loss, characterized by a parameter α, being 0 (no loss), 1 and 3, the latter value corresponding with ~50% of the angular momentum carried away with the lost matter.

Results of these computations for a system of 40 $M_{\odot}$ + 20 $M_{\odot}$, with different values for α and β are shown in Table 3 and in Figure 6.

The computations lead to the following conclusions :

a) as a consequence of the first phase (stellar wind mass loss) the mass ratio of the two components changes as well as the orbital period;

b) mass and momentum losses have practically no influence on the mass and structure of the primary at the end of RLOF. The core of the star governs the evolution regardless of the situation of the outer layers;

c) cancelling the conservative assumptions during the RLOF phase affects principally the period; this is mainly determined by α.

Table 3. Non conservative evolution of a $40M_\odot + 20M_\odot$ system.
1. Stellar wind mass loss : N=300 : phase 1
   End phase 1: $M_1=23.1M_\odot$; $M_2=16.9M_\odot$; P=10.2d
2. Different cases of mass transfer determined by different β- and α-values. t_1 is the start of the overflow phase, t_2 the end.

		M_1	M_2	P(d)	t_2-t_1 (years)
$\beta=0$ (conservative)	$\alpha=0$	11	29	18.8	12200
$\beta=0.5$	$\alpha=1$	10.7	23.1	6.8	11150
	$\alpha=3$	10.3	23.2	2.9	7700
$\beta=0$	$\alpha=0$	11.2	16.9	62.5	11300
	$\alpha=1$	11.0	16.9	22.3	13300
	$\alpha=3$	10.2	16.9	2.4	14100

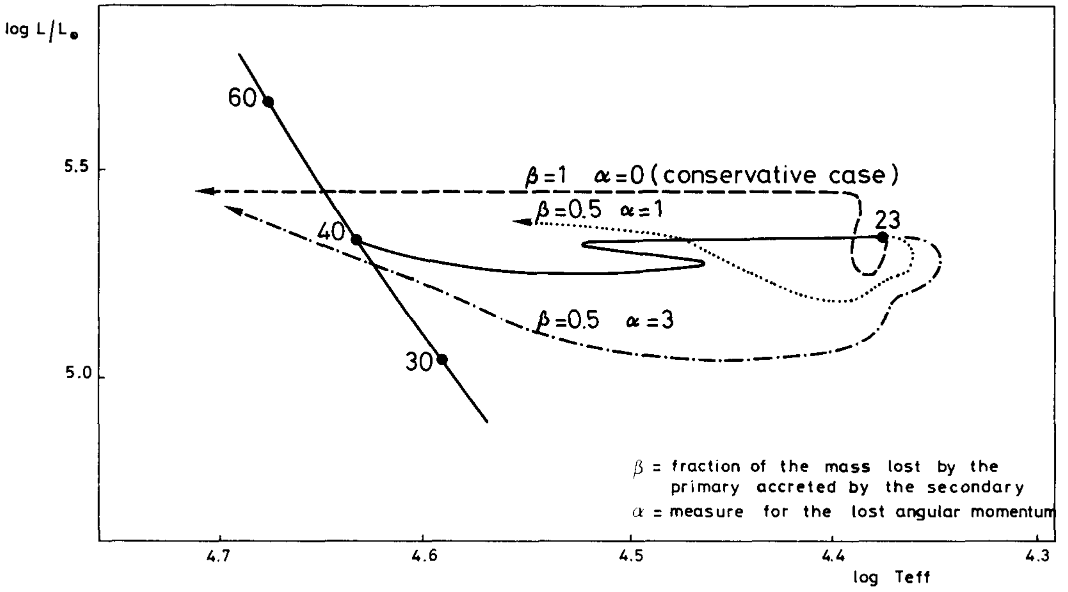

Figure 6. Non conservative evolution for a $40M_\odot + 20M_\odot$ system for various values of the parameters α and β. In full lines the evolutionary track with stellar wind mass loss, N=300.

More arguments are found by comparison of theoretical models with observed stars. A search through the literature was performed by Vanbeveren and de Loore (1980) in order to find massive binary systems with OB type components with sufficiently accurate stellar parameters. An analysis of the stellar parameters leads to the following conclusions :

1. Massive systems in the PROF stage are not converted immediately into WR stars, but have a new normal OB stage. Later on the mass loss rates increase probably by changing conditions in the interior, and the star is observed as a WR star. Vanbeveren and Packet (1979), starting from known WR masses calculated back the mass of the star just after RLOF. From these computations and the observations can be derived that the mass ratio $q = M_2/M_1$ just after RLOF is smaller than 2.

2. As we will see later in more detail the mass ratio of non evolved systems (i.e. systems before RLOF) will increase as a consequence of the mass loss by stellar wind. According to computations of Vanbeveren, De Grêve, van Dessel and de Loore (1979), most of these systems just before RLOF have a mass ratio larger than 0.7.

3. Many massive close binaries evolve according to case B. The observed periods for non evolved and evolved systems (i.e. before and after RLOF) imply that the ratio of the periods after and before RLOF has to be smaller than 1. Comparison of the parameters of observed evolved systems with those of the computed systems before RLOF, and comparison of the observed system parameters of non evolved systems with the evolved models for these systems after RLOF puts constraints on the mass loss during RLOF and on the angular momentum losses. Although it is not possible te derive general results since these parameters are different from case to case, it turns out that at least 50% of the matter lost by the primary has to leave the system (probably more, between 50% and 75%), taking with it some 50% of the angular momentum. Mass accretion has a circularizing effect on the orbit; also observational evidence exists, since alle semidetached systems have circular orbits (Paczynski, 1971; Piotrowski, 1965). The fact that all long period WR stars have large eccentricities reveals that not a large fraction of the expelled matter is accreted by the companion. Hence we can imagine that in certain cases all the mass is flowing out; if this is really the case this would lead to a very comfortable situation comparable with the conservative assumptions, i.e. that we don't have to introduce parameters taking care of the fraction of mass and angular momentum leaving the system.

9. CHANGE OF THE CHEMICAL ABUNDANCES OF THE OUTER LAYERS IN BINARIES

As already mentioned the WR stars are in a post RLOF stage. The systems evolve from massive components which lose a part of their matter by stellar wind during their core hydrogen burning phase (N=300). Willis and Wilson (1978) derived from UV observations that in early WN and WC stars hydrogen is completely missing, hence the outer layers consist of pure helium. Such pure helium layers appear only then at the surface when not more than 10 to 35% of the initial mass is left, depending on

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the evolutionary stage. According to Lamers, Paerels and de Loore (1980) about 20% of the mass is taken away during core hydrogen burning, for single stars (N=100). Hence a more violent process is necessary to remove more matter, and to expose deeper, processed layers. Mass removal by Roche lobe overflow in binaries is a very efficient process in this respect.
The implications of stellar wind mass loss on the production of heavy elements for single stars have been examined by Chiosi and Caimmi (1979) as a combination of the results of Arnett (1978) and Chiosi et al. (1978). The most striking result is that the production of heavy elements (Z>2) is reduced by the inclusion of stellar wind mass losses. In binaries however, the situation is completely different. For single stars mass loss will reduce the stellar mass to ~80% for very massive stars (M~100 M_O) or to 85% (M~40M_O). For binaries, stellar wind in combination with a RLOF stage will reduce the mass of the primary to much smaller values, and material of the initial convective core appears at the surface, and since a large fraction of the expelled matter leaves the system, will enrich the interstellar medium.
Evolutionary models for masses in the range 40 to 100 M_O, with mass loss rates as observed for Of stars (4 to 7.10^{-6} M_O yr^{-1}) were computed by Noels et al. (1981), in order to follow the surface composition of H, He, C, N and O. The result of these computations is that at the surface equilibrium CNO-products appear, i.e. enhanced N and less O, during the core hydrogen phase. In this way late WN stars can be produced.

If we assume that the optical components of X-ray binaries are normal stars at the end of their core hydrogen burning phase, the evolution of these systems can be described by a mass loss equation $\dot{M} = -N\ L/c^2$. Starting from the parameters given for five X-ray binaries by Conti (1978) the post Roche lobe overflow remnants were calculated for N=300

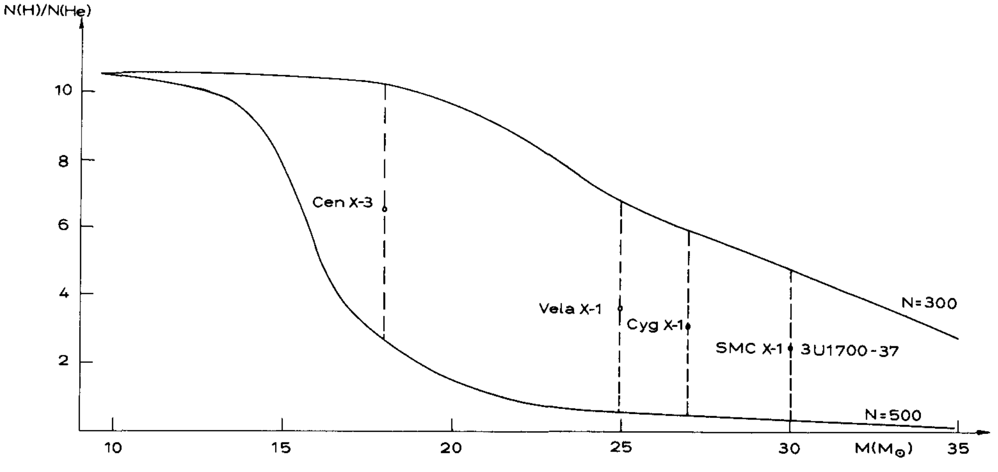

Figure 7. The N(H)/N(He) ratio for post Roche lobe overflow remnants calculated with N=300 and N=500. The position of 5 X-ray binaries is indicated.

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and N=500 (Vanbeveren et al., 1979). Almost all the expelled matter leaves the system, hence a massive helium remnant and a close collapsed companion, a neutron star, are left. Considering the tracks for N=300 and N=500 as upper and lower limits for the X-ray binary region in the luminosity-mass diagram allows an estimate for the N(H)/N(He) ratio of these systems. At least for 4 of these systems this ratio has decreased considerably (Figure 7).

10. THE EFFECT OF MASS LOSS ON THE MASS RATIO DISTRIBUTION

The advanced evolution of binaries, especially the later stages (OB runaway stage, X-ray stage, followed by a further evolution of the non collapsed object, leading to a second WR stage and a second X-ray stage), dependsstrongly on the mass of the primary and the mass ratio of the system. So the lifetime of the secondary after the supernova explosion of its companion is for a $20M_{\odot}$ + $8M_{\odot}$ system of the order of 5.10^6 years, whereas for a $100M_{\odot}$ + $90M_{\odot}$ system this is $<10^5$yrs (Doom and De Grève,1981) In order to examine the occurrence of these advanced stages we have to know the mass ratio distribution at the ZAMS, for massive stars. Garmany et al. (1980) give a list of 40 O type binaries, with sufficiently accurate data. From this list we selected 23 unevolved systems, and by comparing their position in the HR diagram with evolutionary tracks calculated with N=300, the actual masses M_1 and M_2 and mass ratios q can be determined. Moreover, using again these evolutionary tracks and the tables (de Loore et al., 1978a,b) the ZAMS masses M_{1i} and M_{2i} and the ZAMS mass ratio can be derived. The results are given in Table 4, and the actual and ZAMS mass ratio q_i are shown in Figure 8, a and b. The actual q-distribution as a function of the initial mass and the ZAMS distribution, for the N=300 case can be approximated as :

$$q_{actual} = \frac{1 + 0.04 \times M_{1i} \times q_{ZAMS}}{1 + 0.04 \times M_{1i}}$$

and this means

$$q_{actual} > q_{ZAMS}$$

Hence the mass ratio increases during the evolution and at the end of the main sequence will show a still more pronounced peak in the range $0.8 \leq q < 1$. Now we can be concerned about the fact that only O stars are included; if we extend our sample to further evolved initial O stars (with ZAMS masses > $15M_{\odot}$) and occurring now as later types we find the actual ZAMS distribution for O stars displayed in Figure 9, a and b (a total of 31 stars). The distribution shows the same characteristics as the previous sample. An important question is now if the q-distribution reflects the reality or if selection effects mask the real distribution. If we believe that fragmentation is the dominant mechanism for the origin of binaries one should expect two components of nearly the same mass (Lucy, 1980), hence an overabundance of systems with q~1,

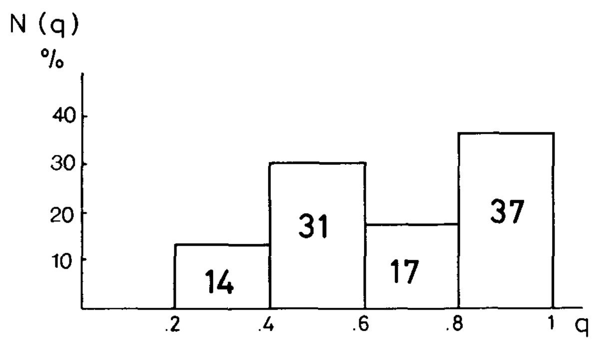

Figure 8a. The actual mass ratio distribution of O-type stars.

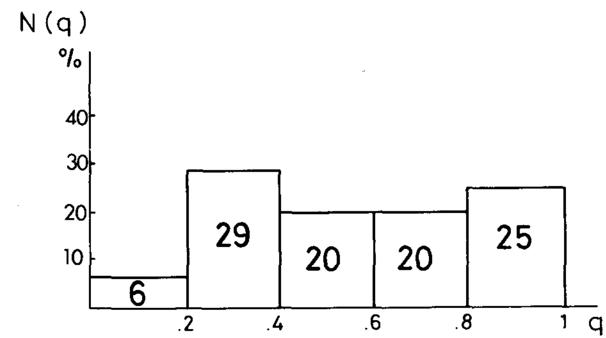

Figure 8b. The ZAMS mass ratio distribution of O-type stars.

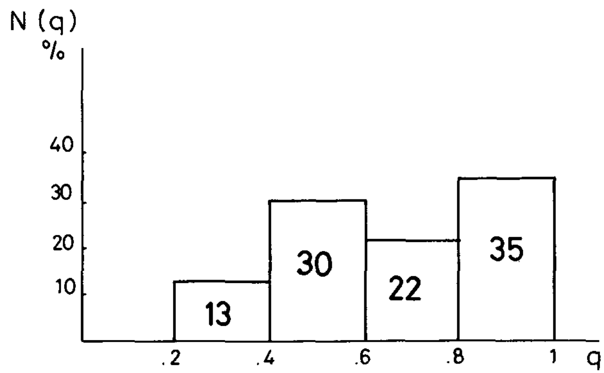

Figure 9a. Actual mass ratio distribution for O-stars, for a sample composed of the previous one completed with 8 later type stars, as farther evolved initial O type ZAMS stars,but still before their mass exchange stage.

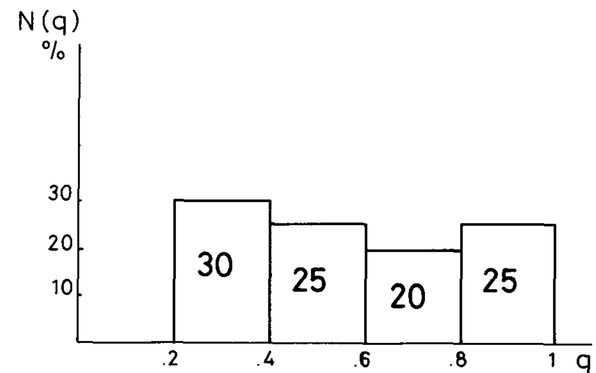

Figure 9b. The ZAMS distribution for this sample.

Table 4. Characteristics of non evolved O-type binaries.

HD	spectral type	log L/L_o	log T_{eff}	M_1	$t/10^6$yr age since ZAMS	M_{ini}	q	M_1	M_2	M_{1i}	M_{2i}	q_i
1337	08	5.38	4.49	26	4	46	.78	26	20	46	28	.61
12323	09V	4.94	4.53	15	0.5	15	?	15		15		
19820	09IV	5.00	4.53	24	2.87	30	.49	24	117	30	12	.39
35921	09.5III	5.06	4.50	23	3.3	32	.37	23	8.5	32	8.5	.27
36486	09.5II	5.90	4.48	33								
37041	09.5V	4.66	4.53	17	0	17	.9	17	15.3	17	15.3	.9
37043	09III	5.38	4.54	38	1.9	38	.59	38	22	50	26	.52
48099		5.09	4.57	30	1.3	35	.59	30	18	35	19	.54
57060	08I	6.02	4.55	42								
57061	09III	5.38	4.52	31	3.2	48	.45	31	14	48	14	.29
75759		4.63	4.53	18	.5	18	.81	18	15	20	16	.81
93205	03V	5.74	4.69	70	0	70	.38	70	27	70	27	.38
93206		5.00	4.48	21	4.2	30	.40	21	8.4	30	8.4	.28
93403	0.5fIII	6.00	4.58	42	3	100	.67	42	28	100	40	.40
135240	09V	5.00	4.53	25	3.0	35	.90?	25	22.5	35	26	.74
149404		5.12	4.52									
150136		5.47	4.62	41	1.5	50	.56	41	23	50	25	.50
152218	09.5III	5.06	4.50	23	4.4		.80	23	18	42	19	.45
152219	09.5IV	4.85	4.50	18	3	22	.70	18	13	22	13	.59
152248	07fI	6.04	4.56	42	3	100	.93	42	39	100	90	.90
155775		4.41	4.50	16	.5	16	.75	16	12	16	12	.75
159176	07V	5.24	4.56	28	3	28	.94	28	26	40	37	.93
165052	06.5V	5.34	4.57	33	2.4	33	.88	33	29	45	37	.82
167771	07.5fIII +09III	5.51	4.54	30	2.7	55	.87	30	26	55	35	.64
191201		4.85	4.53	18	3	23	.93	18	17	23	21	.91
199579	06.5III	5.50	4.57	38	1.9	50	.50	38	19	50	23	.46
209481	08.5III	4.94	4.54	24	2.8	30	.47	24	11	30	11	.37

like the Popov distribution (Figure 10). Since we cannot decide we will use both distributions for the discussion of the later phases of the evolution.

11. THE LIFETIME OF THE SECONDARY AFTER ACCRETION

The lifetime of the secondary after accretion can be computed, assuming that the supernova explosion occurs after a case B of mass exchange, somewhere after core H exhaustion, but before He exhaustion, at a moment where about 10% of the main sequence lifetime of the primary is left. Such computations are carried out by Doom and De Grêve (1981) for the case $\beta = 0.5$. The results are shown in Table 5.
In order to investigate the succession of the events (Wolf Rayet phase, X-ray phase,...) the lifetimes of the secondaries and the rest lifetimes

Table 5. Lifetimes of secondaries after accretion, for initial masses M_1 and mass ratios q, in 10^6 years.

q / M_1	.90	.85	.80	.60	.30
100	0.05	0.06	0.08	0.24	0.73
80	0.06	0.09	0.11	0.28	0.69
60	0.07	0.10	0.15	0.30	1.12
40	0.09	0.18	0.29	0.41	1.32
20	0.18	0.29	0.42	1.10	1.56

of the primaries are compared by calculating the normalized difference d

$$d = \frac{t_{MS_2} - 0.1\ t_{MS_1}}{1.1\ t_{MS_1}}$$

where t_{MS_2} is the computed lifetime of the secondary, $0.1\,t_{MS_1}$ the assumed rest lifetime of the primary and $1.1\ t_{MS_1}$ the total lifetime of the primary. The value of d (positive or negative) as a function of the mass of the primary M_{1i} and the mass ratio q is depicted in Figure 11.

12. DIFFERENT EVOLUTIONARY SCENARIOS FOR MASSIVE SYSTEMS WITH MASS RATIOS ~1 AND EXTREME MASS RATIOS

In Figure 12 are shown the different evolutionary stages expected for a normal evolution, as proposed by van den Heuvel and Heise (1972) and worked out in detail by de Loore et al. (1975). In this scenario the sequence of the various stages is as follows: main sequence stage, mass exchange, Wolf Rayet phase, explosion, OB runaway stage, X-ray stage, a new mass exchange, a possible new X-ray stage, WR runaway phase, possibly a third X-ray stage, a second supernova explosion and disruption of the system. This picture which remains qualitatively valid, has to be adapted for the case of mass losses by stellar wind during the main sequence phase, and also non conservative mass exchange has to be considered. The numbers in the figure were calculated according to these improvements. This scenario is valid if the mass ratio is not too close to 1, say lower than q = 0.8, according to the previous section. If the two masses are nearly equal, the scenario changes in the sense that the OB runaway stage and the normal X-ray stage are lacking. Indeed, the secondary starts Roche lobe overflow immediately after the end of the mass exchange phase of the primary. The situation O star primary with a neutron star companion does not occur. On the other hand we have a curious set of combinations with helium stars: a first short stage of an O star with a helium star companion (normal Wolf-Rayet star) is followed by a situation where the two components are helium stars (a Wolf Rayet star with two helium components) and then finally after explosion of the most evolved helium star, the situation

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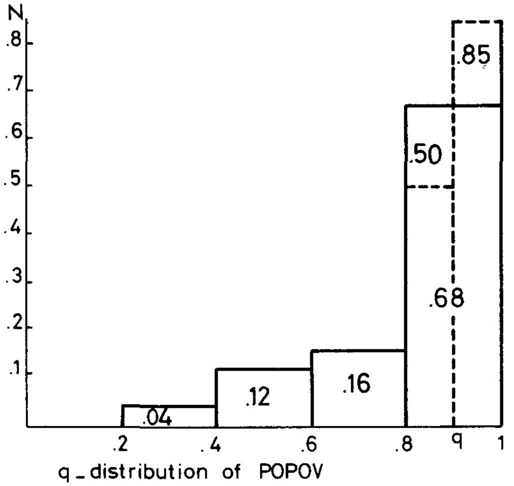

Figure 10. The mass ratio distribution according to Popov.

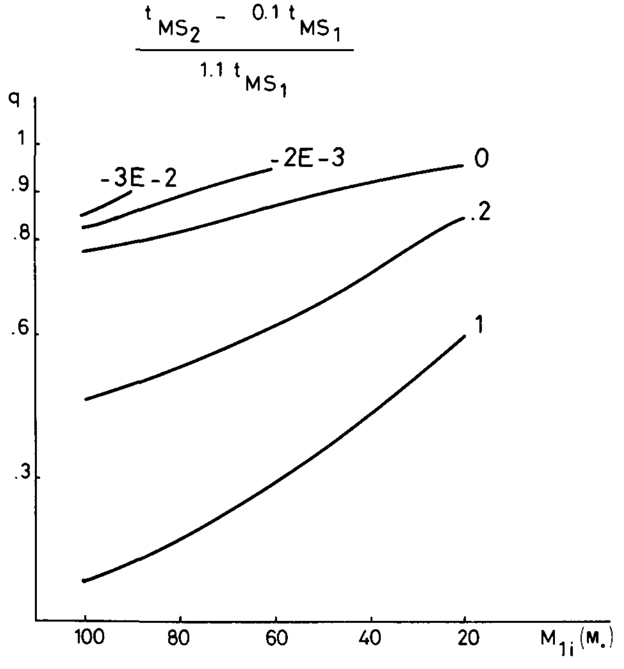

Figure 11. The normalized difference between the lifetime of the rejuvenated secondary and the remaining lifetime of the secondary after mass exchange. *The normalisation factor is the total lifetime of the system.*

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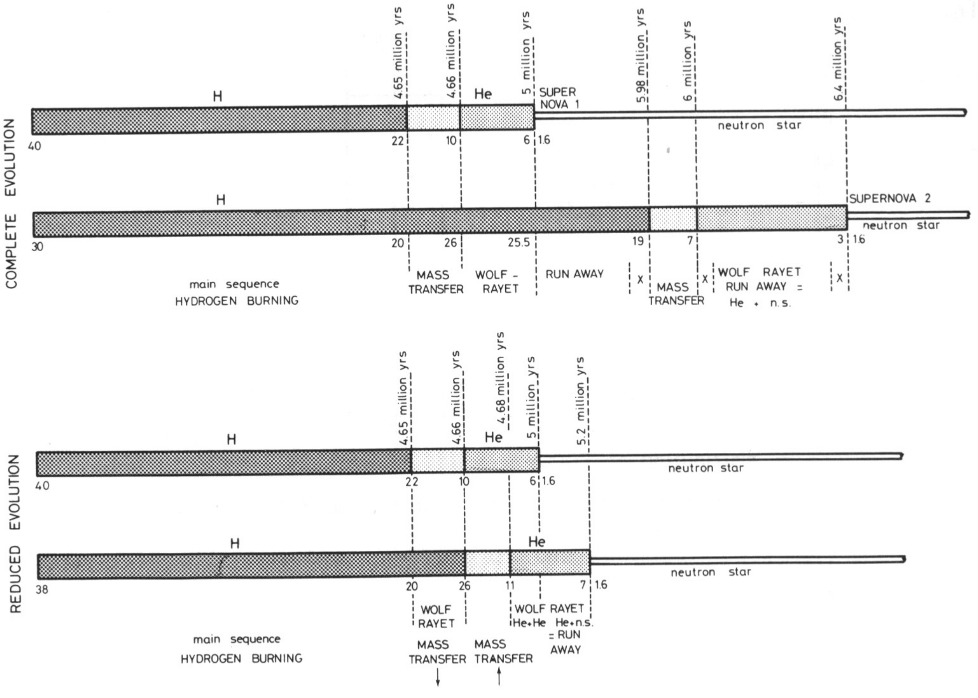

Figure 12. Succesive evolutionary stages for a normal case ($40M_\odot+30M_\odot$) with q=0.75 and for a reverse case ($40M_\odot+38M_\odot$) with q=0.95.

of a helium star with a collapsed companion (a runaway Wolf-Rayet star). There is also the possibility that during this last explosion the system is disrupted, so that a single helium star remains, representing a single Wolf-Rayet star. It should be noticed that this Wolf-Rayet run-away stage is also present in the case of more extreme mass ratio binaries. Examples of each of these cases exist: at the moment 6 Wolf-Rayet runaways are known: HD 50896, HD 93131, HD 96548, HD 192163, HD 197406 and HD 164270 (Firmani et al., 1979; Moffat and Seggewiss, 1979,1980; Moffat and Isserstedt, 1980; Koenigsberger et al., 1980). Also for the theoretical case of two helium stars exists observational evidence. Pesch, Hiltner and Brandt (1960) discovered that the star WR 145 (=MR 111 = AS 422) is a single lined spectroscopic binary with mass function 77 and a period of 22 days, with spectral type WN. Recently Conti classified it as WN+WC. In the 6th Catalogue of galactic Wolf-Rayet stars (van der Hucht et al., 1981) four WN+WC stars appear. They are listed in Table 6.
It is not yet known whether the other three stars are binaries or single transition WN to WC stars.

Table 6. Wolf-Rayet stars with WN and WC characteristics.

WR number	name	spectral type	V
8	HD 62910	WN6 + WC4	10.56
26	MS1	WN + WC	14.64
98	HDE 318016	WN6 + WC7	12.51
145	AS 422	WN + WC	12.3

13. CONCLUSIONS

Mass losses and mass transfer processes are very important for the evolutionary status of binaries. As a result of mass loss by stellar wind and Roche lobe overflow early WN and WC stars can be produced, and the observed atmospheric abundances can be explained. Comparison of observations and evolutionary computations reveal that only the more massive O type binaries evolve into early WN and WC stars. Due to stellar wind mass losses the initial mass ratio of massive systems increases towards unity. The lifetime of the secondary after Roche lobe overflow of the primary depends on the mass of the primary and on the initial mass ratio. The number of OB runaways depends critically on the ZAMS mass ratio distribution: for the Popov distribution the number of OB runaways is a factor of 2 to 3 smaller than for a mass ratio distribution as given in Figure 8. However taking into account the fact that the number of massive O type binaries is rather small (of the order of 4000) the average lifetimes of the sleeping phases is ~300000 years, hence 0.1 of the lifetime of the average systems, and the fact that the selection of observing material centers on systems with large Z, which reduces again the sample with a large factor, makes that not more than ~ ten OB runaways are expected to be found.

REFERENCES

Appenzeller, I.:1970,Astron.Astrophys.5,355.
Arnett,W.D.:1978,Astrophys.J.219,1008.
Barbaro,G., Chiosi,C., Nobili,L.:1972,Astron.Astrophys.18,186.
Chiosi,C., Summa,C.:1970,Astrophys.Space Sci.8,478.
Chiosi,C., Caimmi,R.:1979,Astron.Astrophys.80,234.
Chiosi,C., Nasi,E., Sreenivasan,S.R.:1978,Astron.Astrophys.63,103.
Conti,P.S., Garmany,C.D.:1981,Astrophys.J.,submitted.
Conti,P.S.:1979, IAU Symp.83, "Mass Loss and Evolution of O-Type Stars", eds. P.S.Conti and C.de Loore, Reidel, Dordrecht, the Netherlands
De Grêve,J.P., de Loore,C., van Dessel,E.L.:1978,Astrophys.Space Sci.53, 105.
Doom,C., De Grêve,J.P.:1981, preprint.
Firmani,C., Koenigsberger,G., Bisiacchi,F., Ruiz,E., Solar,A.:1979,IAU Symp.83 "Mass Loss and Evolution of O-Type Stars", eds. P.S.Conti and C.de Loore,Reidel,Dordrecht,the Netherlands.

Garmany,C.D., Conti,P.S., Massey,P.:1980,Astrophys.J.(in press).
Gathier,T., Lamers,H.J.G.L.M.:1981,Astrophys.J.,submitted.
van den Heuvel,E.P.J., Heise,J.:1972,Nat.Phys.Sci.239,67.
van der Hucht,K., Conti,P.S., Lundstrom,I., Stenholm,B.:1981,Space Sci. Review,preprint.
Hutchings,J.B.:1976,Astrophys.J.203,438.
Iben,I.Jr.:1967,Ann.Rev.Astron.Astrophys.5,571.
Kippenhahn,R., Meyer-Hofmeister,E.:1977,Astron.Astrophys.54,539.
Koenigsberger,G., Firmani,C., Bisiacchi,G.F.:1980,Rev.Mex.Astron.Astrof., in press.
Kopal,Z.:1959,"Close Binary Systems",p.125,New York,J.Wiley.
Kuiper,G.P.:1941,Astrophys.J.93,133.
Lamers,H.J.G.L.M., Paerels,F., de Loore,C.:1980,Astron.Astrophys.87,68.
de Loore,C., De Grêve,J.P., Lamers,H.J.G.L.M.:1977,Astron.Astrophys.61, 251.
de Loore,C., De Grêve,J.P., Vanbeveren,D.:1978a,Astron.Astrophys.67,373.
de Loore,C., De Grêve,J.P. Vanbeveren,D.:1978b,Astron.Astrophys.Suppl. 34,363.
de Loore,C.:1981 Proc.5th IAU Reg.Meeting Liège "Variability in Stars and Galaxies, eds.A.Boury and A.Noels.
de Loore,C., De Grêve,J.P., De Cuyper,J.P.:1975,Astrophys.Space Sci.36, 219.
Lucy,L.B.:1980,IAU Symp.88,"Close Binary Stars:Observation and Interpretation", eds.M.J.Plavec,D.M.Popper,R.K.Ulrich, p. 7.
Massey,P.:1981, preprint.
Moffat,A.F.J., Seggewiss,W.:1980,Astron.Astrophys.86,87.
Moffat,A.F.J., Seggewiss,W.:1979,Astron.Astrophys.77,128.
Moffat,A.F.J., Isserstedt,J.:Astron.Astrophys.,in press.
Neo,S., Miyaji,S. Nomoto,K., Sugimoto,D.:1977,Publ.Astron.Soc.Japan 29,249.
Noels,A., Gabriel,M., Conti,P.S.:1981,preprint.
Pesch,P., Hiltner,W.A., Brandt,J.C.:1960,Astrophys.J.132,513.
Paczynski,B.:1971,Ann.Rev.Astron.Astrophys.9,183.
Piotrowski,S.:1965,Bull.Acad.Pol.Sci.Ser.Math.Astron.Phys.12,419.
Plavec,M., Ulrich,R.K., Polidan,R.S.:1973,Publ.Astron.Soc.Pacific 85, 769.
Schwarzschild,M., Härm,R.: 1959,Astrophys.J.129,637.
Stothers,R., Chin,C.W.:1980,Astrophys.J. submitted.
Tanzi,E.,Tarenghi,M., Panagia,N.:1980,private communication.
Thomas,H.C.:1977,Ann.Rev.Astron.Astrophys.J.,submitted.
Ulrich,R.K., Burger,H.L.:1976,Astrophys.J.206,509.
Vanbeveren,D., Packet,W.:1979 Astron.Astrophys.80,242.
Vanbeveren,D., Conti,P.S.:1980,Astron.Astrophys.88,230.
Vanbeveren,D., De Grêve,J.P., van Dessel,E.L., de Loore,C.:1979,Astron. Astrophys.73,19.
Vanbeveren,D., de Loore,C.:1980,Astron.Astrophys.86,21.
Webbink,R.F.:1979,IAU Coll.49 "Changing Trends in Variable Stars Research", Hamilton, New Zealand, eds. F.M.Bateson, J.Smak, I.H.Ulrich, p.102.

Webbink,R.F.:1976,Astrophys.J.209,829.
Webbink,R.F.:1977a,Astrophys.J.211,486.
Webbink,R.F.:1977b,Astrophys.J.211,881
Willis,A.J., Wilson,R.:1978,Monthly Notices Roy.Astron.Soc.82,55.
Yungelson,L.R.:1973,Sov.Astron. A.J. 16,864.

DISCUSSION

SERRANO: There is something that worries me. Apparently, your calculations show that the effect in the heavy elements production is to reduce it by a factor of 3 with respect to results obtained by Chiosi and Caimmi. There is already some problem in explaining the amount of heavy elements in the solar neighborbood (factor of 2). So either we start looking for new ways of cooking these elements or we must conclude that the case you have studied is very uncommon.

NIEMELA: 1) I would like to point out that we actually observe the late WN stars to be more massive than their OB companions. 2) Would an orbital eccentricity effect very much your calculations?

VANBEVEREN: 2) The calculations will not be very much affected because how the Roche lobe overflow is really treated is not important for the final result after Roche lobe overflow.

BISIACCHI: There is something that I question in your evolutionary scenario: you will expect runaway X-ray binaries, but if I remember well, the peculiar velocity of these systems is normal.

DE LOORE: I believe that the average distance to the galactic plane is estimated at $\sim$ 100 pc in X-ray binaries. This is quite reasonable if we follow their evolution after the explosion: probably this explosion occurs asymetrically so that the net effect is an extra force which can be represented by an extra velocity of $\sim$ 100 km. If we calculate now the distance after 10^6 year we find about this distance.

CONTI: I think the question of whether or not binaries have higher stellar wind mass loss than single stars (of similar L, g_{eff}) is not settled. I refer to pre- RLOF of course. In your figure RLOF = 2 you showed binaries preferentially at higher rates. But there are two

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selection effects which invalidate any conclusion at the present time. First, the UV investigations (Conti and Garmany) deliberately avoided the binaries, so the absence of binary systems with low rates is not conclusive. One star was found to be a binary after being observed. Second, the IR rates preferentially sample stars with higher $\dot{M}$. One needs a complete uniform sample of singles and binaries with one unbiased method. Certainly a wind in a binary is modified by a companion but there is no certainty that the rate is increased. An interesting consequence would follow if singles and binaries have similar rates. The X-ray systems, in which the present star is pre-RLOF, give a very good estimate of rates by mass estimates, impossible to determine in single stars. These suggest, as you said, $N \approx 400$. Perhaps $N \approx 400$ also in single stars!

CHIOSI: Firstly, I would like to comment on the correction that is applied to the radius of massive stars ($M > 60_{\odot}$) caused by pulsational instability. I do not understand why such a correction was applied only to models at point B and not also to main sequence models. I wonder if this correction can exist at all as vibrational instability was found to occur only in stars more massive than 100 $M_{\odot}$. Secondly, I never claimed that my scenario for "single" WR stars can be applied also to binary WR's. Therefore the comment that in my picture the mass of WR would be greater than the mass of OB companions is not meaningful. However at closer analysis of the problem the single WR scenario might be used in some binary systems without contradicting this binary nature (for istance, if the separation is very large).

DE LOORE: The only reason that I try to apply the Appenzeller formalism is to show that this could possibly be a way out of the ambiguity between the position of O stars during their core hydrogen burning and the region between ZAMS and TAMS following from computation with different mass loss rates. Therefore I expanded these evolutionary tracks and I did this in a gradual way. The vibrational instability does not start immediately on the ZAMS, as the strenght of the pulsation is too low to have any effect. But after some 30000 years, the pulsation grow and become relevant. Therefore I have left the ZAMS at its original position. Although the investigations of Appenzeller deal with a 130 $M_{\odot}$ star, I believe the results can be applied to lower mass stars, say 60 $M_{\odot}$. I agree with the last remark. It depends indeed on the fact of how your single star computations are taken together to construct binaries.

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CARRASCO: We do not require of exotic acceleration mechanisms to explain the runaway stars. It has been proved that these stars present kinematical properties of old-disk stars, hence meaning that they have loss mass progenitors. (Carrasco et al., 1978, IAU Symp. No. 83).

DE LOORE: An asymmetric explosion is in my opinion not something which has to be called exotic. In one evolutionary scenario we think that the sequence is: OB+ns, X-ray stage, WR+ns as a consequence of mass loss and mass transfer. Wolf Rayet stars with neutron star companions, i.e. WR runaways, have been discovered; for one case, even a period exists. So in this picture the OB+ns companions, i.e. OB runaways, as young objects,fit. We are trying very intensively to detect the binary character of these runaways by observing them.

MAEDER: I was very interested by your computations taking into account the increase of stellar radius due to the d^2r/dt^2 term in the momentum equation. But, I would like to understand quite clearly what has exactly been done in this work. Did you simply take a recipe from Appenzeller's work to increase the stellar radius? Alternatively have you explicitly incorporated the acceleration term in the equations which would mean that in certain cases you would have to follow an incredibly large number of pulsation periods if Appenzeller's technique if used?

DE LOORE: We are working at this problem, and we have included already this term in the program. However what I showed you here is not according to computations. I have only expanded the evolutionary tracks for N = 300, and computed in the ordinary way. I have made this expansion gradually in the sense that the points in the immediate vicinity of the ZAMS have not changed, but farther on the points are displaced farther and farther away. We will perform exact computations, but this is complicated work. The most severe problem is indeed how to follow the pulsations, a problem that is not yet solved. We will try to follow perturbation, then skip a part, and then restart, hence we will try to treat the pulsations by bundles.

FALK: Could you please repeat why you rule out single stars evolving through the core He burning phase as progenitors of the WR stars?

DE LOORE: The mass loss rates are not sufficiently high to peel the star down to have processed products at the surface so that the observed N(H)/N (He) ratio can be explained. During the core He burning phase also mass loss was taken into account, but the core He burning phase is much shorter than the core H burning phase so that not very much mass has to be removed. Some enhanced mass loss mechanism has to be invoked (large stellar wind mass loss during the giant phase forcing the stars to move to the blue part of the HRD or Roche lobe overflow for binaries) to remove more mass.

FALK: So, it is only because your mass loss algorithm does not include a gravity factor (or at least, does not depend on radius) that core He burning stars cannot lose enough mass to become hot stars.

DE LOORE: Gravity was not included explicity into the computation, but even then, assuming that the mass loss should be increased by an order of magnitude, the effect would not be sufficient.

TREVES: Could you comment on the relative weakness of C lines with respect to N lines observed in low mass X-ray binaries, which recalls what is observed in WRN?

DE LOORE: I cannot give you an answer immediately. It is an interesting question. The problem should be examined in detail.

SIMA: If I understood well, according to your calculations, each binary with a large mass produce a supernova twice within its lifetime. Is it in accordance with statistics of Supernovae?

DE GREVE: It is correct that a massive binary produces two SN explosions. However, if you want to give a theoretical estimate of the SN - rate per year, you need the knowledge about the timescales of both components, during the evolution of the system. These timescales have now been computed by C. Doom and myself. With this tool the SN - rate can now be computed properly and compared to the observations.

SAHADE: My reaction to the evolutionary computations is that when identifying specific stars of groups of stars with specific stages of evolution there is the word "if" in the dictionary that ought to be used. The reason being that stars are not only defined by their chemical composition or by their mass or by other parameters, but by a number of parameters and the characteristics of their atmospheres and extended envelopes.