THE EVOLUTION OF MASSIVE STARS - THE PRODUCTION OF BINARY WR STARS

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1. INTRODUCTION

A large part of the stars of the galactic disk are binaries. Abt and Levy (1976,1978) estimate that more than 50% of B type stars are members of binary or multiple systems, and about 50% are close binaries. According to Conti et al. (1980) the total fraction of certain or probable binaries among O stars is about 36 percent. This means that during the evolution their components can fill their Roche volumes, and consequently have to lose mass in order to keep the star within the allowed surface. Several review papers dealing with the evolution of binaries were published recently: Paczynski (1971,1980), van den Heuvel (1976), de Loore (1980,1981), Webbink (1979).

For unevolved binaries, i.e. systems where Roche lobe overflow has not yet taken place, the mass ratio distribution has a peak near 1, but also systems with extreme mass ratios are known.

Close binaries can interact in various ways: during the evolution the components can fill their Roche lobes and mass transfer (and mass loss) can occur, or one of the components can accrete matter by stellar wind mass losses by the companion. Changes of the stellar and system parameters can occur by tidal interaction, by radiation, magnetic fields. In some cases the two components can merge, or can be converted into systems with common envelopes. As long as the components are smaller than their Roche lobes (or tidal lobes) the systems are detached - only weak interactions can occur, i.e. interactions by tides, radiation, stellar winds, magnetic forces.

2. ROCHE LOBE OVERFLOW

During stellar evolution various stages exist where the stellar radius increases: core hydrogen burning, shell hydrogen burning, core helium burning.

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For a given binary system, determined by the masses of the components and the orbital period, the Roche radius can be calculated. If one of the components during its evolution expands so that it fills its Roche lobe (the stellar radius exceeds the Roche radius), mass transfer through the vicinity of the inner Lagrangian point L_1 starts. The system is then semi-detached. In this way the primary can lose 60 to 80% of its initial mass on a thermal timescale. The mass of the remnant M_f of a primary with ZAMS mass M_f after stellar wind mass loss ($\dot{M} = 100\,L/c^2$) and after Roche lobe overflow (starting during early shell hydrogen burning) can be approximated by

$$M_f = (0.74 + 0.16\,M_i)^{1.35}$$

If the mass ratio is near to 1 the two components can evolve "in tandem", i.e. while one component fills its Roche lobe and expells matter, the companion can expand also and fill its Roche lobe. In that case a contact binary is formed. The system can rotate as a solid body. The common surface can reach the outer Lagrangian point L_2, and mass loss through the vicinity of L_2 can occur. This process is only important when the envelope of the binary rotates synchronously with the orbital motion, since otherwise the point L_2 has no dynamical meaning. If the surface of the system is beyond the point L_2 it has a common envelope.

3. MASS LOSS IN BINARIES BEFORE THE ROCHE LOBE OVERFLOW PHASE

Observations of early type stars in the UV, IR, optical and radio-range, reveal that these stars are losing mass at rates of 10^{-8}-10^{-5} $M_\odot yr^{-1}$; the material is accelerated to velocities of the order of 10^3 km s^{-1}. The mechanism at the basis of this outflow of the material is not known, but it is generally accepted that the radiation pressure in the ultraviolet resonance lines accelerates the matter to these large velocities.

All luminous stars with $\log L/L_\odot > 4.3$ (or $M_{bol} < -6$) have observable mass loss rates; less luminous stars show mass loss effects only when $v \sin i > 200$ km s^{-1} (Snow and Marlborough, 1976; Lamers and Snow, 1978). The M_{bol} lower limit for observable mass loss is valid for all spectral types earlier than F.

Stellar evolution during core hydrogen burning occurs at nearly constant luminosity. Stars showing mass loss effects at the ZAMS continue to lose mass during later evolutionary phases; stars with marginal mass loss rates at the ZAMS will not show mass loss effects during later evolutionary phases. The mass loss rates derived from infrared excess by Barlow and Cohen (1977) show a dependence on luminosity

$$\dot{M} \sim L^{1.1}$$

which agrees with the predictions of Castor, Abbott and Klein (1975) for the radiative driven wind model, for $\alpha = 0.9$. From recent radio observations Abbott, Biegung and Churchwell (1980) derived a different relation

$$\dot{M} \sim L^{1.56}$$

On the other hand, Lamers, Paerels and de Loore (1980) and Conti and Garmany (1980), using ultraviolet spectra of O-type stars, showed that the mass loss rates of O-stars depend on the luminosity class. Hence various parametrisations are possible :

1. Pure L-dependent relations
   a) $\log \dot{M} = 1.5 \log L - 14$ (de Loore, 1981)
   which can be compared with the Abbott, Biegung and Churchwell relation $\log \dot{M} = 1.56 \log L - 14.4$ (the expressions are nearly similar for $4.3 < \log L < 6$, i.e. the log L domain where the mass loss rates are important; the differences range between 0.04 and 0.26).
   Garmany et al. (1981) obtained from a weighted least squares fit to 39 stars : $\log \dot{M} = 1.73 \log L - 15.8$, which leads to values a factor of 2 to 5 smaller.

   A different relation between $\dot{M}$ and L can be derived for O-stars of luminosity classes V-III, and for OI stars and Of stars.

   b) for O-stars :
   $\log \dot{M} = 1.68 \log L - 16.81$

   and for Of-stars and OI stars :
   $\log \dot{M} = 1.18 \log L - 12.65$

2. Relations dependent on more parameters (L, M, R)
   a) Andriesse (1979)
   $\log \dot{M} = 1.5 \log L - 13.23 + 2.25 \log R - 2.25 \log M$

   b) Lamers (1981)
   $\log \dot{M} = 1.42 \log L - 15.35 + 0.61 \log R - 0.99 \log M$

For Wolf-Rayet stars the mass loss rates range between 10^{-5} and 5.10^{-5} $M_{\odot} yr^{-1}$ and they are not strongly correlated with luminosity or with spectral type.

4. CONSERVATIVE BINARY EVOLUTION

Until recently most model computations for the evolution of close binaries were made under conservative assumptions, i.e. the total mass and the orbital angular momentum are conserved during the mass transfer phase.

Conservative binary evolution has been reviewed by Plavec (1968), Paczynski (1971,1980), Thomas (1977).

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Observational evidence exists that for some binaries where the primary is losing mass, a fraction of the expelled mass is leaving the system (Huang, 1966; Batten, 1970; Drechsel et al., 1980).

The general picture of the conservative evolution is that the primary can fill its Roche lobe during core hydrogen burning, shell hydrogen burning (the most frequent case) or helium burning. The primary transfers matter towards the secondary, which accretes all the expelled material. When the Roche lobe overflow phase ends, a helium star is left as remnant of the primary. It is assumed that the accreting secondary evolves like a normal main sequence star.
During the part of the transfer phase where the primary (mass losing star) is the more massive one, the orbital period decreases. When the mass ratio is reversed and the mass transfer phase is not finished the orbital period increases. Examples for the first and second case are given by SV Cen (Nakamura et al., 1977; Drechsel et al., 1980) and U Cep. As a consequence of the rapid mass transfer the secondary can expand and fill its own Roche lobe. In this case a contact system is formed, and the two stars have a common envelope (Benson, 1970; Flannery and Ulrich, 1977; Kippenhahn and Meyer-Hofmeister, 1977; Neo et al., 1977).
In the case mass loss starts during core hydrogen burning the most general issue is the formation of a contact system.
In the case mass transfer starts later during shell hydrogen burning, it is easier to avoid this contact phase.
Since we are interested in Wolf-Rayet stars in this symposium only the evolution of massive stars will be considered here.

When the Roche lobe is filled a semi-detached system is formed, and mass transfer starts. The time interval for the mass exchange is given by the Kelvin-Helmholtz time (thermal time scale)

$$t_{KH} = 3.10^7 \ M^2/RL \text{ years}$$

(M, R and L in solar units).
This is a rapid mass transfer, and the maximum mass exchange rate is

$$\dot{M} \sim \Delta M/t_{KH}$$

The rapid mass transfer ends when the primary ignites helium in its core, which has as consequence a decrease of the stellar radius.

Conservative massive close binary evolution computations have been carried out a.o. by Paczynski (1966,1967), de Loore and De Grève (1975 a,b, 1976), de Loore et al. (1974,1975), Tutukov, Yungelson, Kraitcheva (1975), Kippenhahn and Weigert (1967).

5. NON CONSERVATIVE EVOLUTION OF MASSIVE CLOSE BINARIES

De Grève, de Loore and van Dessel (1978) examined the value of conservative evolution for massive close binaries and concluded that in order to produce Wolf-Rayet systems and massive X-ray binaries one has to start from ZAMS systems with extreme mass ratios (far from 1) and very short periods; however this will lead to contact systems. More explicitely it is not possible that systems with initial mass ratios > 0.5 can produce the observed periods and mass ratios. The conservative evolutionary computations lead only to a rough correspondence between observed and calculated parameters. It is not very difficult to include mass and angular momentum losses from the system. One can specify that only a fraction β of the mass lost by the primary is accreted by the secondary, and also that a fraction γ of the total angular momentum is taken away by the matter leaving the system. Estimates for these parameters have been made but the results are far from certain. A way out is to perform theoretical computations for various values of β and γ and to try to estimate their value by comparison between theory and observations. Non-conservative binary computations for low masses have been made by Plavec et al. (1973), Yungelson (1973). Computations for massive stars have been performed by Vanbeveren, De Grève, van Dessel, de Loore (1979). Their computations include :

a) stellar wind mass loss during core and shell hydrogen burning before Roche lobe overflow, case B;
b) mass loss and angular momentum losses during the Roche lobe overflow phase, assuming that 50% of the matter expelled by the primary leaves the system. Different values for the angular momentum losses were adopted. Also the case that all the matter leaves the system is considered, and as comparison the conservative case was calculated.

   α characterizes the amount of angular momentum leaving the system: $\alpha=3$ corresponds to an angular momentum loss of ~ 50 percent, $\alpha=0$ represents the case that all angular momentum is conserved.

Table 1 and Figure 1 show the results of the computations for a 40 $M_\odot$ + 20 $M_\odot$ system.

β	α	M_1	M_2	P(d)	time mass exchange
1	0	11	29	18.8	12200
0.5	1	10.7	23.1	6.8	11150
	3	10.3	23.2	2.9	7700
0	0	11.2	16.9	62.5	11300
	1	11.0	16.9	22.3	13300
	3	10.2	16.9	2.4	14100

Table 1. Results of the non-conservative evolutionary computations for a massive close binary system, 40 $M_\odot$ + 20 $M_\odot$, with an initial period of 5 days.
M_1 and M_2 are the masses of primary and secondary at the end of the Roche lobe overflow phase, P(d) is the period at that moment in days. The time of the mass exchange is given in years.

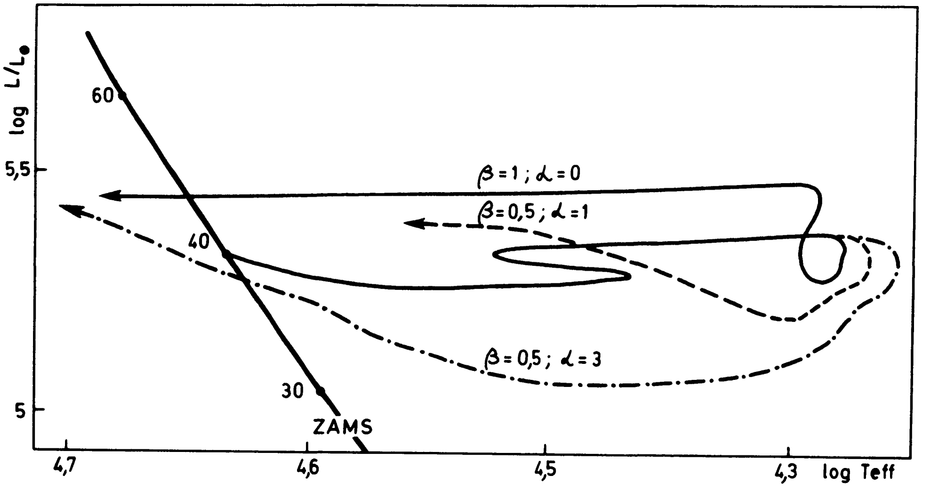

Figure 1. Evolutionary tracks for the primary of a massive close binary (M_1 = 40 $M_\odot$, q = 0.5) for the conservative case (β=1, α=0), the non-conservative cases (β=0.5, α=1 and β=0.5, α=3).

The results of the computations are :

1. as a consequence of the stellar wind the mass ratio of the two components ($\frac{M_2}{M_1}$) comes nearer to 1;

2. mass and angular momentum losses have practically no influence on the mass and structure of the primary at the end of the Roche lobe overflow phase;

3. including non conservative assumptions affects principally the period, mainly determined by the angular momentum losses.

Comparison of the theoretical models with observations by Vanbeveren and de Loore (1980) allows estimates of the parameters α and β. This analysis leads to the following conclusions :

1. massive systems in the post Roche lobe overflow stage are not converted immediately into Wolf-Rayet stars but have a new normal OB stage. Later on the mass loss rates are increased (perhaps by changing conditions in the interior) and then the star is observed as a Wolf-Rayet star;

2. the ratio of the periods after and before Roche lobe overflow has to be smaller than 1;

3. most of the systems before Roche lobe overflow have a mass ratio larger than 0.7.

These considerations reveal that probably between 50 and 75% of the matter has to leave the system, carrying away some 50% of the angular momentum.

6. REMNANTS OF THE PRIMARY AFTER ROCHE LOBE OVERFLOW

From close binary evolution the mass of the primary at the end of the Roche lobe overflow phase can be determined. In Figure 2 are shown the remnants after stellar wind mass losses (N=100) and after Roche lobe overflow.

From a study of 18 known Wolf-Rayet binaries with known solutions for the orbit, Massey (1981) derives as average mass for Wolf-Rayet stars ~ 20 $M_\odot$, ranging from 10 $M_\odot$ to 50 $M_\odot$. From a comparison of the projected orbital separations and eccentricities of O type binaries and Wolf-Rayet binaries Massey concludes that only the more massive O systems evolve into Wolf-Rayet binaries. This agrees with the conclusion of Vanbeveren and de Loore (1980) that for the production of early WN and WC systems,

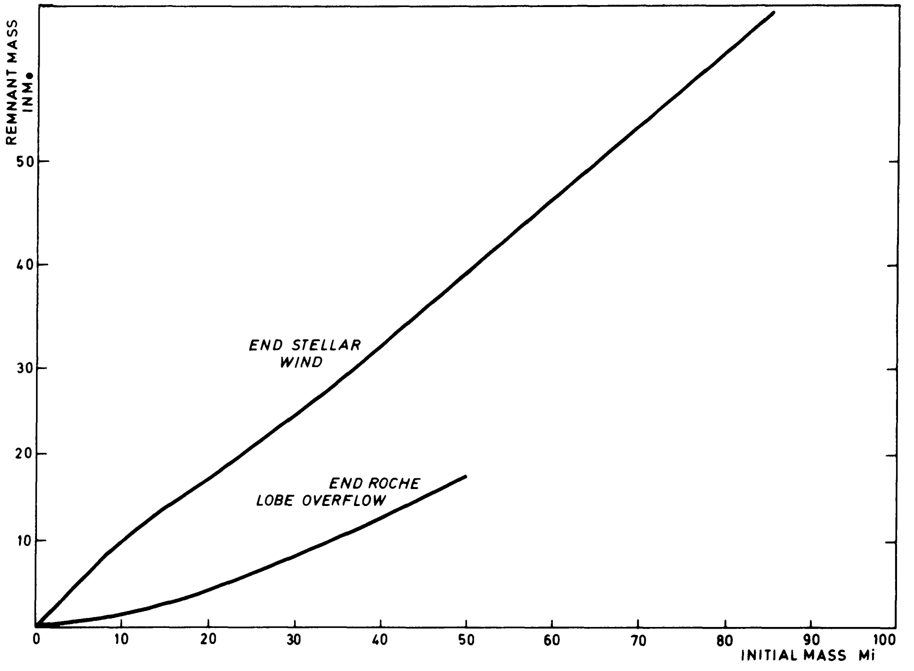

Figure 2. The remaining mass of massive stars in $M_\odot$ at the end of the main sequence, and after the Roche lobe overflow phase

ZAMS masses exceeding 50 $M_\odot$ are needed. Such stars lose already mass, due to stellar wind before the Roche lobe overflow stage is attained. This means that only ZAMS primaries between ~35 and ~120 $M_\odot$ would produce Wolf-Rayet stars: systems with masses between 35 and 50-60 $M_\odot$ evolve into WR systems by Roche lobe overflow; higher mass primaries will not evolve towards the right part of the HRD, but will move to regions at the blue side of the ZAMS. The primaries will not exceed their Roche volume, but can evolve into He-stars. Such high mass stars, singles or binaries, can produce WR stars according to Conti's scenario.

What about the lower mass primaries? If they are not producing Wolf-Rayet stars this would mean that also He-stars with companions of all kinds of spectral type would exist. Is this the case? It would be very interesting to try to observe these stars. Moreover, massive close binaries immediately after the Roche lobe overflow phase present still OB characteristics, and are not immediately converted into Wolf-Rayet stars. Also to obtain information about the duration of the Wolf-Rayet phase it would be interesting to have observations of these systems, consisting of an OB component and a He-companion.

Doom and De Grève (1981) have made an analysis of all kinds of possible combinations of massive stars and remnants (He, compacts, WR+WR,...) and their fractional existence, and also to sustain these predictions observations of O stars with a He-companion would be very helpful.

7. SIMULTANEOUS EVOLUTION OF CLOSE BINARIES

Evolutionary computations, where the structure of the two components is calculated in one programme, are carried out at the Astrophysical Institute of Brussels. Stellar wind mass losses for the two components, later Roche lobe overflow mass exchange and mass accretion are taken into account. The simultaneous evolution of the two components requires a very careful numerical treatment of the solution method of the equations.

a) the atmosphere is treated in a more accurate way and thermohaline mixing in the case of accretion is taken into account (Ulrich, 1972);

b) the extent of the atmosphere is considered as variable.

The test computations seem to confirm the classical picture of the production of Wolf-Rayet stars, although it is premature to draw final conclusions.

Mass accretion has a circularizing effect on the orbit; indeed all semi-detached systems have circular orbits (Paczynski, 1971; Piotrowski, 1965).

The fact that all long periodic Wolf-Rayet stars have large eccentricities reveals that from the matter expelled by the mass losing star only a small fraction can be accreted by its companion. As mentioned before (sec.6), this agrees with the conclusions of Vanbeveren and de Loore (1980).

8. EFFECTS OF OVERSHOOTING

If overshooting is taken into account, these conclusions have to be modified. Indeed, for very massive stars ($M > 50\ M_\odot$), a mass loss rate

$$\dot{M} = 50\ L/c^2$$

and increasing the convective cores by ~15% the evolutionary tracks starting at the ZMAS bend immediately to the blue part of the HRD, towards the helium main sequence.The 40 $M_\odot$ track evolves towards the red

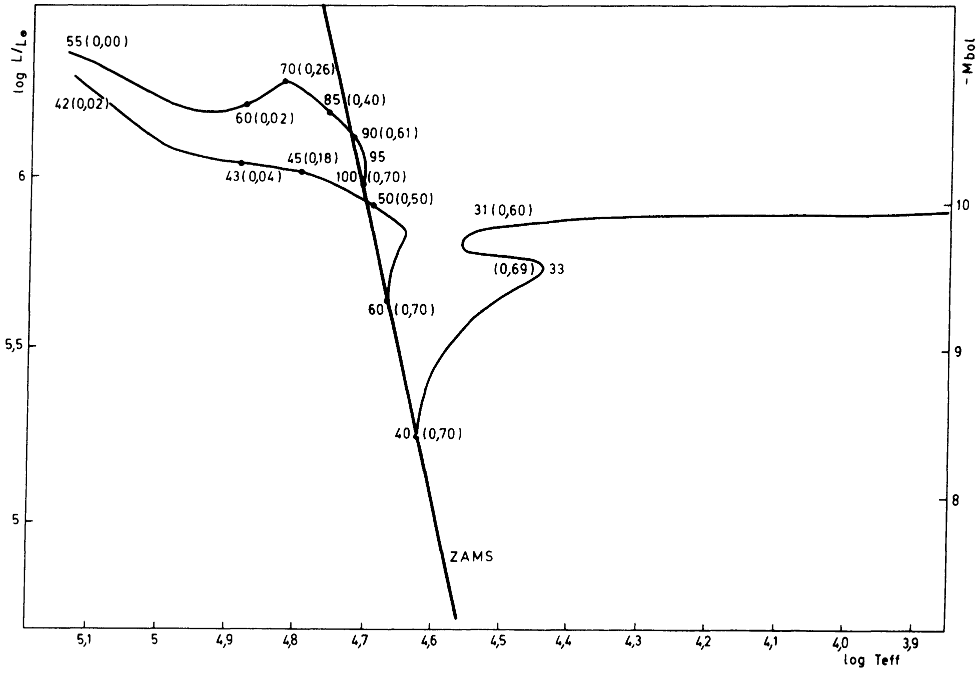

Figure 3. Evolutionary tracks for stars with masses between 40 and 100 $M_\odot$, calculated with a modified Schwarzschild criterion for convection. The remaining masses are indicated along the tracks, and between brackets is given the atmospheric hydrogen abundance by weight.

part of the HRD in agreement with the observations of Humphreys (1978). Evolutionary tracks calculated with these parameters are shown in Figure 3.
The mass of the convective core of ZAMS models, calculated according to the Schwarzschild criterion, with core extension, the remnant left by stellar wind mass losses at the end of core hydrogen burning, are shown in Table 2.
The radius of the more massive stars ($M > 50$ $M_\odot$ is always decreasing, hence Roche lobe overflow for binaires with primary masses larger than 50 $M_\odot$ will not occur.
Massive single stars can evolve into Wolf-Rayet stars; the atmospheric hydrogen abundance of a 100 $M_\odot$ drops to $X = 0.02$ after 8.10^6 years, when $\log T_{eff} \sim 4.87$. Also Wolf-Rayet binaries could be formed in this way, directly, i.e. without mass transfer by Roche lobe overflow.
For stars with initial masses lower than 50 $M_\odot$ the normal close binary evolutionary scenario can be applied, and in such a way Wolf-Rayet binariescan be made in the classical way by Roche lobe overflow.

A more moderate treatment of overshooting, using a non local theory, was performed by Maeder (1981) and Bressan et al. (1981). Evolutionary

Inital mass	Convective core Schwarzschild	Overshooting (~15%)	N=100 Remnant after wind	Case B Remnant after mass transfer
20	9	11	17.7	5.4
30	16	19	25.6	9.7
40	24	28	33.1	14.3
60	40	46	48	
80	58	67	63	
100	78	90	77.4	
120	95	108	93	
140	110	125	108	

Table 2. The mass of the star at the ZAMS, the extent of the convective core according to the Schwarzschild criterion, and with an enlargement of ~15%, the stellar remnant after stellar wind mass loss at the end of core hydrogen burning and after the Roche lobe overflow phase. For initial masses exceeding 50 $M_\odot$ no Roche lobe overflow occurs, as explained at the beginning of this section.

computations, taking into account mass loss and a forced overshooting, - calculated as a formal increase of the extent of the convective core - were carried out by Massevitch, Popova, Tutukov and Yungelson (1979). These computations show a broadening of the hydrogen burning region in the HR diagram.

Various scenarios leading to Wolf-Rayet stars were discussed by Maeder (1981). He also concludes that the more massive single stars can evolve into WR stars, according to the Conti scenario, when turbulent mixing and mass loss are taken into account. For lower mass stars the binary scenario leads to WR stars. Another possibility is that the stars evolve through the red supergiant phase, and then as post red supergiants pass through a Wolf-Rayet phase.

9. ADVANCED EVOLUTION - 2ND WOLF-RAYET PHASE

A non-conservative evolutionary scenario leading to X-ray binaries and finally to runaway neutron stars was presented by de Loore (1981). The scenario is shown in Table 3.

The minimum mass of the primary leading to a neutron star after a supernova event is estimated from evolutionary computations at ~ 14 $M_\odot$ (De Grève and de Loore, 1977), and between 8 and 13 $M_\odot$ by Massevitch and Tutukov, 1981. A scenario for massive close binary evolution leading to a binary X-ray source was proposed by van den Heuvel and Heise (1972) and calculated in detail independently by Tutukov and Yungelson (1973), de Loore et al. (1974,1975) and de Loore and De Grève (1975a,b, 1976).

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Primary	Secondary	q	P_{orb}(d)	$t/10^6$yrs	stage
·40	20	0.5	5.08	0	ZAMS - stellar wind mass loss
23.06	16.9	0.73	10.20	4.5986	Start mass transfer
10.65	23.1	2.17	6.8	4.6113	End mass transfer Helium star + OB = Wolf-Rayet stage
1.5	23.1	15.4	8	5.2	Supernova explosion OB runaway phase
					Stellar wind or Roche lobe overflow X-ray stage
1.5	16.2	10.8	15.8	11.5	Second Wolf-Rayet stage (WR runaway)
1.5	5.84	3.9	9.98		Spiral in Second X-ray stage
1.5	1.5				Supernova explosion

Table 3. Non-conservative evolution of massive stars

After explosion of the remnant of the evolved primary a neutron star of 1 to 2 solar masses is left. The system has a large probability to remain bound (de Loore et al., 1975). The space velocity is 50-80 km s^{-1}, typical for OB runaways. The optical component can attain a distance of ~100 pc from the galactic plane, typical for X-ray binaries. The stellar wind matter is partially accreted by the neutron star. The X-ray luminosity remains weak until the optical component is nearly filling its Roche lobe. If the optical component fills its Roche lobe the neutron star is engulfed by the matter expelled by the primary, the X-rays are quenched. The interval between the time that the primary nearly fills its Roche lobe and the Roche lobe overflow determines the X-ray phase. When the optical component fills its Roche lobe a common envelope is formed; indeed the accretion by the neutron star is limited by the Eddington-limit to 10^{-8}-10^{-6} $M_{\odot}yr^{-1}$ while the mass loss rate of the optical companion is much larger. This common envelope stage was proposed by Paczynski (1980), and calculated by Taam, Bodenheimer and Ostriker (1978), Tutukov and Yungelson (1979).

For the further evolution two possible branches are present: a first possibility is that the neutron star is engulfed by its companion in the common envelope and this leads to a red supergiant with a compact core (Thorne-Zytkow object); a second possibility is that the bulk of the transferred matter leaves the system. The orbit shrinks rapidly as a consequence of the large specific orbital angular momentum of the expelled matter (van den Heuvel and de Loore,. 1973). Remnants of such expelled envelopes can be observed during several 10000 years as a bright nebula with a radius of 2 to 3 parsec around a "single Wolf-Rayet star". An example of such a runaway Wolf-Rayet star is HD 96548, at a distance of 4 kpc, Z = 330 pc. In these cases neutron stars are formed with large space velocities. In this context slow pulsars ($<z> > \sim 80$ pc) should then be the final products of single stars, and fast pulsars ($<z> > 150$ pc) should be produced by close binary evolution. The supernova explosion is probably not symmetric; computations of the disruption probabilities are carried out by De Cuyper (1981). With the assumption of a kick velocity of 100 km s^{-1} and as remnant a neutron star of 1.5 $M_{\odot}$, these probabilities for the first supernova explosion are of the order of 70-80% for ZAMS primaries in the range 40-100 $M_{\odot}$. This kick value is derived from the pulsar distribution around the galactic plane, and reflects the fact that an average is considered of stars of different initial mass; hence the influence of lower mass stars will be dominant. For very massive stars the kick velocity could be larger, and could possibly attain values of several hundreds of km s^{-1}. In this case the disruption probability during the supernova event for very massive close binaries could be much larger.

In the case of Roche lobe overflow of the rejuvenated secondary and the subsequent mass transfer and mass loss, as well as in the case of spiralling in the outer layers with the initial composition are removed from the star and layers with larger and larger helium abundances appear at the surface. The O-star is on its way to become a helium star, and shows more and more Wolf-Rayet characteristics. Possibly SS 433 is an example of an evolved massive close binary at such an advanced stage (van den Heuvel et al., 1980). The mass loss rate is ~ 10^{-4} $M_{\odot}yr^{-1}$ (Firmani and Bisiacchi, 1981; Shlovski, 1981) and the spectral type ranges between Of and WR. Probably the X-ray system is surrounded by an envelope of matter expelled by the non compact component. This agrees with the picture of van den Heuvel (1980) of SS 433 being in a second X-ray stage, where the larger part of the mass expelled by the non compact component is stored in a disk. This component loses matter that is more and more enriched in helium, since this material is expelled from deeper, hence processed layers. Hence the next stage should be a second Wolf-Rayet stage, i.e. a helium star with a neutron star companion. Such systems are the evolutionary products from binaries through a supernova event; they are assumed to be found at large distances of their place of birth.
A list of observed Wolf-Rayet runaway stars is shown in Table 4.

Object	Subtype	Reference
HD 50896	WN 5	Firmani et al., 1979
HD 93131	WN 7	McLean, 1980
		Moffat and Seggewiss, 1980
HD 96548	WN 8	Moffat and Isserstedt, 1980
HD 192163	WN 6	Koenigsberger et al., 1980
HD 197406	WN 7	Moffat and Seggewiss, 1979a,b,1980
HD 164270	WC 9	P=1.76d f(M)=0.015

Table 4. Observed Wolf-Rayet runaways

The subsequent evolution where the compact star is spiralling in leads to binaries with ultra-short periods like Cyg X-3 (van den Heuvel and de Loore, 1973). Finally these systems undergo a second supernova explosion, where practically in all cases the systems are disrupted, leaving two neutron stars, an old one and a young pulsar. In exceptional cases the system can remain bound as is the case of the binary pulsar PSR 1913+16.

Probably this picture of Roche lobe overflow from the rejuvenated secondary is an oversimplification and in some cases matter will be stored in disks. Such disks have been observed, e.g. in Beta Lyrae and in a number of X-ray binaries. They can be observed spectroscopically as well as photometrically. No more-dimension models exist, and it is not yet possible to calculate the structure or the evolution of such more-realistic models.

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DISCUSSION FOLLOWING DE LOORE

Chiosi: If you add to the secondary component nuclearly enriched material, you need thermohaline mixing. How is this reflected in the envelope of the O-star? The effect that massive stars cannot suffer the Roche lobe overflow, because they move towards the left in the HRD, is partly due to the overshooting. I think that is is mainly due to the mass loss. The question is, can you get a constraint on the overshooting and the mass loss?

Maeder: Overshooting seems to be very popular nowadays. However, I wonder whether the proper weight is given to the various possible hydrodynamical effects, particularly when binary evolution is considered. For example, if mass transfer is able to remove say 40% of a stellar mass in a binary, why wouldn't you also consider the effects of tidally induced mixing as important ones. Such effects could be much more important than the overshooting.

de Loore: The problem of accretion is a very difficult one. We used as solution for this problem the thermohaline mixing. However, we have to look further into this problem. Convection can be treated in different ways; the weakest way to do this is using the Schwarzschild criterion; then you can include the effect that the core becomes larger, by deforming that criterion, and making the effect of convection larger. This has been done by different authors (Tutukov, Maeder...). All procedures used for the increase of the convective core have the same effects: increasing the convective core, without using mass losses widens the main sequence; adopting then large mass loss rates makes the main sequence narrower. So one has to combine the two effects to model the observations. In this case for the most massive stars ($M > 50\ M_\odot$) the tracks move towards the blue part of the diagram. This is the case if one adopts overshooting, like we have done, or if one uses turbulent diffusion, you have the same features. The best way to proceed is to adopt reasonable mass loss rates, and then to use various overshooting rates, to model the observations (e.g. Humphreys for the Galaxy, the Magellanic Clouds,...).

Garmany: Conti and I are doing a reexamination of the luminosity function of the O-stars which has implications for the work of both de Loore and Chiosi. We have compiled a catalogue of O-stars both from published data and some new spectral classification. This is complete to a distance of 2.5 kpc, based on star counts and the expected apparent magnitude of O9V stars. All of these stars have both photometry and spectral types with luminosity classes, so it is possible to place the stars in a theoretical HR diagram and compare the results with different evolutionary tracks and with the number of WR stars in the same space volumn, based on the work which van der Hucht reported on earlier. There

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are 400 O-stars within 2.5 kpc, and 32 WR stars within the same volumn according to van der Hucht. About 9 to 12 of these WR stars are binaries. When this data is compared with the evolutionary tracks of de Loore (1978), keeping in mind that the WR lifetime is about 10% of the O-star main sequence lifetime, there is a problem with some suggested scenarios. One needs to count all O stars more massive than about 30 $M_{\odot}$ in order to explain the observed number of WR stars.
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