THE EVOLUTION OF CLOSE BINARY STARS: CONDITIONS IN THE WINDS

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Abstract. The influence of mass transfer in an OB-type binary on the colliding wind characteristics of the following phase of WR binary is examined. We look to the changes in composition and orbital characteristics. Special attention is given to the formation of WR+OB systems and the colliding wind characteristics. The mass-luminosity behaviour after mass transfer is examined. We discuss the influence of the internal state, the composition of the wind, and rotational effects on the mass gainer. Recent models of both single stars and close binaries allow us to derive the dependence of these characteristics on the initial masses of the components. From this, constraints for the wind regimes at the WR+OB stage result.

Key words: stars: Wolf-Rayet – binary systems – evolution – mass transfer

1. Introduction

The modelling of the evolution of massive close (and hence interacting) binaries provides valuable information to the study of the colliding wind problem, because mass transfer modifies structure and composition of the outer layers, and alters the further evolution. We can distinguish the following situations for interaction: O+O, WR+O, O(MT)+O, WR(MT)+O, with MT denoting additional mass transfer from one component to the other.

To reach the WR stage, single O stars have to lose a large fraction of their H-rich envelope via radiation pressure (Conti 1976; Lamers *et al.* 1991). This process is more effective in the hottest, most massive stars, as well as in stars with high metallicity. For the latter, the evolutionary models of Maeder (1991) predict that in regions of metallicity as low as 0.1 $Z_\odot$ only stars originally more massive than 85 $M_\odot$ can go through a WR phase. Higher main sequence mass loss lowers the limit. So does mass transfer in close binaries. Hence, the WR/O number ratio in a population with constant star formation rate is influenced by the metallicity, the shape of the IMF slope (slope and upper cut-off mass) but also by the characteristics of the binary population in it. Braun & Langer (1993) recently showed that including pulsational instabilities in very massive stars introduces a new type of evolutionary sequence: $O \rightarrow Of \rightarrow WNL(H) \rightarrow LBV \rightarrow WNL \rightarrow WNE \rightarrow WC \rightarrow SN$. The pulsational instability therefore could be a mechanism that prevents RLOF in very massive binaries.

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2. Massive close binary evolution

2.1 PRESENT UNDERSTANDING

We now have a number of extended grids of evolutionary sequences available describing the physical state of both components and of the system. De Loore & De Greve (1992) calculated the evolution of binaries with masses between 20 and 40 $M_\odot$, with non-conservative mass transfer occurring on a thermal time-scale (case B). The models, with solar composition, were consistent with the corresponding single models of Meynet & Maeder (1991). This grid was extended (with up-dated physics) by de Loore & Vanbeveren (1994) to massive binaries with Magellanic Cloud composition. These models are consistent with the single models of Schaller *et al.* (1993). The importance of such grids follows from the study by Rathnasree & Ray (1992), who found that some 60% of the OB supergiants in the Large Magellanic Cloud may occur in binaries. The period distribution of the post main sequence binaries (including WR+O binaries) appears to be bimodal, constraining the evolutionary scenarios.

In a comparison of models with OB-type binaries, Figueiredo *et al.* (1994) explored the correspondence between solar composition models and observed detached systems, and examined the status and origin of some semidetached and contact systems. The most massive system in the sample, EM Car, showed a mass deviation (defined as $< M_{th} > - M_{obs}$) of less than 7% and 3% for primary and secondary, respectively. Similar results were obtained for most of the other less massive systems. The deviations showed no systematic effect of a mass excess. For the more advanced stages we recall some conclusions from the analysis of De Greve & de Loore (1992):

- The massive companions in the observed WR binaries have masses larger than or equal to 30 $M_\odot$ (Schulte-Ladbeck 1989)
- Only the secondaries from models with $M_{1i} > 25 - 30$ $M_\odot$ evolve in the HRD into the region of the observed OB companions of WR stars.
- The spread in effective temperature around the theoretical models points either to a spread in initial mass ratios around the theoretical ones (0.6 and 0.9), or to a more complex behaviour of the mass loss from the system (*i.e.*, different from the 50% loss applied in the models).

The last two conclusions depend clearly on the fraction of mass lost from the system. A larger accretion fraction decreases the lower mass limit. Exploring the extremes leads to a range of 16 $M_\odot$ (conservative, $q_i = 0.9$) to 42 $M_\odot$ (no accretion, $q_i = 0.6$) as lower limit for the initial mass of the primary.

- Massive WC stars ($M(WC) \sim 10$ $M_\odot$) can only be expected from original primaries more massive than 30 $M_\odot$.

Contrary to single star evolution (Schaller *et al.* 1993), stars with smaller initial masses (and hence lower luminosity), undergoing Roche Lobe Over-

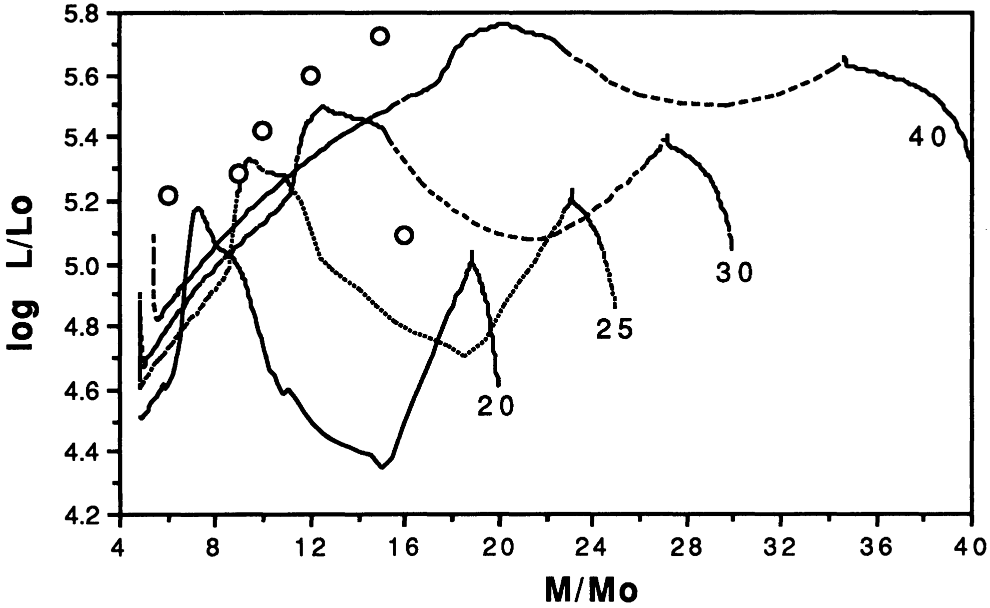

Fig. 1. Mass-luminosity tracks of losers with M_{1i} = 20 to 40 $M_\odot$ during and after RLOF (de Loore & De Greve 1992), together with observed WR stars (Smith & Maeder 1989)

Flow (RLOF), return to the blue part of the HRD at the end of the mass transfer. As a result close binary evolution of M_{1i} = 30 to 20 $M_\odot$ results in the following WNL and WNE stars after RLOF:

- WNL: log$L/L_\odot$~4.5 ($M(WR)$~7 $M_\odot$) to 5.1 ($M(WR)$~9 $M_\odot$)
- WNE: log$L/L_\odot$~4.3 ($M(WR)$~6 $M_\odot$) to 4.8 ($M(WR)$~7 $M_\odot$)
- WC : log$L/L_\odot$~4.7 ($M(WR)$~5 $M_\odot$; for the lowest M_{1i} value of 30 $M_\odot$)

Figure 1 shows the evolutionary tracks of mass transferring stars and the position of observed WR stars in the mass-luminosity diagram.

2.2 MASS TRANSFER BEHAVIOUR

In order to deal with the theoretical models, we adopt the following assumptions.

- If $M > 10\ M_\odot$ and $X_{at} < 0.4$, we consider the star to be a WR star, with mass loss rate determined by the mass ($\approx M^{2.5}$, Langer 1989).
- The mixing mechanism in the outer layers of the secondary is thermohaline mixing . The term thermohaline convection describes hydrodynamic instabilities which occur when a layer of warm salt water is above a layer of fresh cold water of slight higher density. The situation is similar to that in a star in which layers of higher molecular weight are above a region of lower molecular weight. Such regions are secularly unstable.

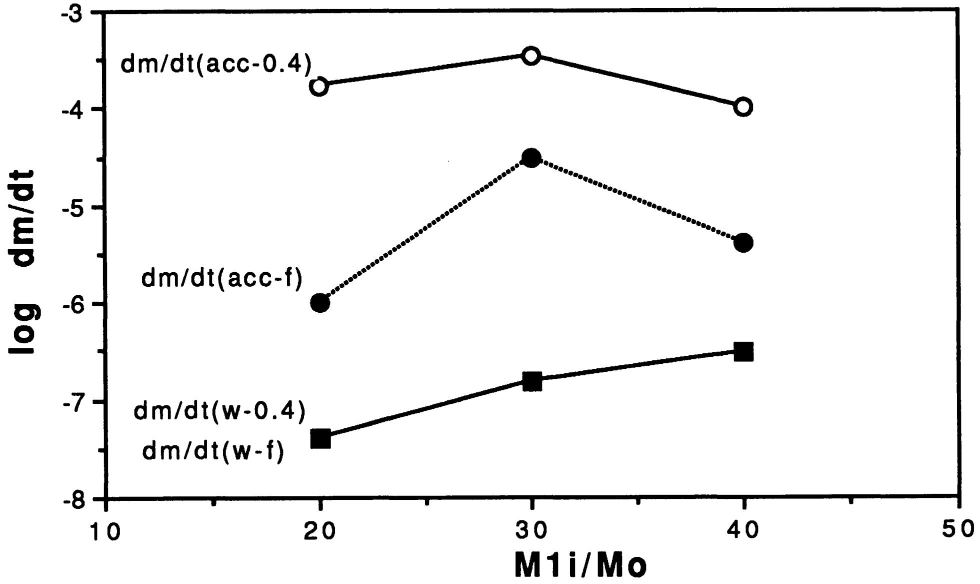

Fig. 2. Accretion rates *vs.* stellar wind mass loss rates when $X_{at}(loser) = 0.4$ and at the end of the mass transfer, for various systems (De Greve & de Loore 1992)

It is of interest to investigate the situation where X_{at} becomes lower than 0.4, and formally spoken, we deal with a Roche lobe filling WR star in a close binary. From our calculations it follows that this stage lasts for about 5000 years for all systems. If we compare the mass loss rates of the loser (*i.e.*, the WR mass loss rate and the RLOF mass loss rate) at the beginning of that stage and at the end of the RLOF, for various initial masses, we conclude the following:

- At the onset of the WR mass loss this mass loss rate determines the RLOF mass loss in the 40 $M_\odot$ loser, but is clearly smaller for lower masses. The mass ratio $M(\mathrm{O})/M(\mathrm{WR})$ is in the range 1.5 to 2.
- At the end of the RLOF the WR mass loss rate of the 40 $M_\odot$ loser exceeds the mass transfer rate by a factor 3. For the other masses it is still lower. The mass ratio is in the range 2 to 3.

For the O-type companion we compare the incoming accretion rate with the outflowing wind (most probably only in the equatorial region). Figure 2 shows that the accretion rates are always much larger than the stellar wind mass loss, by 1 to 3 orders of magnitude and more. The composition changes of the outer layers as a result of accretion of nuclear-processed material from an evolved companion have barely be investigated. Computations of the evolution of close binary stars usually adopt the concept of thermohaline mixing (de Loore & De Greve 1992), eventually supplemented with accretion mixing

(Sarna 1992), or assume that the accreted material has the same chemical composition as the surface layers of the gainer (Braun & Langer 1993). At the end of the mass transfer the hydrogen content in the outer layers of the gainer has decreased by a few % (De Greve 1991), to be compared to the average content in the outer layers of the loser, $X_{atl} = 0.27$. For a low mass binary Proffitt (1989) investigated the stability of the composition inversion in detail. The inversion is eliminated in a time that is shorter than the evolutionary timescale of the star. Even if the gradient of the composition inversion is sufficiently small to be stable against large-scale motions, small-scale turbulence is expected to destroy the inverted composition gradient.

Up to now the models assume implicitly that for the transferred mass the Z-elements mix in a similar way to the hydrogen and helium with the outer layers of the accretion star. Under that assumption De Greve & de Loore (1992) found that as a result of the mixing during the mass accretion, the N/C (mass fraction) ratio at the surface of the gainer increases tenfold from an initial value of 0.30 to a value between 3 and 3.5.

Braun & Langer (1993) followed the evolution of the mass-accreting component in the framework of a time-dependent convection theory (Langer *et al.* 1983). Masses ranged from 12 to 20 $M_\odot$, and constant accretion rates of 10^{-4} and 10^{-3} $M_\odot yr^{-1}$ were adopted. They found that the standard rejuvenation picture only holds for large amounts of accreted matter, small initial masses, early accretion and a high efficiency for the diffusion. In the other cases the stars develop smaller helium cores and tend to remain in the blue part of the HRD, where they finally explode as a blue supergiant similar to SN 1987a. A large amount of accretion is 8 $M_\odot$, a small amount is 3 $M_\odot$. In the computations of de Loore & De Greve (1992) and de Loore & Vanbeveren (1994) the accreted mass ranges from 3.5 to 7 $M_\odot$ (if we adopt as lower limit for WR formation $M_{1i} = 20$ $M_\odot$, then the range is 5 to 7 $M_\odot$).

The spin-up of the mass accreting star as a result of the accretion of mass, and its influence on the further evolution of the gainer is still one of the less investigated problems. Already reported upon earlier (De Greve 1991), we recall that Packet (1988) demonstrated that in the case of rigid rotation the star rapidly spins up to breakup velocity in the equatorial plane. In the case of differential rotation the induced mixing may redistribute angular momentum and chemical elements in the star (Endal & Sofia 1978). Rotation laws close to uniform specific angular momentum may increase the radiative gradient and thereby the convective core mass (Clement 1993). This will lengthen the duration of the central hydrogen burning (Fliegner & Langer 1993). The stellar wind mass loss leads to a rapid spin-down of the models (Fliegner & Langer, this volume).

In an SPH (Smooth Particle Hydrodynamics) three-dimensional analysis Belvedere *et al.* (1993) examined the existence, as to disc formation, of upper and lower limits to the equatorial rotational speed of the secondary. They found, for lower mass systems (masses 1 and 5 $M_\odot$), that disc formation can occur only in very limited ranges of the secondary's rotational velocity.

3. Wind conditions in binaries during various evolutionary phases

The average mass loss rate over the main sequence varies strongly with initial mass. Over a mass range from 14 to 60 $M_\odot$ the mass loss rate changes by 3 orders of magnitude. However, if we consider a main sequence close binary system with mass ratio between 0.9 and 0.6 the ratio of the mass loss rates varies from ~1.5 ($q_i = 0.9$) to ~5 ($q_i = 0.6$). Only for the lower mass of 20 $M_\odot$ and mass ratio 0.6 is a very large ratio of 20 is obtained.

As a direct result of the interaction of the colliding winds X-ray emission is produced in the shock region. This adds additional energy to the gas in the wind and influences the ionization structure of it ($L_{x,abs} > 10^{36}$ ergs/s, Myasnikov & Zhekov 1993). Because this matches the ionization energies of the heavier and most abundant elements like C, N and O ($E > 0.1$ keV), they deduce that binary WR stars have more intense spectral lines of highly ionized elements than single WR stars.

Neglecting effects coming from rotation, magnetic fields, turbulence, etc., the phase space determining the evolution of close binaries is given by the parameters M_{1i}, q_i and P_i (and the fraction accreted by the gainer!). We started to investigate this phase space for massive systems that can show enhanced X-ray emission in various stages of the evolution. To do this we used the restriction given by Chlebowski & Garmany (1991), *i.e.*, the major axis must be less than 5 times the sum of the radii and the components must have roughly similar luminosities. The latter was translated into the condition $\mathrm{abs}(\log(L_1/L_\odot)\text{-}\log(L_2/L_\odot)) < 0.05$. Trivially we also have $a > R_1 + R_2$. We looked at the Zero Age Main Sequence (ZAMS) state, and at the state when the most massive star (the loser in this paper) was at the Terminal Age Main Sequence. In the future we will look also to the advanced WR+O stage.

We investigated the following ranges of the parameters: $20 < M_{1i}/M_\odot < 40$ (step 5 $M_\odot$), $0.5 < q_i < 1.0$ (step 0.1), $2 < P_i(d) < 20$ (step 1 d).

For ZAMS systems the conditions are met for systems with mass ratios larger than or equal to 0.8, and periods that must be smaller than 7 ($M_{1i} = 20\ M_\odot$) to 10 days ($M_{1i} = 40\ M_\odot$). When the primary is at the TAMS, the systems are limited to $q_i \geq 0.9$ (except for 40 $M_\odot$: $q_i \geq 0.8$) and a maximum period that varies from 50 (20 $M_\odot$) to some 100 days (40 $M_\odot$).

We also verified in what systems we can expect a shock region that folds back on the secondary component (by requiring that x_2, the relative distance to the secondary component of the bow shock along the semimajor axis, is of the order of its radius). The condition of the relative distances gives

TABLE I

Relative radius R_2/a of the secondary and ratio $\dot{M}_2/\dot{M}_1$ to have a bow shock at that position.

R_2/a	0.1	0.2	0.3	0.4
$\dot{M}_2/\dot{M}_1$	0.012	0.063	0.18	0.44

TABLE II

Relative bow shock position for the system AO Cas, compared to r_2 of the secondary. The second line gives the results derived with evolutionary models, the third line those with radii adopted from Gies & Wiggs 1991 (GW91). Mass loss rates are in solar masses per year,$r_2 = R_2/a$ and x_2 is explained in the text.

Model	$R_1/R_\odot$	$R_2/R_\odot$	$log L_1/L_\odot$	$log L_2/L_\odot$	$log\dot{M}_1$	$log\dot{M}_2$	r_2	x_2
program	12.6	9.9	5.234	4.634	-6.40	-7.36	0.32	0.27
GW91	10.3	9.9	5.06	4.83	-6.63	-7.35	0.26	0.32

$\lambda = \frac{x_2^2}{(1-x_2)^2}$, with λ representing the ratio of the momenta (at v_{inf}) of secondary to primary (Luo *et al.* 1990). Assuming that in these massive stars the final velocity is more or less the same in both components, we can derive the needed ratio of the mass loss rates for various values of the relative radius of the secondary (R_2/a). The results are shown in Table I. For main sequence systems the distance of the bow shock position (on the semimajor axis) to the center of the secondary typically ranges between 0.45 ($q_i = 0.9$) and 0.31 ($q_i = 0.6$), to be compared with the relative radius of that star that can take values between 0.1 and 0.4, for periods up to 20 days. For massive WR binaries with periods up to 20 days, the relative radius of an evolved main sequence star (which is the typical companion of the WR star) is mostly smaller than 0.2. Radii larger than 0.2 – 0.25 are found only for massive WR systems with short periods (~5 d) and mass ratios close to 3. Hence, because the mass loss rates of the components in these systems differ by one magnitude or more, one can expect the bow shock to be in the close vicinity of the secondary star for all the WR binaries. From the observations we have a well documented case, in between the main sequence and the WR stage. The Hα, He I λ 6678 and UV lines of the short period semi-detached system AO Cas show evidence for a bow shock wrapped tightly around the secondary star (Gies & Wiggs 1991). The mass ratio found by the authors is 1.47±0.08. The less massive star in AO Cas nearly fills its Roche Lobe. Using the results from evolutionary models, we find the characteristics given in Table II. The second row shows the results with the radii and T_{eff} adopted from Gies & Wiggs (1991). If we use a wind velocity law as given by Friend & Abbott (1986), then we find that the wind velocities of the two components at the region of the shock have reached values of ~1480 and ~780 km/s (along the semi-major axis), respectively. However, we neglected any effect of the Roche lobe filling component (*i.e.*, possibly a denser and slower wind from the primary along the axis, Gies & Wiggs 1991).

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DISCUSSION:

Langer: Do you in your calculations of Case B systems encounter at all common envelope phases, and does this depend on the maximum mass transfer rate during Roche lobe overflow?

De Greve: We encounter short contact phases which I would not call common envelope phases. The secondary's outer 1% of the mass swells up as a result of accretion, and maintains marginal contact in our models. It also follows from the models that the degree of contact depends on the initial mass ratio (which determines the maximum mass transfer rate, apart from the period and the angular momentum loss). Lower initial mass ratios than used in our models therefore might lead to a common envelope phase.

Corcoran: Is the period distribution of O binaries significantly different than for the WR binaries? Does this indicate anything about the importance of dynamical evolution since in the non-conservative case $\dot{P}/P \propto -\dot{M}_{total} / M_{total}$?

De Greve: I think Peter Conti is better placed to answer this question. As far as the models are concerned we chose an angular momentum loss (parameterised) such that periods are obtained of the same order of magnitude as the initial ones. Modelling of individual systems may give a clue to the value of the parameter.

Conti: I believe Phil Massey looked at this about a decade ago; the period distributions of O+O and O+WR were similar, as was the eccentricity distribution. The latter gives a strong constraint on RLOF processes.

Cherepashchuk: Did you try to estimate the evolutionary status of SS433? It is very interesting and unexpected that a common envelope is not found in this binary system, but angular momentum loss is realised through the formation of a supercritical accretion disk.

De Greve: I think it is not appropriate to model this system with a code that is linear and does not take into account the formation of an accretion disk. Precisely the removal of angular momentum through the disk is a crucial aspect of the evolution of the system.

Moffat: You mentioned that the N/C ratio in some OB stars in MXRBs is high, indicating that processed matter may have been accreted from the original primary via mass transfer. However, there are also a fairly large number of OB stars with anomalous N/C ratios (Walborn), although such stars may indeed have a high binary frequency. This might then support your mass transfer hypothesis.

De Greve: Nolan Walborn indeed repeatedly reported on these anomalies. However, we're still lacking good quantitative estimates to give us a clue to the problem of the amount of accretion. But I agree with you that only a proper hydrodynamical study of the phenomenon will give us the right answer.