CONSERVATIVE AND NON-CONSERVATIVE EVOLUTIONARY COMPUTATIONS IN CONNECTION WITH WOLF-RAYET BINARIES.

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1. INTRODUCTION

We consider the evolution of massive close binaries. The reader is referred to the first contribution by the same authors during this conference for the general ideas. The present contribution deals with the implications for the Wolf-Rayet phase, i.e. that part of the evolution where the primary is liable to show W-R characteristics (as usual the primary is defined as the originally more massive component). We refer to the evolution after the exchange of mass between the components, or even during the exchange phase (see section 3).

In Section 2 we recall some of the results from conservative exchange calculations. These computations were extended in two ways. Firstly, we include mass loss through stellar wind from ZAMS on for both components as long as they evolve separately (first phase). Secondly, we allowed for mass and momentum loss from the system during the ensuing critical lobe overflow and mass exchange phase. For convenience, we shall further specify here a second phase of violent mass transfer and a third phase of slow exchange, during which the primary slowly regains its previous luminosity.

2. COMPUTATIONS UNDER THE ASSUMPTION OF CONSERVATIVE MASS EXCHANGE

Our conservative computations have been described extensively by De Grève et al. (1978). Such computations can produce models of W-R like stars, with $X_{atm} \approx 0.20$ (content of H by mass), suitable luminosity and effective temperature and with masses within the range of the observed values. It should be remarked, though, that in order to obtain a remnant primary mass of e.g. 15 $M_{\odot}$, one has to start from a star of $\approx$ 40 $M_{\odot}$; a large fraction of the mass is then exchanged in about 1000 years. It is difficult to imagine an exchange rate of 0.02 $M_{\odot}$/year on the average as a conservative process. Anyway, one cannot obtain systems with periods in the order of a few days (and some of such are observed) from conservative computations; that is, if one

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wants to avoid contact systems. It has also been shown by De Grève et al. (1978) that systems with initial mass ratio $q_i > 0.5$ cannot produce the observed (final) periods and mass ratios. All in all, the conservative computations can only give a rough correspondence between observed and theoretical characteristics.

One of the important things we learned (or saw confirmed) from these computations, is that the remnant of the primary after the process of mass exchange is determined by the initial primary mass and composition. The choice of system parameters such as mass ratio and separation has no influence upon the final structure of the primary.

An example of evolutionary tracks in the H-R diagram is shown in Figure 1.

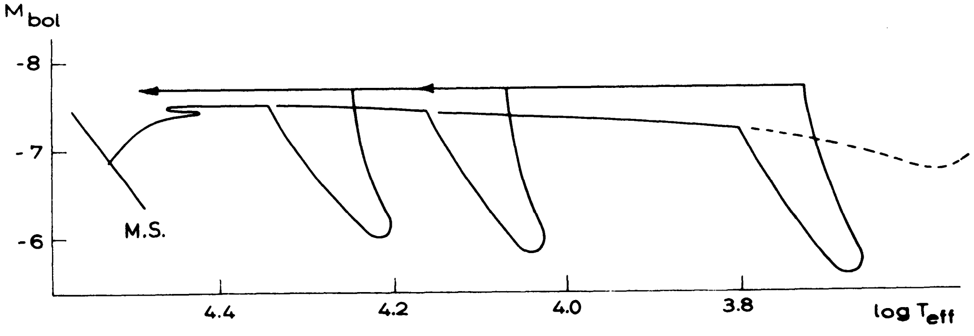

Figure 1. Evolutionary tracks for a 20 $M_\odot$ star with a 14 $M_\odot$ companion, conservative mass exchange. Initial separations : 40 $R_\odot$, 100 $R_\odot$, 490 $R_\odot$.

3. NON-CONSERVATIVE EVOLUTION AND THE WOLF-RAYET PHASE

The problems mentioned in section 2 disappear if the refinements described in the introduction are included in the computations.

For the stellar wind mass loss (first phase) the computations were performed as described by de Loore et al. (1977). The choice of the proportionality parameter N ($\dot{M}$ = N L c^{-2}) affects the value of the remnant mass (cf. Figure 1 in our first contribution). The size and structure of the primary after the first phase determine the final characteristics of the W-R star. Like in the conservative case, these are independent of separation and choice of secondary, but also of the assumptions about the amount of matter and momentum that is lost to the system or exchanged.

The computations for phase 2 and 3, including mass and angular momentum losses, were performed by means of two parameters β

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and α, where $1-\beta$ is the fraction of mass shed by the primary that is going out of the system and α describes the angular momentum losses through the relation

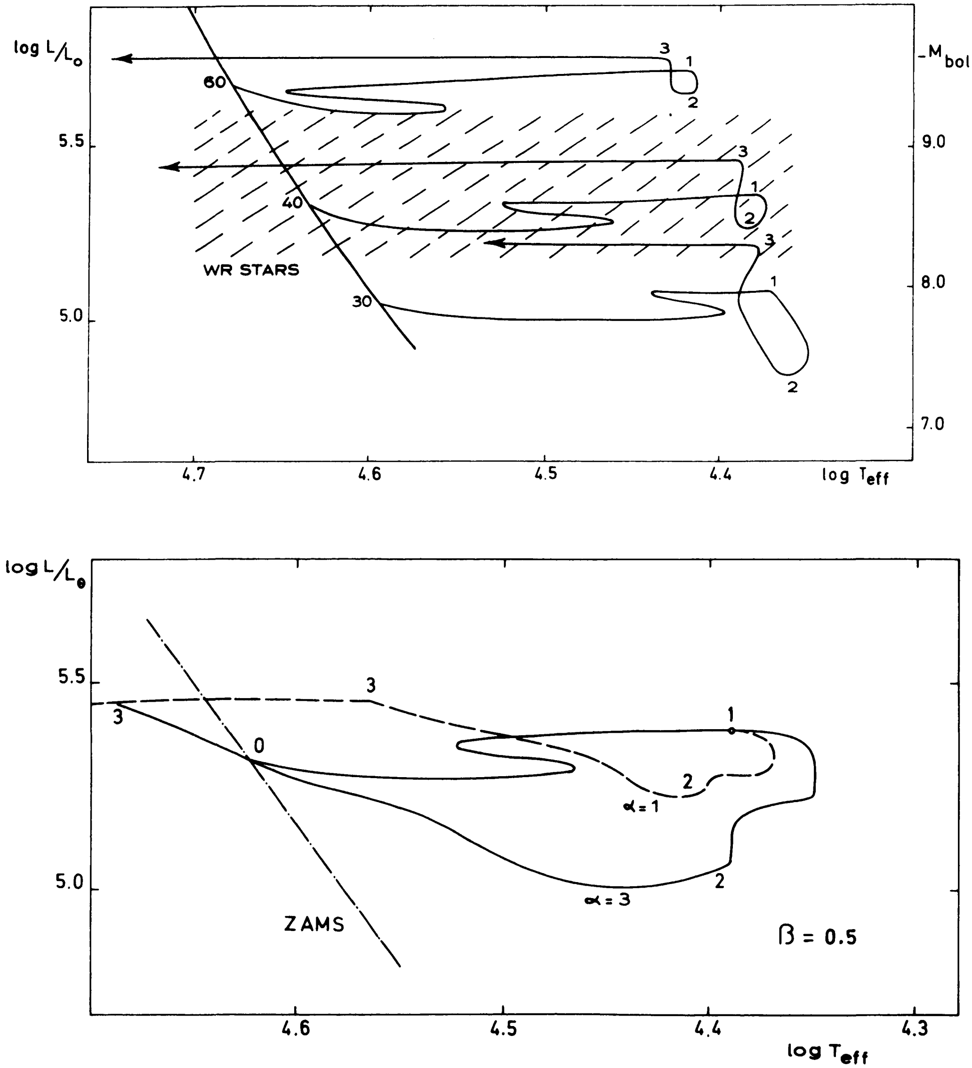
$$\Delta H/H = 1 - \left(1 - \frac{\Delta M}{M_{1i} + M_{2i}}\right)^{\alpha} , \quad \alpha \geq 0$$

The detailed derivation of this equation is given in Vanbeveren et al. (1978). In that paper calculations are given for systems with primary masses ranging from 30 $M_\odot$ to 60 $M_\odot$. Examples of these computations are shown in Figure 2. Typical values for mass exchange rate and time scale are :

phase 2 : 2 - 3 x 10^{-3} $M_\odot$/yr , 2000 - 4000 year

phase 3 : 1 - 2.5 x 10^{-4} $M_\odot$/yr, 7000 - 18000 year.

The systems we thus obtain at the end of phase 3 represent very well the characteristics of the observed W-R binaries. In other words, one can find a suitable initial system + evolutionary history for each of the observed systems. In particular, the observed combination of period and mass ratio can be obtained by an appropriate choice of mass and angular momentum loss (apart from the initial values for P and q one has to choose). For all these parameters a wide range of values is a priori possible; this leads to a variety of final configurations and gives the impression that the set of parameters is indetermined. We can, however, put certain restrictions on them.
(i) From the observed overluminosity of X-ray binaries N-values of $\approx$ 300 to 500 can be derived (Vanbeveren et al., 1978).
(ii) The observed combination of period and mass ratio for W-R binaries leads to restricted values for β and α. For the shortest periods (e.g. HD 214419 : P = 1.64 days; Khaliullin, 1972) one needs $\alpha \geq 3$. The fact that in general P < 100 days seem to exclude values of $\beta \approx 1$. From the analysis of some 10 W-R systems (De Grève et al., 1978, table 5) typical values of $\alpha \approx 3$ and $\beta \approx 0.5$ are found. Physically this means that about 50 % of the transferred mass leaves the system, carrying away about 50 % of the total orbital angular momentum. These rather high losses can be explained from the radial outflow of matter (because of the radiation pressure), rather than a directed flow in the vicinity of L_1, and from the expected occurence of a contact phase shortly after the beginning of phase 2 (cf. Kippenhahn and Meyer-Hofmeister, 1977). It was already found earlier (De Grève et al., 1978) that the later mass exchange sets in, the more violent the process is; in other words, the systems with large initial period will be subject to heavier mass loss during phase 2 and thus the period will be drastically reduced. This agrees with the observed scarcity of final periods larger than a few tens of days.



Figures 2a and 2b. Evolutionary tracks for the primary of a massive close binary system (companion star of half the primary mass). Stellar wind phase (N=300) : between points 0 (ZAMS) and 1. Mass transfer phase (2nd and 3rd phase) : between points 1 and 3.

Fig. 2a : Conservative mass exchange. The hatched area indicates the zone where W-R stars are found (Conti, 1976).

Fig. 2b : Non-conservative mass exchange with $\beta = 0.5$, $\alpha = 1$ and $\alpha = 3$.

(iii) Concerning the mass ratio q : consider the systems of Table 5 in De Grève et al. (1978) and the mass estimates therein. If half of the mass is lost from the system, the masses of the secondaries can only be obtained if the initial mass ratio is close to unity. This means either that $q \simeq 1$ is favoured during the formation of massive binary stars, or that the companion star goes unnoticed if it is of smaller mass. The latter explanation is sustained by the fact that the star which evolves into a W-R becomes overluminous for its mass. Also, in some of the systems there is a trace of the companion, but the determination of orbital elements is not possible. Thus we expect that systems with small initial q [(*)] will in general produce a W-R primary that apparently is single. There may also be W-R stars with a compact companion (see our first paper this volume), which would also appear to be single.

Finally, we want to examine if we can infer something from the observed effective temperatures. The range of values one finds in the litterature is very wide, but there seems to be an upper limit to the estimations, situated around $\log T_{eff} = 4.75$. Some of the estimates used to be too high because of the use of plane parallel atmospheres (cf. Cassinelli and Hartman, 1975). On the other hand, the effective temperatures that come out of our evolutionary computations are also systematically too high, because we had no models for extended atmospheres. Even then, it seems to us we can rule out the idea that the observed W-R stars are stars on the He-M.S., because we are dealing there with $\log T_{eff} \geq 5.0$. In fact, the box in the H-R diagram in which the W-R stars are observed (see e.g. Conti, 1976) agrees very well with (i) the primary stars in the stage of slow mass transfer (phase 3); see e.g. in Figure 2b the track for $\alpha = 3$; (ii) the ensuing evolutionary phase, after termination of mass exchange, of rather fast contraction towards the He-M.S.; a tentative explanation for an upper limit to T_{eff} for the W-R phenomenon might be that the contraction of the star puts an end to the existence of a large extended envelope. The star reaches the $\log T_{eff} = 4.75$ zone about 30 000 years after the end of phase 3, i.e. 2 to 4 times the duration of slow mass exchange. It takes another 30 000 years to attain $\log T_{eff} = 4.90$. The evolutionary time-scales may be considered as lower limits, because the effect of the extended atmosphere will be to keep the star at smaller T_{eff}.

(*) $q < 0.25$ is probably excluded, because the massive star will then destroy its low mass companion during the formation (Hutchings 1976).

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