THE EVOLUTIONARY HISTORY OF BE/X-RAY BINARIES

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A 2.5 $M_\odot$ helium star remnant of a Case B mass transfer is evolved to off-centre neon ignition and a second mass transfer phase, Case BB, is explored. The model for the formation of Be/X-ray binaries by mass-transfer dominated evolution in an intermediate mass binary is confirmed.

INTRODUCTION

Rappaport and Van den Heuvel (1982) suggest that Be stars with neutron star companions are descendants from a mass-transfer dominated, more or less conservative evolution of systems with initial primary stars of intermediate masses (~10 to 20 $M_\odot$). The Be/X-ray binaries form an abundant class of X-rays sources with wide orbits (periods > 15 - 20 days). The Be or Oe components tend to have masses of ~10 to 20 $M_\odot$, most of them are close to the main sequence (see Rappaport and Van den Heuvel, 1982). Van der Linden (1982) calculated the evolution of binaries with primary masses $\leq$ 12 $M_\odot$ undergoing conservative Case B mass transfer. His post-mass transfer systems have system parameters similar to those of Be binaries (cf. Kříž and Harmanec, 1975). The rapid rotation of the Be star is probably due to the mass transfer. If the remnant of the original primary is a helium star of 2-4 $M_\odot$, its C-O core may become larger than the Chandrasekhar mass in the subsequent evolution and it is expected to collapse to a neutron star (see the review of Van den Heuvel, 1983). The evolution of such helium stars up to carbon ignition in the core was followed by De Grève and De Loore (1977) and Delgado and Thomas (1981). After this, the change of the radius with time is only roughly known or not at all (cf. Nomoto, 1981). A second phase of mass transfer by Roche-lobe overflow (Case BB) is possible if the original primary is not too massive (< 14 $M_\odot$), cf. De Grève and De Loore (1977). So far, Case BB mass-transfer after carbon exhaustion in the core is yet unexplored for helium stars with masses of 2 to 4 $M_\odot$. The final evolution of a ~ 2.5 $M_\odot$ helium core of a 10 $M_\odot$ single hydrogen star leads to the formation of a neutron star, cf. Woosley et al. (1980) and Hillebrandt (1982). In this paper we describe the evolution of a 2.5 $M_\odot$ helium star through helium- and carbon-burning up to off-centre neon ignition. Case BB mass-transfer is investigated with a companion of 17 $M_\odot$. This system is the result of conservative mass-exchange from a binary with initial components of 13 + 6.5 $M_\odot$.

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MODEL CALCULATIONS AND RESULTS

The evolutionary program of Van der Linden (1982) was modified to compute the evolutionary stages of 2-4 $M_\odot$ helium stars beyond helium exhaustion in the core up to neon-burning. Simple reaction networks are included for the relevant burning phases (see Habets, 1984). The composition of the initial model (by mass) was taken to be Y = 0.97 and Z = 0.03 (i.e. .75% ^{12}C, .75% ^{16}O and 1.5% ^{14}N). The period P (= $20^d.29$) and orbital separation A (= 84.2 $R_\odot$) of the binary were chosen such that BB mass transfer sets in after carbon exhaustion in the core and such that under conservative assumptions the 13 + 6.5 $M_\odot$ progenitor system was in Case B (P = $2^d.58$). In Figures 1 and 2 the evolution of the helium stars is shown for several stages: A-B, helium main sequence and exhaustion of helium in the core, B-C, radiative shell helium-burning and gravitational contraction of the carbon core, C-D, ignition of carbon, convective core and radiative shell carbon-burning, D-E, convective shell carbon-burning and gravitational contraction of the O-Ne-Mg core, E ignition of neon and convective off-centre neon-burning. During phase D-E the core-mass (i.e. mass of the convective helium core and of the C-O core, which is defined by the region interior to the helium shell with maximal energy generation) grows larger than the Chandrasekhar limiting mass (Figure 2). The treatment of mass transfer is similar to that by Van der Linden. The total amount of mass transferred is 0.3 $M_\odot$ (in ~ 2.9×10^3 yr = 12 $\tau_{thermal}$) and the final period is 28^d with A = 105 $R_\odot$. After this, two short-lasting (4-10 years) mass-transfer phases with maximal $\dot{M}$ ~ $10^{-4.7}$ $M_\odot$ /yr can not be avoided just before neon ignites. The last exchange phase has not been calculated. The evolution of the inner regions is depicted in Figures 3a and 3b. The dotted lines limit the C-O core. Notice that the extent of the C-O core is not much affected by the mass exchange.

The post-carbon compositional and thermodynamic structure of the inner regions of the 10 $M_\odot$ star as computed by Woosley et al. is similar to the one of our 2.5 $M_\odot$ helium star (even if mass loss is included). Therefore we expect that the final evolution will be almost the same, i.e. neon and oxygen ignite off-centre, but the inner 0.14 - 0.15 $M_\odot$ central region of neon and oxygen remains unburned. The central Ne-Si core contracts, the helium layer will be ejected, the remnant evolves through core collapse into a neutron star of ~ 1.44 $M_\odot$ (cf. Hillebrandt). Consequently, the proposed scenario for the formation of Be/X-ray binaries can indeed explain the observed features of these systems. The occurence of the BB mass transfer after carbon exhaustion in the core does not alter the above picture considerably. The supernova explosions will be hydrogen-deficient (Type I?) and the amount of mass ejected will be relatively small (< 0.7-1 $M_\odot$), which will not strongly affect the orbit.

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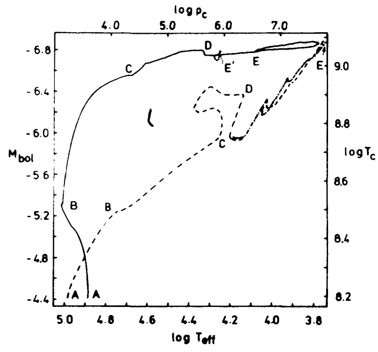

Fig.1: Fully drawn curve: the evolutionary track of the 2.5 $M_\odot$ helium star in the HR diagram. Dashed curve: plot of central temperature vs. density of the evolving star. The dotted part of these curves is with Case BB of mass-transfer.

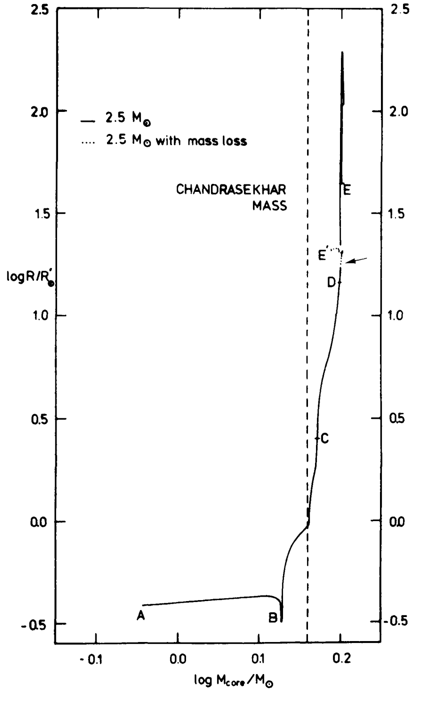

Fig.2: Radius as function of core mass. The arrow indicates the onset of mass exchange in the 2.5 + 17 $M_\odot$ system. For the letters in Figures 1 and 2 see the text.

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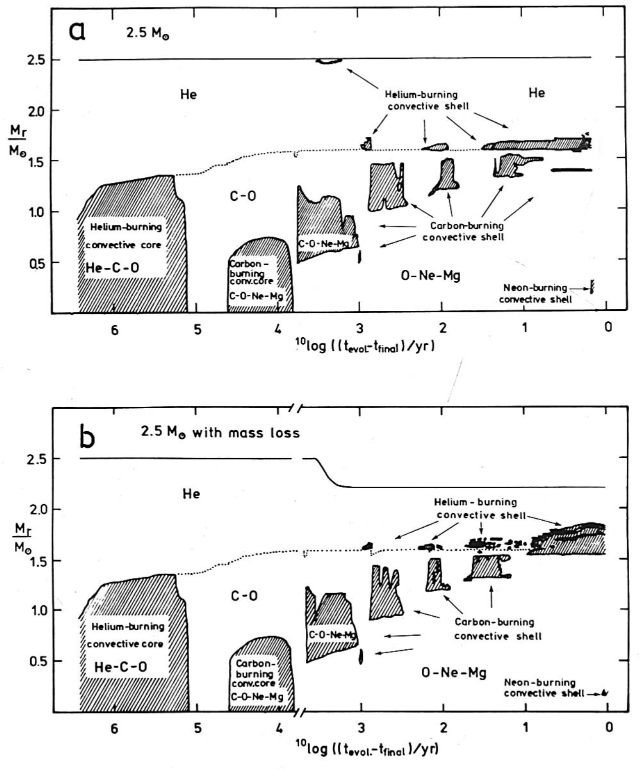

Fig. 3a: The evolution of the interior regions of the 2.5 M⊙ helium star without mass loss. 3b: Same with Case BB mass loss to the 17 M⊙ companion.

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