Convection and compact stellar remnants in massive close binaries

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Abstract. The progenitor evolution of the massive X-ray binary Wray 977/GX 301-2 – a B supergiant of about 40 $M_\odot$ and a neutron star companion – is investigated using new massive close binary models with the aim to constrain the upper mass limit for neutron star formation in single stars, M_{NS}, and to discuss the influence of the treatment of convection on this limit. We argue for a quasi-conservative evolution of this system with a 26 $M_\odot$ progenitor of the neutron star. We show that the existence of the neutron star implies $21M_\odot < M_{NS} < 26M_\odot$ when convection is treated with the Ledoux criterion and core-overshooting is disallowed. For models with convection according to the Schwarzschild criterion and with core-overshooting we find $13M_\odot < M_{NS} < 15M_\odot$. We conclude from the fact that in SN 1987A a 20 $M_\odot$ star exploded as a supernova that the larger value for M_{NS} is preferable. This result favors the Ledoux criterion for convection over the Schwarzschild criterion and implies that convective overshooting may only be of limited efficiency.

1. Introduction

In this paper we present models for the evolution of the massive X-ray binary Wray 977/GX 301-2 from zero age to its present stage. This system contains a neutron star and the B supergiant Wray 977. It is of interest here because one can, from the presence of the neutron star, determine the ZAMS mass limit M_{NS} for neutron star/black hole formation in single stars (Ergma & van den Heuvel 1998). As we outline below, the strong influence of convection and overshooting on stellar CO-core masses allows to obtain constraints on the efficiency of convective mixing

2. Computational method

The evolution of massive close binary systems is computed with a binary code generated by Braun (1998) based on a stellar evolution code for single stars (cf. Langer 1998). It envokes the simultaneous evolution of the two stellar components of a binary and computes mass transfer within the Roche approximation. Mass loss due to stellar winds is included for both components (see below). As the calculations presented here deal only with contact-free evolutionary stages, no other source of mass loss is considered and our models can thus be called quasi-conservative.

We apply the stellar wind mass loss rates of Nieuwenhuijzen & de Jager (1990), except for hot stars where we use the results of Kudritzki et al. (1989). For stars with a surface hydrogen mass fraction $X_s < 0.4$ we adopt the relation of Braun (1998) based on empirical mass loss rates of Wolf-Rayet stars. However, to account for recent revisions by Hamann & Koesterke (1998), who suggested that previously derived mass loss rates for Wolf-Rayet stars are overestimated by a factor of 2...3, we also computed sequences where this rate has been multiplied by a factor 0.5. Convection and semiconvection has been treated according to Langer et al. (1983), using a semiconvective efficiency parameter of $\alpha_{sc} = 0.02$.

3. A model for Wray 977/GX 301-2

Kaper & Najarro (1998) measured log T_{eff}/[K] of 4.23...4.30 and a radius of 60 to 70 $R_\odot$ for the B star, preferring 4.23 and 62 $R_\odot$. A radius of 62 $R_\odot$ combined with the empirical mass function of Wray 977 (Kaper et al. 1995) and the absence of eclipses implies a lower mass limit for the B star of 39...40 $M_\odot$. The observed period of the binary is 44.15 days.

To obtain a lower limit for M_{NS}, we attempt to find the primary with the lowest possible initial mass for the neutron star GX 301-2. But we also need to have enough mass in the system to be able to increase the mass of the initially less massive component – the mass gainer – up to at least 40 $M_\odot$. This requires an initial mass ratio near 1 and quasi-conservative evolution.

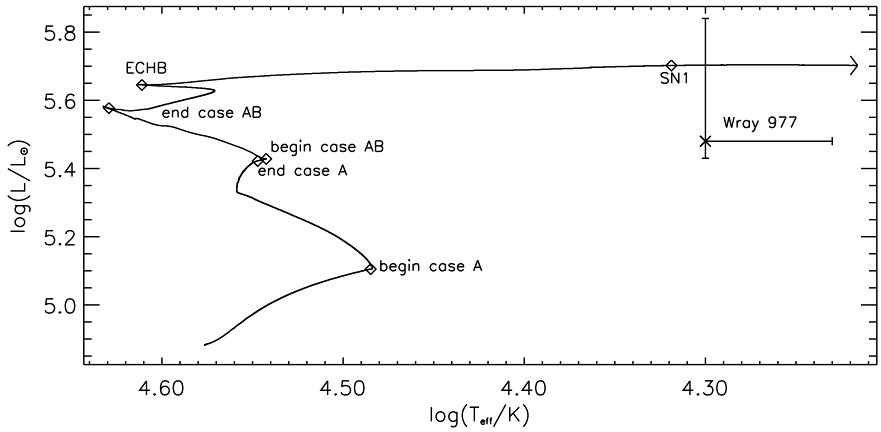

Figure 1. Evolutionary track of our model for Wray 977 in the HR diagram, from the zero age main sequence up to a central helium mass fraction of $Y_c = 0.14$; this model agrees with all empirical constraints of the binary system. The position of Wray 977 in the HR diagramm is indicated according to Kaper & Najarro (1998). Beginning and end of the various mass transfer phases are marked, as well as the end of core hydrogen burning (ECHB). The label SN1 corresponds to the time of the supernova explosion of the neutron star progenitor.

We have computed 30 different systems. The one which fulfils all constraints imposed by Wray 977 (see Fig. 1) has the initial parameters: primary star mass

26 $M_\odot$, secondary star mass 25 $M_\odot$, period 3.5 days. The maximum mass of the mass gainer in this system is 42.41 $M_\odot$, which is, however, reduced to 40.5 $M_\odot$ by the time it corresponds to Wray 977. The final period of the system of 64 days – without considering a kick from the SN explosion – is in fair agreement with the observed period. We emphasize that our progenitor model for Wray 977/GX 301-2, in particular the initial mass of the neutron star progenitor as well as its final CO-core mass, depend only very weakly on the convection criterion or core overshooting. In contrast to single stars, the final CO-core masses of the mass looser in massive binaries ($M > 25M_\odot$) are determined by the WR wind mass loss (see Fig. 2). With standard WR mass loss rates the final CO-core masses are not larger for larger initial masses, i.e. for larger WR star masses after the mass transfer. With convective core overshooting, more massive WR stars form but no increase in the final CO-core mass is expected (c.f. Fig. 2, dotted line). For reduced WR wind mass loss rates, there ist a slight increase of the CO-core mass for larger initial masses (c.f. Fig. 2, solid line).

Clearly there is no need for a larger progenitor mass than 26 $M_\odot$ for the neutron star in Wray 977/GX 301-2. In particular, we disagree with Ergma & van den Heuvel (1998) that the progenitor of GX 301-2 must have been more massive than 50 $M_\odot$.

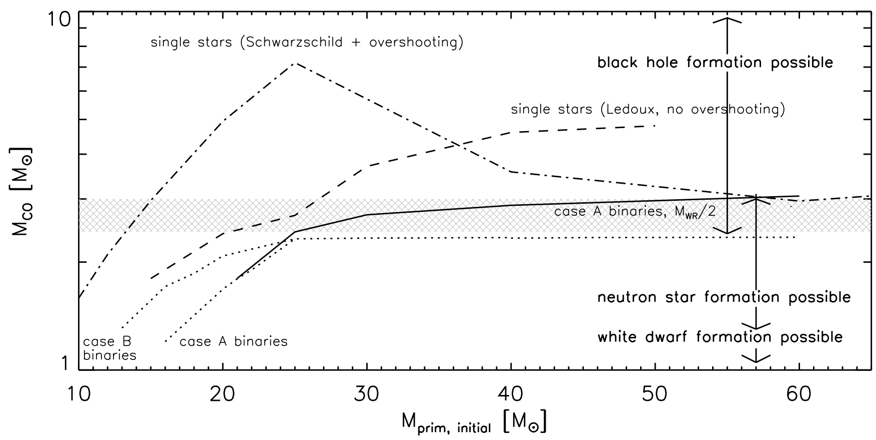

Figure 2. Final CO-core mass of the initially more massive components of massive close binaries as function of its initial mass, for case A and case B systems (cf. Wellstein & Langer 1999) for nominal Wolf-Rayet mass loss (dotted lines, below 25 $M_\odot$ the upper line marks case B systems) and — for the case A — also for half the nominal Wolf-Rayet mass loss rate (solid line), compared to the final CO-core mass of single stars (dashed line; cf. Langer & Henkel 1995; dotted-dashed line; cf. Maeder 1992). For the shaded area we can not decide between neutron star or black hole formation (see text).

4. The mass limit for neutron star/black hole formation, M_{NS}

The progenitor of the neutron star in Wray 977/GX 301-2 must have had a CO-core mass of at least 2.4 $M_\odot$, corresponding to the minimum initial mass of the mass looser of 26 $M_\odot$. Thus we can derive from Fig. 2 a minimum black hole progenitor mass of 21 $M_\odot$ for single stars computed with Ledoux criterion and without overshooting (intersection of dashed line with the lower boundary of the hatched band in Fig.2). For single stars computed with the Schwarzschild criterion and overshooting (Maeder 1992) we derive a limit of 13 $M_\odot$ from the same arguments. The presence of black holes in massive binaries, e.g. that in Cyg X-1, excludes the standard WR wind mass loss rates (dotted lines in Fig. 2), because for this we find no systems with more massive final CO-cores than for the neutron star progenitor of GX 301-2 (cf. also Ergma & van den Heuvel 1998). For the reduced WR wind mass loss rate we derive – assuming that at least some of the mass loosers in binaries reach massive enough CO-cores to collapse to a black hole – an upper CO-core mass limit up to which neutron star formation might be possible of 3 $M_\odot$ (upper boundary of hatched band in Fig. 2). This corresponds to single stars of initial mass 26 $M_\odot$ with the Ledoux criterion and 15 $M_\odot$ with the Schwarzschild criterion and overshooting.

Since the progenitor of the supernova SN 1987A had a luminosity corresponding to a 6 $M_\odot$ He-core, its progenitor was in the range 18...20 $M_\odot$ (Arnett et al. 1989). 20 $M_\odot$ models computed with overshooting develop CO-cores of 4.9 $M_\odot$, which is 1.9 $M_\odot$ above the upper limit we have obtained for M_{NS}. Despite of the possibility of delayed black hole formation due to fallback of matter on a neutron star, a succesful supernova explosion for CO-core masses so far above M_{NS} appears rather unlikely. This result favors the Ledoux criterion for convection over the Schwarzschild criterion and implies that convective overshooting may only be of limited efficiency.

Acknowledgments. We are grateful to Lex Kaper for communicating his results on Wray 977 prior to publication, and for many useful discussions. This work has been supported by the Deutsche Forschungsgemeinschaft through grants La 587/15-1 and 16-1.

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