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Implications of massive close binaries for black hole formation and supernovae

S. Wellstein and N. Langer

Institut für Physik, Universität Potsdam, Am Neuen Palais 10, D-14415 Potsdam, Germany

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Abstract. The progenitor evolution of the massive X-ray binary Wray 977 is investigated using new models of massive close binary evolution. These models yield constraints on the mass limit for neutron star/black hole formation in single stars, $M_{\rm BH}$. We argue for quasi-conservative evolution in this system, and we find $M_{\rm BH} > 13..21\,{\rm M}_\odot$ from the existence of a neutron star in Wray 977, with the uncertainty being due to uncertainties in the treatment of convection. Our results revise earlier published much larger values of $M_{\rm BH}$ derived from the parameters of Wray 977.

Then, on the basis of a grid of 37 evolutionary models for massive close binaries with various initial masses, mass ratios and periods, we derive primary initial-final mass, initial mass-final helium core mass, and initial mass-final CO-core mass relations for the various mass transfer cases of close binary evolution. From these models we derive for single stars that $M_{\rm BH} \lesssim 25\,{\rm M}_\odot$, independent of whether most black hole binaries formed through the Case A/B or the Case C binary channel. Using our grid of binary models, we obtain a consistent scenario for the formation of black holes in binary systems.

We emphasize that in binaries the critical initial mass limits for neutron star/black hole formation and for white dwarf/neutron star formation are very different from the corresponding values in single stars. While the first may well be above $100\,{\rm M}_\odot$ in Case A/B binaries, the latter is found to be in the range $12...15\,{\rm M}_\odot$ instead of the canonical value of $8...10\,{\rm M}_\odot$ usually quoted for single stars. This effect should not be neglected in population synthesis studies of massive binary systems. Also, neutron star and black hole mass functions obtained for single stars can not per se compared to the masses of compact objects in binary systems.

Massive close binaries produce also Type Ib and Ic supernovae. We find two different types of supernova progenitor structure in our models, one with remaining helium masses of the order of $1\,{\rm M}_\odot$ which stems from an intermediate progenitor initial mass range (about $16...25\,{\rm M}_\odot$), and another with one order of magnitude smaller remaining helium masses from initial masses above and below this. A possible connection to the distinction of Type Ib and Type Ic supernovae, and implications from the Type Ic supernova SN1998bw and its associated γ-ray burst are discussed.

Key words: stars: circumstellar matter – stars: evolution – stars: neutron – stars: supernovae: general – stars: white dwarfs

Send offprint requests to: S. Wellstein
(stephan@astro.physik.uni-potsdam.de)
or N. Langer (ntl@astro.physik.uni-potsdam.de)

1. Introduction

The evolution of stars is considerably complicated by the presence of a close companion, which may lead to either extreme mass loss, to strong mass accretion, or even to the merging of both stars. An overview of the evolutionary possibilities in massive close binaries is given by Podsiadlowski et al. (1992), while evolutionary models for parts of the – unfavorably large – initial parameters space of binaries have been computed, e.g., by Paczinsky (1967), Kippenhahn (1969), de Loore & De Greve (1992), Pols (1994); see also Vanbeveren (1998ab, and references therein). On the other hand, close binaries provide unique possibilities to test and constrain uncertainties inherent in the evolution of stars in general.

An example is given by Ergma & van den Heuvel (1998), who showed that massive close binary systems containing a compact stellar remnant (neutron star or black hole) can constrain the initial mass limit for black hole formation $M_{\rm BH}$. In the present paper, we want to pursue this idea in a quantitative way. In principle, the problem is simple: a valid progenitor model for a system containing a neutron star yields the initial mass of the neutron star progenitor and thus a lower limit to $M_{\rm BH}$, and systems containing a black hole yield an upper limit to $M_{\rm BH}$. This procedure is not hopeless, even though the calculations of the progenitor evolution of the observed systems can not provide the information whether a model component in its final stage evolves into a neutron star or a black hole: The observed orbital period together with the properties of the normal star in the system may allow only for a very limited range of initial masses for the progenitor of the compact component. On the other hand, all the uncertainties involved with the theoretical description of mass transfer in massive close binaries enter the problem and increase the error bar on the progenitor masses.

Note that $M_{\rm BH}$ is not a well defined quantity in binary systems; i.e., whether a star in a binary system forms a black hole or a neutron star depends not only on its initial mass but also on its evolutionary history (see below). We assume implicitly in this paper that $M_{\rm BH}$ is in fact well defined for single stars. This is also not guaranteed. E.g., the initial rotation rate may be a parameter to be considered in addition to the initial mass (cf., Heger et al. 1999). Ergma & van den Heuvel (1998) even argue from the properties of massive close binaries with compact companions that in single stars, $M_{\rm BH}$ must be depending on a second parameter. However, even though we can not show the contrary, we attempt here to disprove their main argument for this.

Two criteria may help to chose those observed systems which are best suited to constrain $M_{\rm BH}$. First, if one would pick systems for which one could assume that the system progenitor evolution proceeded more or less conservatively, i.e. that most of the system initial mass remained in the system, one could avoid the huge uncertainties inherent in theories of mass outflow from the system, either through the second Lagrangian point or in the course of a common envelope evolution (Podsiadlowski et al. 1992). Since strong mass outflow efficiently removes angular momentum and thus results in short periods, one should avoid the systems with the shortest periods. Second, it would be most efficient to investigate systems of which one can hope that the compact star's progenitor mass is close to $M_{\rm BH}$. For systems containing a neutron star, this means one should look for the most massive systems.

The massive X-ray binary Wray 977/GX 301-2 (4U 1223-62) fulfills both criteria. It contains an X-ray pulsar (GX 301-2) and the B supergiant Wray 977 (BP Cru). The latest and most reliable determination of the stellar parameters of Wray 977 has been performed by Kaper & Najarro (1999). They found $\log {\rm T}_{eff}/[K] = 4.23...4.30$ and a radius of $R = 60...70\,{\rm R}_\odot$, with preferred values of 4.23 and 62 $\rm R_\odot$. A radius of 62 $\rm R_\odot$ combined with the empirical mass function of Wray 977/GX 301-2 (Kaper et al. 1995) and the absence of eclipses implies a lower mass limit for the B star of $M = 39...40\,{\rm M}_\odot$. An independent lower mass limit for Wray 977 of $\sim 40\,{\rm M}_\odot$ has been derived spectroscopically from the velocity amplitude by Kaper & Najarro (1999). Constraints on the properties of Wray 977 obtained by Koh et al. (1997) agree with these values. The observed period of the binary is 44.15 days.

Ergma & van den Heuvel (1998) concluded that the neutron star progenitor mass was initially larger than the present mass of the B star. Here, we present massive close binary models from zero age until beyond the death of the primary component (defined here as the initially more massive star in the system), which constrain the progenitor evolution of Wray 977/GX 301-2. After describing our computational method in Sect. 2, we present our best model for Wray 977/GX 301-2's progenitor evolution in Sect. 3, which results in an initial mass for GX 301-2 of only $26\,{\rm M}_\odot$. In Sect. 4, we discuss the evolution of the stellar, the helium core, and the CO-core masses of primaries in massive binary system on the basis of a new grid of computed systems. In Sect. 5, our grid of binary models is used to derive the transformation of the initial mass limit for neutron star formation obtained from binaries to the single star case. In Sect. 6 we analyze the evolution of the chemical structure of massive primaries and implications for Type Ib/c supernovae. In Sect. 7 we summarize our results to a global picture of massive close binary evolution and a scenario for the formation of black hole and neutron star binaries.

2. Computational methods

We computed the evolution of massive close binary systems using a computer code generated by Braun (1997) on the basis of an implicit hydrodynamic stellar evolution code for single stars (cf. Langer 1991, 1998). It invokes the simultaneous evolution of the two stellar components of a binary and computes mass transfer within the Roche approximation (Kopal 1978). The entropy of the accreted material is assumed to be equal to that of the surface of the secondary star, where gravitational energy release due to mass accretion is treated as in Neo et al. (1977); see also Braun & Langer (1995). Even though mass loss due to stellar winds is included for both components (see below) – with a corresponding angular momentum loss according to Brookshaw & Tavani (1993) – the present calculations deal only with contact-free evolutionary stages, and therefore no other source of mass outflow from the system is included. Our models can thus be called quasi-conservative.

We use standard stellar wind mass loss rates, i.e., the rate of Nieuwenhuijzen & de Jager (1990), except for hot stars. For OB stars ($\log\, T_{\rm eff} > 15\,000$ K), we use the theoretical radiation driven wind models of Kudritzki et al. (1989) with wind parameters $k = 0.085$, $\alpha = 0.657$, $\delta = 0.095$, and $\beta = 1$ (Pauldrach et al. 1994). I.e., the dependence of the mass loss rate on the luminosity, effective temperature, mass, and surface hydrogen mass fraction is taken into account. For hydrogen-poor stars, i.e. stars with a surface hydrogen mass fraction $X_{\rm s} < 0.4$, we used a relation based on the empirical mass loss rates of Wolf-Rayet stars derived by Hamann et al. (1995) for massive stars $\log\, L/{\rm L}_\odot \geq 4.5$ and by Hamann et al. (1982) for helium stars in the range $3.5 \leq \log\, L/{\rm L}_\odot \leq 4.5$, i.e.

$$\log\left(-\dot{M}_{\rm WR}/(\,{\rm M}_\odot\,{\rm yr}^{-1})\right) = \begin{cases} -11.95 + 1.5\log\, L/{\rm L}_\odot - 2.85 X_{\rm s} \\ \qquad\qquad \text{for } \log\, L/{\rm L}_\odot \geq 4.5 \\ -35.8 + 6.8\log\, L/{\rm L}_\odot \\ \qquad\qquad \text{for } \log\, L/{\rm L}_\odot < 4.5 \end{cases} \quad (1)$$

Note that for core helium burning helium stars, this equation gives mass loss rates very close to that proposed by Langer (1989). To account for recent revisions of empirical Wolf-Rayet mass loss rates by Hamann & Koesterke (1998), who suggested that previously derived values for massive Wolf-Rayet stars may overestimate the mass loss by a factor of 2...3, we also computed sequences where this rate has been multiplied by a factor 0.5, i.e.,

$$\log\left(-\dot{M}_{\rm WR}/(\,{\rm M}_\odot\,{\rm yr}^{-1})\right)$$

$$= \begin{cases} -12.25 + 1.5 \log\, L/\mathrm{L}_\odot - 2.85 X_\mathrm{s} \\ \qquad\qquad \text{for } \log\, L/\mathrm{L}_\odot \geq 4.45 \\ -35.8 + 6.8 \log\, L/\mathrm{L}_\odot \\ \qquad\qquad \text{for } \log\, L/\mathrm{L}_\odot < 4.45 \end{cases} \quad (2)$$

Convection and semiconvection have been treated according to Langer et al. (1983), mostly using a semiconvective efficiency parameter of $\alpha_\mathrm{sc} = 0.01$ (cf. also Braun & Langer 1995). Time-dependent thermohaline mixing is followed in a diffusion scheme according to Wellstein et al. (1999; cf. also Braun 1997), which is based on an analysis of Kippenhahn et al. (1980).

Opacities are taken from Iglesias & Rogers (1996). Changes in the chemical composition are computed using a nuclear network including the pp-chains, the CNO-tri-cycle, and the major helium-, carbon and oxygen burning reactions. For the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ nuclear reaction rate we followed Weaver & Woosley (1993) and used a value of 1.7 times that of Caughlan & Fowler (1988). Further details about the computer program and input physics can be found in Langer (1998) and references therein. All models in this work use an approximately solar initial chemical composition with a mass fraction of all elements heavier than helium ("metals") of $Z = 0.02$. The mass fractions of hydrogen and helium are set to $X = 0.7$ and $Y = 1 - X - Z = 0.28$, respectively. The abundance ratios of the isotopes for a given element are chosen to have the solar system meteoritic abundance ratios according to Grevesse & Noels (1993).

3. The smallest possible initial mass of GX 301-2

The derivation of initial masses of neutron star progenitors in binaries can only yield lower limits to M_BH. These limits are immediately valid for single stars, since the stronger mass loss in primaries of close binaries compared to that in single stars can cause more massive primaries than single stars to form neutron stars, but not vice versa. As due to the uncertainties in the binary evolution models one always ends up with a possible range of initial masses for the neutron star progenitor in a given system, only the smallest mass in this range leads to a stringent constraint on M_BH. Therefore, we attempt to find the lowest possible initial mass for the progenitor of the neutron star GX 301-2.

3.1. Restricting the initial system parameters

Since the neutron star progenitor evolved first into a supernova, the B star Wray 977 is very likely the initially less massive star in the binary system – we thus designate it here as the secondary component. Note that even though a reversal of the supernova order – i.e., the secondary component exploding earlier than the primary – is possible (e.g., Pols 1994, or System No. 10 in Sect. 4 below), this assumption would lead to larger neutron star progenitor masses than the assumption of the normal supernova order. If we define, as usual, β as the fraction of the mass transfered from the primary to the secondary which remains in the binary system, i.e. the fraction $1 - \beta$ is ejected from the system, one can easily see that $\beta \to 1$ (i.e. conservative evolution) leads to the smallest possible initial masses for the neutron star progenitor. E.g., assuming $\beta = 0$ implies that the progenitor mass of GX 301-2 must be larger than Wray 977's present mass, i.e., $M_\mathrm{1,i} \gtrsim 40\,\mathrm{M}_\odot$ (cf. Ergma & van den Heuvel 1998), while every solar mass which is successfully transfered form the neutron star progenitor to Wray 977 allows the initial mass of GX 301-2 to have been roughly one solar mass smaller.

Furthermore, smaller neutron star progenitor masses can be achieved the closer the initial mass ratio q is to one. Keeping the total mass M in the system constant up to the first supernova explosion ($\beta = 1$), the smallest possible initial mass of the neutron star progenitor is $M/2$, which corresponds to $q = 1$.

Finally, we need to know the initial period of our most constraining binary model. There are two reasons which made us prefer a Case A evolution (mass transfer during core hydrogen burning). First, simple estimates – which are possible and meaningful for conservative systems – show that initial periods corresponding to Case A result in final periods which are in the range of that found in Wray 977/GX 301-2 (Pols 1994). Second, Case A mass transfer yields smaller values for M_BH in single stars than Case B or C[1] (as will be shown in detail below), and as we are looking for the lower limit on M_BH we thus need to consider Case A.

3.2. A progenitor model for Wray 977/GX 301-2

The binary model (System No. 8; cf. Table 1) with initial parameters selected in this way has a primary star initial mass of $26\,\mathrm{M}_\odot$, a secondary initial mass of $25\,\mathrm{M}_\odot$, and an initial period of 3.5 days. The evolution of both components in the HR diagram is displayed in Fig. 1. It proceeds through Case A mass transfer, for which a rapid and a slow phase can be distinguished and which is followed by a Case AB mass transfer after the core hydrogen exhaustion of the primary (cf. Fig. 3).

The secondary evolves to a maximum mass of $42.4\,\mathrm{M}_\odot$, which is reduced by stellar winds later on. After the Case AB mass transfer, the primary is a helium star of $6.4\,\mathrm{M}_\odot$ (i.e., a Wolf-Rayet star) which evolves to a final mass of $3.2\,\mathrm{M}_\odot$ due to wind mass loss (cf. Fig. 2). Note that the initial helium star mass of this $26\,\mathrm{M}_\odot$ primary is smaller than the corresponding mass in a $25\,\mathrm{M}_\odot$ primary undergoing Case B mass transfer (System No. 9 in Table 1 below), since in Case A primaries the hydrogen burning convective core mass is reduced due to the mass transfer (cf. Fig. 2).

Our System No. 8 does not only represent the academic case which yields the minimum initial progenitor mass of the neutron star GX 301-2. It also fulfills all empirical constraints imposed by Wray 977/GX 301-2 (cf. Sect. 1, and see Fig. 1) and is thus a viable progenitor model for this system. The mass of the B star at the time of the supernova explosion of the primary is $40.5\,\mathrm{M}_\odot$, and the final period of the system of 46.22 d before and 47.3 d

[1] as Kippenhahn & Weigert (1967) and Podsiadlowski et al. (1992), we define the Cases A, B, and C evolution corresponding to mass transfer during core hydrogen burning, after core hydrogen burning but before core helium exhaustion, and after core helium exhaustion, respectively

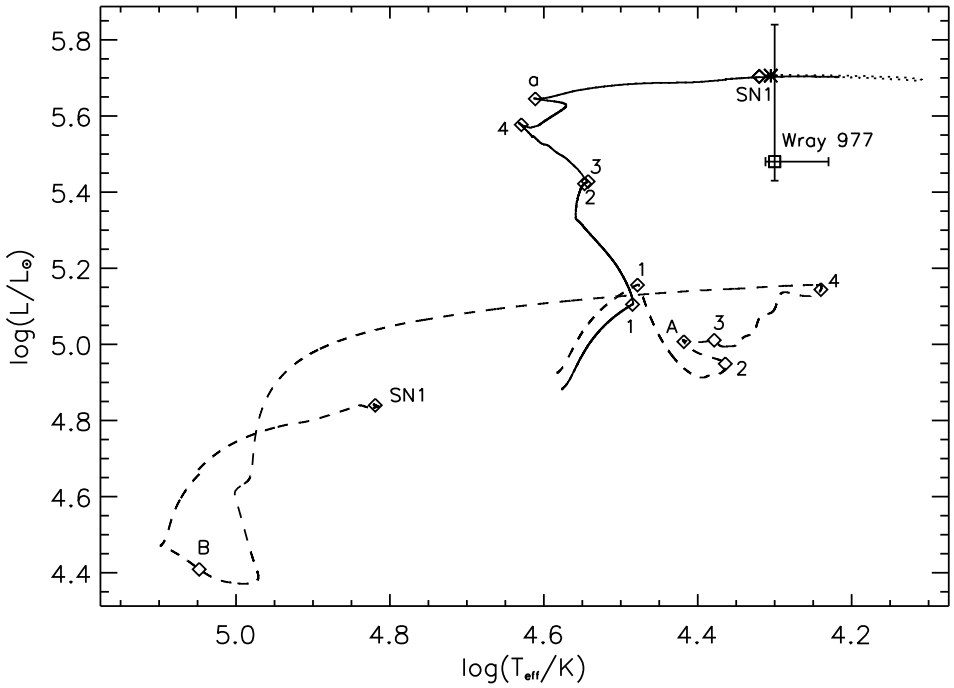

Fig. 1. Evolution of the components of our progenitor model for Wray 977/GX 301-2 (model No. 8; cf. Table 1) in the HR diagram. The dashed line corresponds to the evolution of the primary from the zero age main sequence to its supernova explosion. The solid line corresponds to the evolution of the secondary from the zero age main sequence until the onset of reverse mass transfer onto the neutron star (solid line); the dotted continuation of the solid line designates the secondary's evolution up to its supernova explosion (marked by a asterisk) if the neutron star companion were absent. The end of the solid line corresponds to a central helium mass fraction of the secondary of $Y_{\rm c} = 0.14$. Beginning and end of the various mass transfer phases are marked as follows. 1: begin of Case A, 2: end of Case A, 3: begin of Case AB, 4: end of Case AB. A/a designates core hydrogen exhaustion for the primary/secondary, B the end of primary's core helium burning. The position of both components at the time of the primary's supernova explosion is marked by a diamond and labeled 'SN1'. The position of Wray 977 according to Kaper & Najarro (1999) is indicated (square) together with the error bars.

after the supernova explosion – without considering a supernova induced kick on the neutron star – is in good agreement with the observed period. Note that the possibility of supernova kicks render conclusions based on the observed period as difficult since the observed eccentricity of $e = 0.47$ is rather large; it only constrains the period of the spherical orbit before the supernova explosion approximately to the range 15 d...59 d.

While the luminosity of the mass gainer in our model No.8 ($\log L/\mathrm{L}_\odot \simeq 5.7$) is within the observational error bar, it is slightly more luminous than the value preferred by Kaper & Najarro (1999) ($\log L/\mathrm{L}_\odot \simeq 5.5$). To analyze the uncertainties of the post-main sequence luminosity in our models, we have computed several $25 + 24\,\mathrm{M}_\odot$ Case A systems with different assumptions for the semiconvective efficiency parameter $\alpha_{\rm sc}$. This parameter, which controls the so called rejuvenation process in the accreting main sequence star (cf. Hellings 1983, Braun & Langer 1995), has no influence on the evolution of the mass transfer, the stellar masses or the binary period. However, it does affect the evolutionary track of the secondary after the mass transfer. Most important, it determines the temperature and radius evolution after core hydrogen exhaustion, and to a smaller extent it influences the stellar luminosity during this phase. From Fig. 4 we see that smaller values of $\alpha_{\rm sc}$ lead to smaller post-main sequence luminosities. While the semiconvection parameter has no relevance for our discussion of the critical mass limit for neutron star formation, it is important for the probability to find systems like Wray 977/GX 301-2 – which is much higher for lower $\alpha_{\rm sc}$ – and for its future evolution (cf. Fig. 4). Note that System No. 8 has been computed with an efficiency parameter for semiconvection of $\alpha_{\rm sc} = 0.02$ (see Table 1).

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 convective core overshooting. This is particularly true for the implication that the primary component forms a neutron star since, in contrast to single stars, the final masses of the mass loser in massive binaries ($\mathrm{M} > 25\,\mathrm{M}_\odot$) are determined by the WR wind mass loss (see Sects. 4.1 and 4.2, and Fig. 5 below).

Finally, we want to mention that the surface composition of Wray 977 might be an additional way to discriminate evolutionary scenarios for its progenitor evolution. While according to scenarios which propose a completely non-conservative evolution ($\beta = 0$) the surface chemical composition would be unaltered, our model predicts a enrichment factor for nitrogen of 5.5 and depletion factors of carbon and oxygen of 0.33, and 0.75, respectively. All isotopes of Li, Be and B are totally depleted.

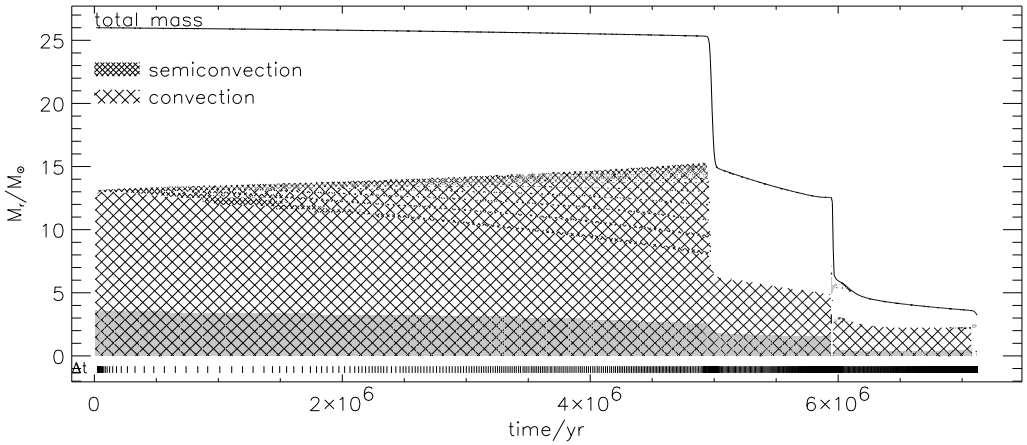

Fig. 2. Evolution of the internal structure of the primary component of System No. 8 – i.e., our progenitor model for GX 301-2 – as function of time. Convection and semiconvection are marked as indicated, and gray shading designates regions of nuclear energy generation. The upper solid line indicates the total mass of the star. The rapid phase of the Case A mass transfer and the Case AB mass transfer correspond to the sharp decreases of the total mass at about 4.9 and 5.9 Myr, respectively. Core hydrogen exhaustion coincides roughly with Case AB mass transfer. Core helium burning ends at $t \simeq 7.1$ Myr. The computations stops at core neon ignition. The decrease in mass between 4.9 and 5.9 Myr (about 2.5 $\mathrm{M}_\odot$) is due to slow Case A mass transfer, that for $t \gtrsim 6$ Myr (about 3.2 $\mathrm{M}_\odot$) due to WR winds. The final mass of the star before it explodes as supernova is 3.17 $\mathrm{M}_\odot$ (cf. Table 1).

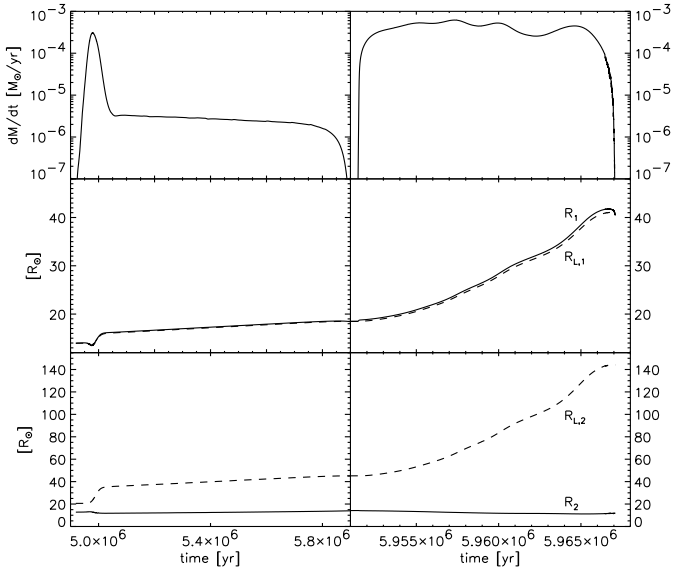

Fig. 3. Details of the mass transfer evolution of our progenitor model for Wray 977/GX 301-2, System No. 8. The left panel covers the Case A mass transfer phase, the right panel the Case AB. Shown are: the mass transfer rate (upper panel), stellar radius R_1 (solid line) and Roche radius $R_{\mathrm{L},1}$(dashed line) of the primary (middle panel), and stellar radius R_2 (solid line) and Roche radius $R_{\mathrm{L},2}$(dashed line) of the secondary (lower panel).

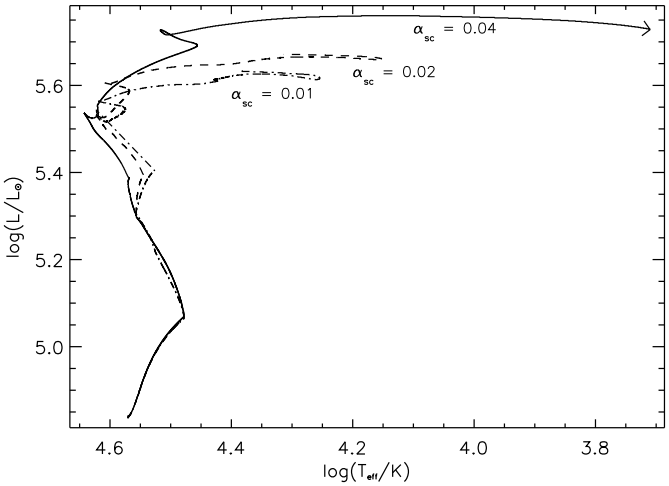

Fig. 4. Tracks in the HR diagram for the secondaries of the Systems No. 10 ($\alpha_{\mathrm{sc}} = 0.01$, dashed-dotted line), No. 10a ($\alpha_{\mathrm{sc}} = 0.02$, dashed line), and No. 10b ($\alpha_{\mathrm{sc}} = 0.04$, solid line), which have the same initial stellar masses of 25 + 24 $\mathrm{M}_\odot$ and the same initial period of 3.5 d (cf. Table 1). For Systems No. 10 and 10a, the tracks cover the evolution of the star from the zero age main sequence until the supernova explosion, reverse mass transfer does not occur. In System No. 10b, the secondary star rejuvenates during core hydrogen burning; reverse mass transfer would occur but is not taken into account in this calculation; the track ends before core helium ignition.

3.3. Potential problems of the progenitor model

Our progenitor model for Wray 977/GX 301-2 has two potential problems which we want to discuss here for completeness, even though they may turn out not to be essential.

The first concerns effects which the stellar wind of the secondary star might have on the accretion efficiency parameter β. In principle, one could imagine a situation where the secondary's wind drags part of the material which has left the primary and is on its way to the secondary with it to infinity. However, detailed models for such a situation are not available. We are optimistic that this effect is not too important in our case since most of the mass transfer from the primary to the secondary does not occur through an accretion disk, but instead, according to the estimates of Ulrich & Burger (1976), the gas

stream impacts directly onto the surface of the secondary. This is so for the complete Case A mass transfer as well as for the ensuing Case AB mass transfer in our System No. 8. Thus, the Case A binaries are those among the massive close binaries for which a conservative evolution appears most appropriate.

The second potential problem is that for certain initial and physical parameters the supernova order in Case A systems can reverse, i.e., the secondary can explode before the primary does. We have shown in Sect. 3.2 that Case A models exist for which the supernova order is not inverted (as needed to explain Wray 977/GX 301-2; e.g. our model No. 8). However, with $\alpha_{\rm sc} = 0.01$ a reverse supernova order would most likely occur in this system, as we conclude from our model No. 10 (cf. Table 1). This does not mean that for $\alpha_{\rm sc} = 0.01$ a supernova order reversal would occur for all conservative Case A systems; rather a slight decrease of the initial secondary mass or a slight increase of the initial period would avoid this to happen. It is therefore conceivable that for any value of $\alpha_{\rm sc}$ the initial period-initial mass ratio parameter space for Case A systems for which the primary explodes first as a supernova is not empty (cf. also Pols 1994; Wellstein et al. 1999).

3.4. Alternative progenitor scenarios for Wray 977

During our literature search, we did not find any other evolutionary calculations which were tailored to fit the system Wray 977/GX 301-2.

Several "scenarios" for the progenitor evolution of this system have been considered. Brown et al. (1996), relying on the mass determination of $\gtrsim 48\,{\rm M}_\odot$ for Wray 977 by Kaper et al. (1995), prefer $45\,{\rm M}_\odot$ as the progenitor mass of GX 301-2. They do not consider constraints imposed by the binary period. In Vanbeveren et al.'s (1998a) scenario the system consists initially of a $40+36\,{\rm M}_\odot$ pair in a 50 d orbit, which, in a non-conservative ($\beta = 0.5$) Case B mass transfer, evolves into an $18.5 + 41\,{\rm M}_\odot$ helium star-O star pair in a 28 d orbit. Interestingly, this is almost the same configuration which results from the detailed evolutionary calculations of de Loore & De Greve (1992) starting also with a $40 + 36\,{\rm M}_\odot$ pair but with a much smaller orbital period of 19.6 d. Finally, Ergma & van den Heuvel (1998) prefer a completely non-conservative scenario ($\beta = 0$) which implies an initial mass of GX 301-2 in excess of $50\,{\rm M}_\odot$, from which they draw far reaching conclusions, in particular regarding the initial mass limit for black hole formation.

In all of these scenarios, mass needs to be removed from the system. However, the processes which would do this are not well understood. Consequently, the amount of mass which leaves the system, and the amount of angular momentum which is removed together with the mass are not well constrained and need to be parameterized. This shows, e.g., when the above mentioned results of Vanbeveren et al. (1998a) and de Loore & De Greve (1992) are compared, which differ in their treatments of angular momentum loss. Consequently, the period of Wray 977/GX 301-2, or likewise the orbital separation of the two components, can not be precisely predicted in these scenarios. Only the scenario of Ergma & van den Heuvel (1998) does not include binary-induced mass loss from the system and is thus free of this uncertainty.

All of the above scenarios favor an initial mass of the neutron star GX 301-2 in the range of $40...50\,{\rm M}_\odot$. Several of the papers mentioned above conclude that therefore single stars with initial masses in this range should form neutron stars as well. According to our detailed Case A evolutionary model presented in Sect. 3.2 such conclusions can not be supported. On the contrary, we find a likely, and at least a possible, initial mass of GX 301-2 of only $26\,{\rm M}_\odot$. Furthermore, as will be outlined in Sect. 5 below, this implies only that single stars of initially $21\,{\rm M}_\odot$, not of $26\,{\rm M}_\odot$, form a neutron star. While this appears to be in comfortable agreement with (admittedly uncertain) expectations from single star calculations (e.g., Woosley & Weaver 1995), neutron stars from $40...50\,{\rm M}_\odot$ stars are not, which made Ergma & van den Heuvel (1998) conclude that the type of remnant of the mass loser – neutron star or black hole – must depend on additional stellar parameters, for example magnetic fields or rotation. Although we can not rule out that such effects play a role, we can not conclude from our results that such effects should be present.

4. The final stellar and core masses of massive primaries

In this section, we present the results of calculations for the evolution of massive close binaries for a wide range of primary star initial masses and for various initial system parameters. The evolution of the primary components is followed up to central neon ignition in most cases. Our goal is to derive final properties of the primaries, in particular their final masses and core masses. Those are used in the next section to constrain the critical initial mass limit for neutron star/black hole formation in *single stars*. As a by-product we also obtain results for the evolution of the surface chemical composition of the primaries, which is relevant for the understanding of Type Ib/c supernovae; these issues are discussed in Sect. 6.

We compute binary models for primary star initial masses from 13 to $60\,{\rm M}_\odot$, and for various initial orbital periods and mass ratios. We also study the differences between Case A and Case B mass transfer for the resulting core masses. Since there are indications that the mass loss rates for Wolf-Rayet stars (i.e., helium stars) have been overestimated in the past (Hamann & Koesterke 1998), we computed sequences where our standard helium star mass loss rate (cf. Sect. 2) has been multiplied by 0.5, in one case even by 0.25. An overview over the grid of computed systems can be obtained from Table 1.

Our calculations are restricted to Case A and early Case B systems. The latter are defined as such where the mass transfer occurs early enough during the post-main sequence expansion of the primary that contact is avoided. The theory for the evolution of late Case B and Case C systems is not yet very well developed; often it is assumed that such system go through a common envelope evolution and either merge – in this case they are not relevant for the conclusions of our work – or expell the hydrogen-rich envelope of the primary during the spiral-in phase of the secondary (e.g., Podsiadlowski et al. 1992). Since

Table 1. Key properties of the computed binary systems. Given are the initial primary and secondary masses $M_{1,\rm i}$ and $M_{2,\rm i}$, the initial mass ratio $q_{\rm i} = M_{2,\rm i}/M_{1,\rm i}$, initial and final period $P_{\rm i}$ and $P_{\rm f}$, the maximum mass of the secondary $M_{2,\rm max}$, the mass transfer case, initial and final helium core mass of the primary $M_{\rm He,i}$ and $M_{\rm He,f}$ (note that the latter is equal to the final mass of the primary component for all considered cases), final CO-core mass of the primary $M_{\rm CO,f}$, the central carbon mass fraction of the primary at core helium exhaustion $\rm C_c$, the primaries final helium and carbon surface mass fraction $\rm He_s$ and $\rm C_s$, and the amount of helium left in the pre-supernova structure of the primary $\Delta M_{\rm He}$. Models 2′, 5′, 7′, 10′, 15′ and 17′ are computed with the WR-wind mass loss rates multiplied by a factor 0.5 (Eq. 2 in Sect. 2), that for System No. 1″ with 0.25. No final periods have been derived for these systems. All systems have been computed with a semiconvection parameter of $\alpha_{\rm sc} = 0.01$ unless indicated otherwise. System No. 8 corresponds to our progenitor model for the massive X-ray binary Wray 977/GX 301-2 and is discussed in detail in Sect. 3.2

	$M_{1,\rm i}$ $\rm M_\odot$	$M_{2,\rm i}$ $\rm M_\odot$	$q_{\rm i}$	$P_{\rm i}$ d	$P_{\rm f}$ d	$M_{2,\rm max}$ $\rm M_\odot$	Case	$M_{\rm He,i}$ $\rm M_\odot$	$M_{\rm He,f}$ $\rm M_\odot$	$M_{\rm CO,f}$ $\rm M_\odot$	$\rm C_c$	$\rm He_s$	$\rm C_s$	$\Delta M_{\rm He}$ $\rm M_\odot$
1[a]	60	34	0.57	20	59[a]	58.9[a]	B	26.8	3.13	2.35	0.35	0.41	0.48	0.24
1″[a]	60	34	0.57	20	–	–	B	26.8	7.55	5.93	0.25	0.14	0.47	0.12
2	60	34	0.57	6.2	17.9	59.6	A+AB	25.8	3.10	2.34	0.35	0.50	0.42	0.29
2′	60	34	0.57	6.2	–	59.6	A+AB	25.8	4.07	3.07	0.32	0.28	0.53	0.17
3	60	40	0.67	7.0	18.9	64.7	A+AB	26.1	3.11	2.35	0.35	0.50	0.42	0.29
4	46	34	0.74	5.0	18.0	55.9	A+AB	18.2	3.10	2.34	0.35	0.48	0.44	0.27
5	40	30	0.75	4.0	16.5	51.2	A+AB	14.2	3.11	2.33	0.36	0.55	0.38	0.33
5′	40	30	0.75	4.0	–	51.2	A+AB	14.2	3.84	2.87	0.33	0.34	0.51	0.20
6[a]	40	25	0.63	40	130[a]	45.0[a]	B	16.9	3.11	2.34	0.35	0.50	0.42	0.29
7	30	24	0.80	4.0	22.0	41.9	A+AB	9.92	3.12	2.33	0.36	0.59	0.36	0.36
7′	30	24	0.80	4.0	–	41.9	A+AB	9.92	3.63	2.71	0.34	0.93	0.05	0.33
8[b]	**26**	**25**	**0.96**	**3.5**	**46.2**	**42.4**	**A+AB**	**6.41**	**3.17**	**2.33**	**0.37**	**0.98**	**0.00**	**0.62**
9	25	24	0.96	5.0	34.9	39.2	B	8.32	3.12	2.32	0.36	0.96	0.02	0.39
10[c]	25	24	0.96	3.5	44.1	40.6	A+AB	6.02	3.19	2.36	0.37	0.98	0.00	0.66
10a[b]	25	24	0.96	3.5	47.6	40.6	A+AB	6.06	3.19	2.31	0.37	0.98	0.00	0.71
10b[b]	25	24	0.96	3.5	–	40.6	A+AB	6.06	–	–	–	–	–	–
10′ [c]	25	24	0.96	3.5	–	40.6	A+AB	6.06	3.39	2.42	0.36	0.98	0.00	0.79
11	25	19	0.76	4.0	35.7	35.9	A+AB	6.27	3.18	2.32	0.37	0.98	0.00	0.71
12	25	16	0.64	4.0	28.3	32.3	A+AB	6.19	3.16	2.24	0.37	0.98	0.00	0.78
13	22	18	0.82	3.0	49.2	34.2	A+AB	4.48	3.13	1.90	0.37	0.98	0.00	1.12
14	21	19	0.90	5.0	43.4	33.2	B	6.00	3.14	2.03	0.36	0.98	0.00	0.98
15	21	19	0.90	3.0	60.2	34.4	A+AB	4.20	3.15	1.80	0.37	0.98	0.00	1.20
15′	21	19	0.90	3.0	–	34.4	A+AB	4.20	3.45	1.80	0.36	0.98	0.00	1.54
16[b]	21	19	0.90	3.0	57.7	34.5	A+AB	4.23	3.07	1.73	0.35	0.98	0.00	1.25
17	20	18	0.90	5.0	45.8	31.7	B	5.56	3.15	2.17	0.37	0.98	0.00	0.73
17′	20	18	0.90	5.0	–	31.7	B	5.56	3.39	2.18	0.36	0.98	0.00	0.95
18	20	18	0.90	3.5	55.2	32.5	A+AB	4.30	3.00	1.69	0.37	0.98	0.00	1.23
19	20	16	0.80	3.5	47.8	30.7	A+AB	4.24	3.03	1.75	0.37	0.98	0.00	1.18
20	20	14	0.70	3.5	48.4	28.9	A+AB+ABB	4.20	2.71	1.58	0.37	0.98	0.00	1.06
21	20	18	0.90	2.5	65.5[d]	33.2	A+AB+ABB	3.55	2.7[d]	1.56[d]	0.36	0.98	0.00	1.07[d]
22	19	17	0.90	5.0	46.7	30.2	B	5.18	3.15	2.12	0.36	0.98	0.00	0.90
23	18	17	0.94	5.0	49.3	29.5	B	4.90	3.17	1.93	0.36	0.98	0.00	1.13
24	18	16	0.89	5.0	45.7	28.6	B	4.89	3.15	1.77	0.36	0.98	0.00	1.26
25	18	16	0.89	3.0	167	29.7	A+AB+ABB	3.27	2.02	1.48	0.38	0.98	0.00	0.51
26	16	15	0.94	8.0	172.1	25.7	B+BB	3.83	2.32	1.51	0.36	0.98	0.00	0.74
27	16	11	0.69	3.0	264[d]	24.2	A+AB+ABB	2.63	1.45[d]	1.21[d]	0.40	0.98	0.00	0.15[d]
28	13	12	0.92	3.1	175[d]	22.0	B+BB	2.80	1.42[d]	1.31[d]	0.40	0.98	0.00	0.11[d]

[a] system was treated conservatively although a common envelope phase is expected. The final period and the maximum secondary mass may thus be greatly overestimated

[b] sequence was computed with $\alpha_{\rm sc} = 0.02$, except for System No. 10b, where $\alpha_{\rm sc} = 0.04$ was used

[c] reverse supernova order (no influence on core masses)

[d] masses are only upper ($M_{\rm He,f}$, $\Delta M_{\rm He}$) or lower ($M_{\rm CO,f}$) limits, and the final period is only a lower limit, since the Case BB or ABB mass trasfer phase was not finished at the end of the calculations.

this process also removes considerable amounts of orbital angular momentum rather small orbital separations and periods are expected from this type of evolution.

Three types of post-main sequence evolutionary tracks can be distinguished. The first (say, Type 1) leads the star to the red supergiant branch at the begining of core helium burning

but allows the stellar radius to increase after core helium exhaustion to values which exceed those achieved earlier. Tracks like this are in fact common, but the post-helium burning radius excess is mostly not very large, in particular for stars with initial masses above $20\,M_\odot$ (e.g., Schaller et al. 1992). The second type of track (Type 2) reaches the Hayashi-line only at the end of core helium burning. However, this kind of evolution is found only for small metallicity (cf., Schaller et al. 1992, Langer & Maeder 1994), and the observed large number of red supergiants discards it as a common case. There is also an intermediate type of evolutionary track (Type 3), where the star reaches the Hayashi line for the first time *during* central helium burning (e.g., the $20\,M_\odot$ track at Z=0.02 or the $60\,M_\odot$ track at Z=0.001 of Schaller et al. 1992).

Unfortunately, it is not possible at the present time to correctly predict stars of which mass and metallicity follow which type of track. The reason is that the temperature and radius evolution of stars more massive than $\sim 10\,M_\odot$ is an extremely sensitive function of internal mixing efficiencies (cf. Stothers & Chin 1992, Langer & Maeder 1994) or mass loss rates (cf. Schaller et al. 1992 and Meynet et al. 1994), which suffer from large uncertainties. Note that this problem must lead to large uncertainties in any prediction of the number of black hole binaries, which is not always adequately emphasized in population synthesis studies. Since in the present paper we deal only with stars of roughly solar metallicity, we neglect the possibility of Type 2 tracks in the following discussion. We also negect the unusual Type 3 tracks; however, as we can not prove that they are not common, we note here that the initial-final mass relation for primaries of this type would be inbetween that found for the Case A/B systems and that of single stars (cf. Fig. 5 below).

With these assumptions, the evolution of the primaries for systems which do not merge or experience reverse mass transfer depends only on the time during their evolution when the hydrogen-rich envelope is removed. Consequently, the primaries of late Case B systems evolve like primaries of early Case B systems of the same initial mass. Furthermore, as in Case C systems the mass transfer starts only after core helium exhaustion, and stellar wind mass loss after the mass transfer can be neglected due to the short remaining stellar life time, the helium cores of the primaries in these systems evolve like the helium cores of single stars of the corresponding initial mass.

4.1. Initial-final mass relations for primaries

The results obtained for the initial-final mass relations of the primaries in massive close binaries are shown in Fig. 5a. The data for Case A and Case B systems are taken from Table 1, where the primaries final helium core mass is designated as $M_{\rm He,i}$. Since all of them are devoid of hydrogen in their presupernova stage, the final helium core mass is equal to their final mass. Except for Systems No. 21, 27 and 28, mass loss occuring beyond the end of our calculations (neon ignition in most cases) can safely be neglected due to the short remaining life time of the star.

As expected from earlier work, the initial and therefore also the final helium core masses of Case B primaries do basically not depend on the initial mass ratio or the initial orbital period (e.g., de Loore & De Greve 1992). Simply, the mass transfer stops only when almost all of the hydrogen-rich envelope is removed from the primary. However, since the period evolution does depend on the two mentioned initial parameters, this simple logic does not apply any more to primaries which evolve to final masses below $2.5...3\,M_\odot$, since helium stars with masses smaller than this tend to evolve into red giants (cf., Habets 1986) which then may or may not lead to a so called Case BB mass transfer (Delgado & Thomas 1981). We do not investigate this process in detail here since it turns out that it does not affect the initial mass limit for neutron star/black hole formation. It is certainly important, though, for investigations of the initial mass limit for white dwarf/neutron star formation in binary systems.

Fig. 5a shows that the initial-final mass relation of Case A systems differs from that of Case B systems for initial primary masses below $\sim 20\,M_\odot$. The reason is that Case A mass transfer leads to smaller initial helium core masses compared to Case B, which has been demonstrated in detail in Sect. 3.2 at the example of our progenitor model for Wray 977. Note that there is no strict initial-final mass relation for Case A systems at all since the initial helium core mass depends on time during core hydrogen burning when the mass transfer starts. Smaller initial helium star masses are thus obtained for smaller initial periods (compare, e.g., systems No. 18 and 21). A dependence on the initial mass ratio seems to be very small or absent (cf. Systems No. 18, 19, and 20).

That the initial-final mass relations for Case A and B primaries are almost identical above $\gtrsim 25\,M_\odot$ is due to the fact that, for our standard mass loss rate (Eq. 1 in Sect. 2), the final masses become independent of the initial helium star mass (Langer 1989). Even when the Wolf-Rayet mass loss rate is reduced by a factor of 2 (Eq. 2 in Sect. 2), the initial-final mass relation remains rather flat, although a slight positive slope is found in this case (Fig. 5a). Due to this mass convergence, also the efficiency of convective core overshooting on the initial-final mass relation above $\gtrsim 25\,M_\odot$ can be assumed to be small.

Fig. 5a shows also the initial mass-final helium core mass relations for single stars obtained from the literature which, as mentioned above, might also aply to Case C mass transfer systems. It is surprising that the treatment of convection, in particular the so called convective core overshooting, introduces a much larger uncertainty to the initial-final mass relation of single stars than to that of Case A/B binaries. The models of Langer & Henkel (1995), which have been computed with the same treatment of convection as the models presented here, predict smaller final helium core masses for stars below $\sim 30\,M_\odot$ but larger ones in the mass range $30...60\,M_\odot$. For much higher initial masses, both sets of models can be assumed to converge, as the curve derived from the models of Maeder (1992) and that of the Case A/B binaries do, due to the effect of mass convergence (all computations use very similar Wolf-Rayet mass loss rates).

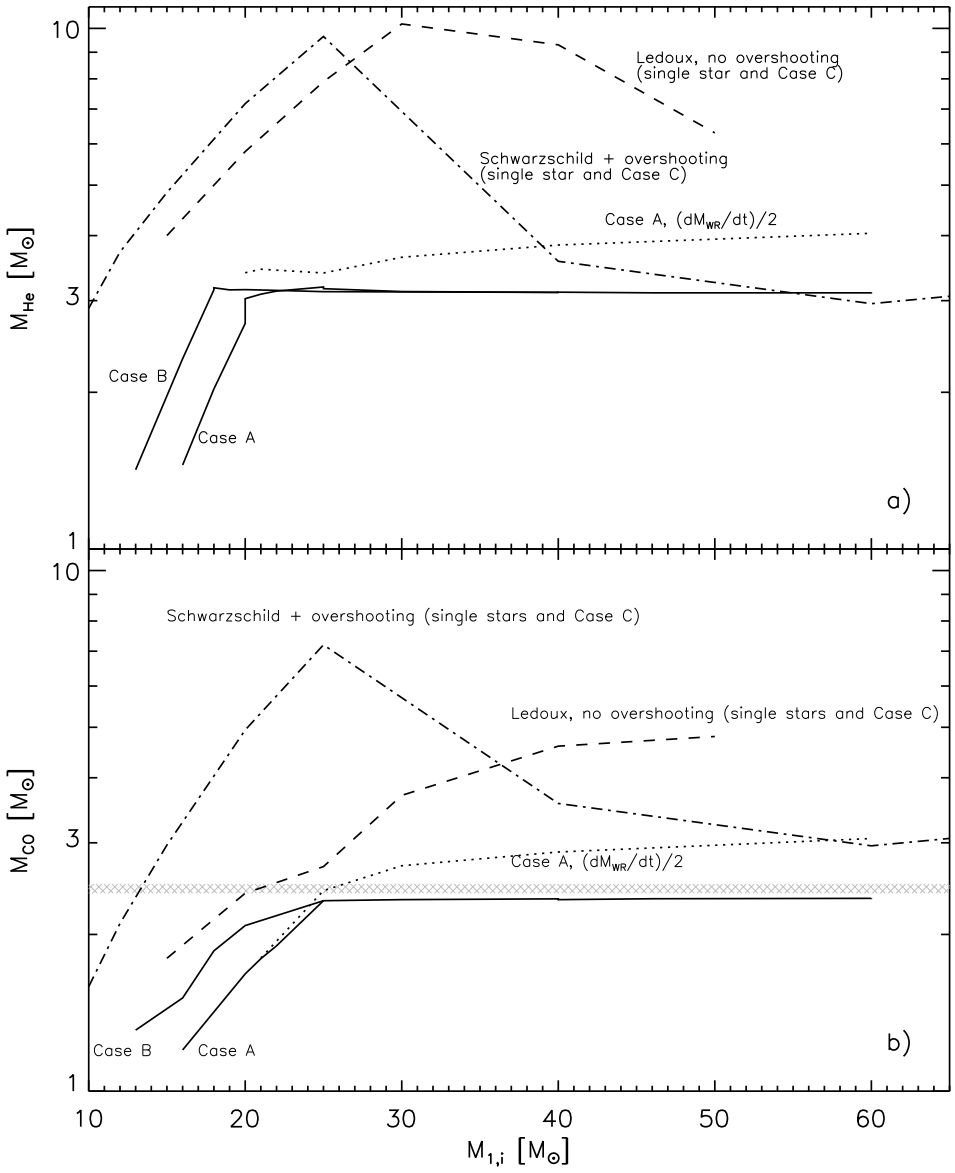

Fig. 5. a Final He-core masses of the primaries of massive close binaries as function of their initial mass, for Case A and Case B systems (cf. Table 1) for nominal Wolf-Rayet mass loss (solid lines, below 25 $M_\odot$ the upper line marks Case B systems) and – for the Case A – also for half the nominal Wolf-Rayet mass loss rate (dotted line), compared to the final helium core masses of single stars (dashed line; cf. Langer & Henkel 1995; dotted-dashed line; cf. Maeder 1992) which may give a good approximation to the non-merging fraction of the Case C systems. **b**: The same as **a**, but for the final CO-core masses. The gray horizontal line marks the final CO-core mass of our progenitor model for the neutron star companion to Wray 977, GX 301-2

4.2. Initial mass - final CO-core mass relations

In order to draw conclusions for the initial mass limit for the formation of neutron stars/black holes, the initial-final mass relation is not sufficient, since – due to the strong mass loss, particularly in binary systems – stars with the same final mass or even with the same final helium core mass may evolve different final CO-core masses. This can be seen in Fig. 5b, where we plot the CO-core masses as function of the initial mass for the same models as in Fig. 5a. E.g., the Case A and B primaries with initial masses between 20 and 25 $M_\odot$ end up with the same final helium core mass but with largely different CO-core masses.

Above initial primary masses of $\sim 25\,M_\odot$, the final CO-core masses are determined by the Wolf-Rayet winds. As in the case of the final helium core masses, the slope of the initial mass-final CO-core mass relation is zero for the larger Wolf-Rayet mass loss rate and slightly positive for the smaller mass loss rate. Again, the mass transfer type (A or B) or the treatment of convection can be assumed to have very little influence.

4.3. Constraints from massive X-ray binaries

Our 26 $M_\odot$ progenitor for GX 301-2 (cf. Sect. 3.2) has a final CO-core mass of 2.33 $M_\odot$. Note that the initial mass-final CO-core mass for Case A/B primaries is particularly certain around this mass. While uncertainties in the treatment of convection become relevant only below $\sim 25\,M_\odot$ (cf. Sect. 4.2), significant differences in the final CO-core masses due to differences in the Wolf-Rayet mass loss rate occur only for higher initial primary masses.

As 26 $M_\odot$ is the lowest possible initial mass for GX 301-2 we can conclude that from Fig. 5 that Case A and B primaries with initial masses equal or less than this do not form black holes, but instead evolve into neutron stars or white dwarfs.

On the other hand, the flatness of the initial mass-final CO-core mass relation for Case A/B primaries makes it very hard to form black holes for *any* initial primary mass, and impossible to form high mass black holes (cf. Sect. 5.2). In fact, for the larger Wolf-Rayet mass loss rate any black hole formation would be excluded. For the reduced Wolf-Rayet mass loss rate it may be possible to form black holes, but it would be low mass black holes according to our definition in Sect. 5.2 (cf. Fig. 5a). We computed one massive system with a $60\,M_\odot$ primary aplying only 1/4th of the Wolf-Rayet mass loss rate (model No. $1''$; cf. Table 1). The primary ended as a $7.5\,M_\odot$ Wolf-Rayet star. A $36\,M_\odot$ helium core – which may correspond to a $85\,M_\odot$ star – computed with the same mass loss rate ended with $7.9\,M_\odot$.

We conclude that, with the present stellar wind mass loss rates, it appears to be impossible to explain a system like Cygnus X-1 with a black hole mass of $\sim 10\,M_\odot$ (Gies & Bolten 1982, 1986; Herrero et al. 1995) through Case A or Case B mass transfer. Also the other two potential massive black hole binaries, LMC X-3 with a black hole mass of $5.5 \pm 1\,M_\odot$ (Kuiper et al. 1988), and LMC X-1 with a probable black hole mass of $6\,M_\odot$ (Hutchings et al. 1987) are not likely to be Case A or B remnants. Only if the Wolf-Rayet mass loss rates turn out to be substantially smaller than one fourth of Eq. 1, a Case A/B evolution for the progenitor of Cygnus X-1 will be possible, as suggested by Vanbeveren et al. (1998bc). Anyway, a Case C evolution appears possible for this system. E.g., for Cygnus X-1, Gies & Bolten (1986) find that the mass of the optical component should be $\gtrsim 20\,M_\odot$, while Herrero et al. (1995),by performing a detailed spectral synthesis, find a most likely mass of $17.8\,M_\odot$. Thus, the progenitor of the black hole could have had an initial mass $\gtrsim 25\,M_\odot$, which is consistent with a large black hole mass according to Fig. 5a.

Interestingly, Brown et al. (1999) have recently proposed Case C mass transfer (mass transfer after central helium exhaustion) as a possibility to obtain massive ($\sim 7\,M_\odot$; cf. Baylin et al. 1998) black holes in the six known low mass black hole binaries; in fact, due to the extrapolated large population of Galactic low mass black hole binaries (Romani 1998), Portegies Zwart et al. (1997) found alternative explanations extremely difficult.

According to Fig. 5a, these black holes should then come from an intermediate mass range, i.e. roughly 25...50 $M_\odot$, since the most massive Case C primaries, like single stars, are supposed to evolve through a Luminous Blue Variable phase (Langer et al. 1994) where they lose the major part of their hydrogen-rich envelope before core helium ignition and quickly transform into Wolf-Rayet stars. They therefore would most likely avoid mass transfer altogether (Vanbeveren 1991, Langer 1995). According to Fig. 5a, the maximum black hole initial mass in Case C systems, assuming that the hydrogen-rich envelope is completely expelled at the end of the spiral-in process, is of the order of $10\,M_\odot$. Lower stellar wind mass loss rates could lead to even higher initial black hole masses.

From Fig. 5 it seems also conceivable that the average black hole mass in black hole binaries is rather large, i.e., well above the final masses of Case A/B primaries, as suggested by Baylin et al. (1998). A distinction of two different regimes of remnant masses has already been elaborated by Brown et al. (1996). While it can not be excluded that the most massive Case A/B primaries form black holes of relatively low mass ($\sim 3\,M_\odot$), their number is not expected to be very large and is possibly zero (Fig. 5b). On the other hand, assuming that in a failed supernova the whole helium core forms the initial black hole (cf. Fryer 1999) implies that most of those which form in Case C systems will have initial masses in excess of $\sim 5\,M_\odot$ (Fig. 5a).

5. Transforming the mass limit from binaries to single stars

5.1. Assumptions

For single stars which do not lose their hydrogen-rich envelope completely it is well known that the evolution of the stellar core is decoupled from the envelope evolution. This allows the study of the inner properties of stars during their late evolutionary phases – and thus also the investigation of their fate – by just computing the evolution of helium cores of a given mass (Arnett 1977, Woosley & Weaver 1988, Thielemann et al. 1996).

For stars which do lose their hydrogen-rich envelope well before core helium exhaustion, i.e., in particular the primaries of massive close binary systems, this approximation is not possible any more because the mass of the helium core decreases during core helium burning. However, as the mass loss never reaches the next inner core, the CO-core, we will make the assumption in the following that the final CO-core mass determines the fate of a massive star. In particular we assume that CO cores with a mass below a critical value form neutron stars or white dwarfs, while more massive CO-cores form black holes.

We note that the central carbon abundance at core helium exhaustion $C_{\rm c}$ is in principle a futher independant parameter to be considered. It determines whether core carbon burning occurs radiatively or convective, which affects the core entropy and the final iron core mass (cf. Woosley & Weaver 1995, Brown et al. 1999). As more massive stars perform core helium burning at higher temperatures, the general trend is that $C_{\rm c}$ is smaller for higher initial masses. There appears to be a critical carbon mass fraction of about 15% below which carbon burning is radiative (Weaver & Woosley 1993, Woosley & Weaver 1995, Heger et al. 1999), and the initial mass-final iron core mass-relation jumps discontinously to a larger value (Timmes et al. 1996 Brown et al. 1999). The situation is complicated by the fact that $C_{\rm c}$ is not only dependant on the initial stellar mass. For stars which lose the hydrogen-rich envelope during their evolution and uncover their helium core – i.e. in particular the primaries of massive close binaries –, a higher mass loss during core helium burning leads to larger values of $C_{\rm c}$ (Woosley et al. 1995, cf. also Table 1).

Even though Woosley & Weaver (1995) find stars more massive than $\sim 19\,M_\odot$ fall short of the critical carbon value of $\sim 15\%$, recent models of Heger et al. (1999) which include effects of rotational mixing find higher values of $C_{\rm c}$ for single stars up to $25\,M_\odot$. Langer (1991) has shown that, for given initial mass and mass loss history, $C_{\rm c}$ depends sensitively on assumptions about convection (cf. Table 1 in Langer 1991). Furthermore, it depends on the still poorly known $^{12}{\rm C}(\alpha,\gamma)$ nuclear

reaction rate (Hoffman et al. 1999). Consequently, the values of $C_{\rm c}$ must be considered as uncertain.

However, the central carbon mass fractions of our primaries are all well above the critical value of $\sim 15\%$ (cf. Table 1). We can thus assume a smooth CO-core mass-final iron core mass-relation for our models (neglecting the statistical fluctuations in such a relation due to silicon shell burning episodes; cf. Woosley & Weaver 1995). Furthermore, as all our models have extended convective core carbon burning phases. As outlined by Brown et al. (1999) this results in rather low core entropies and and relatively small iron core masses. All together, we have reasons to assume that $C_{\rm c}$ is not an essential independent parameter affecting the results of the present study.

In principle, also further parameters might be important, i.e, the stellar angular momentum or magnetic field; those are not considered here.

5.2. Results

The approximation often made for single stars that the fate depends monotonously on the initial stellar mass is not generally applicable for close binary components. This can be seen in Fig. 5b, which shows that the final CO-core mass (and thus the fate) for a given initial mass depends on the previous mass transfer evolution.

The progenitor of the neutron star in Wray 977/GX 301-2 must have had a CO-core mass of at least $2.33\,{\rm M}_\odot$, corresponding to the minimum initial mass of the primary of $26\,{\rm M}_\odot$. Fig. 5b shows that single stars above $21\,{\rm M}_\odot$ form CO-cores of at least $2.33\,{\rm M}_\odot$. This allows us to derive a minimum black hole progenitor mass for single stars of $21\,{\rm M}_\odot$ from Fig. 5b. This initial mass limit refers to models computed with the Ledoux criterion for convection (Langer & Henkel 1995). For single stars computed with the Schwarzschild criterion and overshooting (Maeder 1992) we derive a limit of $13\ {\rm M}_\odot$ from the same arguments. Since the two assumptions about convection can be considered as the two extreme cases, we conclude that single stars with initial masses below 13...21 $\rm M_\odot$ form neutron stars.

We want to emphasize that this is the strongest statement that, at the present time, can be derived from the existence of a neutron star companion to Wray 977. In particular, even though especially the lower limit of $13\,{\rm M}_\odot$ appears disappointingly un-constraining, we must consider arguments in the literature which derive much higher initial mass limits for neutron star formation from the system Wray 977/GX 301-2 as wrong.

If the hitherto poorly investigated Case C mass transfer in massive stars would always lead to the merging of both components, the presence of black holes in massive binaries, e.g. that in Cyg X-1, would exclude the standard WR wind mass loss rates (dotted lines in Fig. 5), because using 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 – assuming that at least some of the mass losers in binaries reach massive enough CO-cores to collapse to a black hole – we derive an upper CO-core mass limit up to which neutron star formation might be possible of $3\,{\rm M}_\odot$. This would correspond to a single star initial mass limit of $26\,{\rm M}_\odot$ with the Ledoux criterion and of $15\,{\rm M}_\odot$ with the Schwarzschild criterion and overshooting. These are lower mass limits for black hole formation in single stars *if* Case A/B binaries could be shown to produce any black hole at all.

It is interesting to distinguish the delayed black hole formation due to fall back (e.g., Woosley & Weaver 1995), thermal effects (Wilson et al. 1986, Woosley & Weaver 1986), or effects of the equation of state (Brown & Bethe 1994), and the prompt formation of black holes. While delayed black hole formation gives rise to a "normal" supernova explosion, prompt black hole formation does not, although also in this case the hydrogen-rich envelope may be ejected (MacFadyen & Woosley 1999, Fryer 1999). In the first case, the black hole mass equals the mass of the initially formed neutron star plus the mass of the matter which falls onto it later-on. Thus, black holes of rather low mass may form like this (Brown & Bethe 1994, Brown et al. 1996). For the prompt stellar collapse to a black hole, it may be a reasonable assumption that the black hole mass roughly equals the final helium core mass (MacFadyen & Woosley 1999, Fryer 1999). Even though these assumptions are uncertain and their confirmation must await a better understanding of the core collapse supernova mechanism, it probably makes sense that promptly formed black holes have larger masses than those formed through the delayed scenarios (Brown & Bethe 1994, cf., however, Woosley & Weaver 1995). In the line of Brown & Bethe (1994), we will thus consider the first as high mass black holes (HMBHs) with the mass of the progenitor's helium core mass, and the latter as low mass black holes (LMBHs) with a mass of $\lesssim 3\,{\rm M}_\odot$.

The observation that Supernova 1987A, which had a progenitor of $\sim 20\,{\rm M}_\odot$, did not promptly form a black hole (Arnett et al. 1989) can give important constraints on the black hole formation limits. Considering the single star models computed with the Schwarzschild criterion and overshooting, we conclude from Fig. 5b that prompt black hole formation can only occur in CO-cores more massive than $\sim 5\,{\rm M}_\odot$. This limits the formation of high mass black holes in single stars or Case C binaries to the initial mass range 20...32 $\rm M_\odot$. Masses of high mass black holes of the range 5...10 $\rm M_\odot$ could be produced (Fig. 5a). Case A/B binaries could not form high mass black holes, and even the production of low mass black holes might be excluded as the core mass range which is able to yield to delayed black hole formation is rather narrow (cf. Brown et al. 1999). If the existence of a neutron star in the remnant of SN 1987A were confirmed (cf., Wu et al. 1998, Fryer et al. 1999) the models using the Schwarzschild criterion and overshooting might have a problem, since only a very small initial mass range might be left to form high mass black holes.

For models using the Ledoux criterion for convection, these mass limits work out quite differently. From the neutron star companion to Wray 977, which resulted in a single star initial mass limit for black hole formation of $> 21\,{\rm M}_\odot$ (see above), it follows that SN 1987A formed a neutron star, in accord with current models and observations (Wu et al. 1998, Fryer et al. 1999). No further firm initial mass limit can be derived from

Fig. 5b, neither for low nor for high mass black hole formation. However, as stars above 21 $M_\odot$ form much more massive CO-cores than stars around 20 $M_\odot$, in particular stars with initial masses above $\sim 30\,M_\odot$ (Fig. 5b), it is conceivable that single stars and Case C primaries above $\sim 30\,M_\odot$ or so form high mass black holes. As for the models computed with the Schwarzschild criterion, Case A/B binaries would not produce high mass black holes.

For the case that *all* black holes in close binaries form through the Case C channel, we can only derive a less stringent lower mass limit for black hole formation as for the case that *some* black holes from in Case A/B binaries. The limit then comes from the fact that the Case C, at solar metallicity, is restricted to initial primary masses of less than $\sim 40\,M_\odot$ (cf. Sect. 4.3). The large number of low mass black hole binaries (Portegies Zwart et al. 1997, Romani 1998) with massive black holes ($\sim 7\,M_\odot$; cf. Baylin et al. 1998) makes it plausible that single stars in the mass range 25...40 $M_\odot$ form high mass black holes.

Thus, independent of whether black hole binaries form preferentially through Case A/B or Case C, we conclude that very likely single stars with initial masses above $\sim 25\,M_\odot$ form black holes. This value is in agreement with the recent result from core collapse simulations of Fryer (1999).

6. The structure of supernova progenitors

The massive close binary models discussed in the previous sections do not only give predictions for the final stellar masses of both components, but they also yield the final mechanical and chemical structure of their envelopes. While those primaries of our systems which do not collapse directly to black holes become Type Ib or Ic supernovae, the final explosions of the secondaries are hydrogen-rich and have thus to be classified as Type II supernovae (cf. Langer & Woosley 1996).

The mechanical structure of the secondaries of massive close binaries can differ appreciably form single star Type II supernova progenitors. While the latter are red supergiants, our secondaries are typically blue supergiants in their final stages. Whether or not massive secondaries explode as blue or red supergiants depends critically on the semiconvective mixing efficiency during the accretion phase (cf. Fig. 4), i.e., whether or not the secondary rejuvenates (Hellings 1983, Braun & Langer 1995). In fact, for the the semiconvective mixing efficiency adopted here we can estimate a number ratio of Type II supernovae from blue supergiants to Type Ib/c supernovae of order unity. This does not contradict the fact that many more Type Ib/c supernovae are observed, since exploding blue supergiants are about 4 magnitudes dimmer than Type Ib supernovae (Young & Branch 1989), as demonstrated by Supernova 1987A (Arnett et al. 1989).

As mentioned above, the primaries of the systems studied in this work will mostly produce Type Ib/c supernovae. As a main criterion to distinguish Type Ib and Type Ic supernovae is the detection of helium lines in Ibs but their absence in Ics (Harkness & Wheeler 1990), we list in Table 1 the remaining

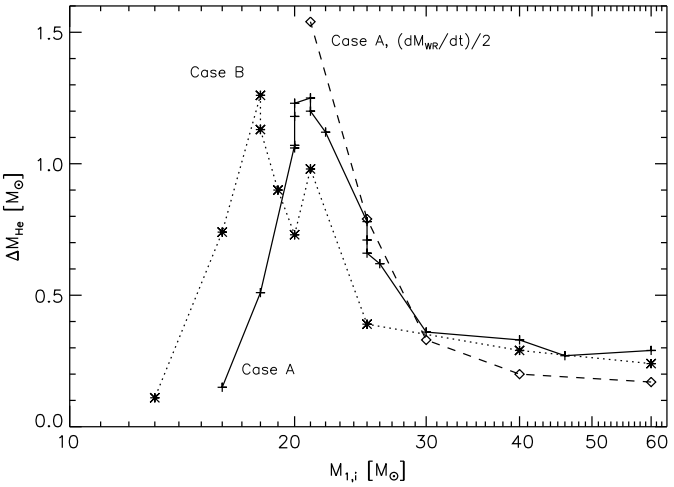

Fig. 6. The amount of helium present in the primary components at their immediate pre-supernova stage as function of their initial mass, for the computed Case A (solid line) and Case B (dotted line) systems. The dashed line corresponds to Case A systems computed with a WR wind mass loss rate reduced by 50%.

mass of helium in the envelope of the primaries at the time of their supernova explosion. Fig. 6 shows this quantity plotted as a function of the primaries initial mass, separately for Case A and Case B systems. It shows that substantial amounts of helium (i.e. more than $0.5\,M_\odot$) remain only in a limited initial mass range, i.e. above $\sim 15\,M_\odot$ and below $\sim 25\,M_\odot$. Progenitors with lower or higher initial masses, although they do not become helium free, may end up with as little as $\sim 0.1\,M_\odot$ of helium.

For progenitors below $\sim 15\,M_\odot$, the reason for the low amounts of helium in the pre-supernova structure is the occurrence of a Case BB or Case ABB mass transfer as the low mass primaries, at the end of their helium-star phase, extend to red giant dimensions (cf. Sect. 4.1). These objects end with a total mass very close to the Chandrasekhar mass. For the Case A, this happens in our models for primary initial masses below 18 $M_\odot$, although even the 20 $M_\odot$ primaries undergo a brief Case ABB mass transfer which is, however, too short to remove significant amounts of mass. A comparable situation occurs in System No. 26, a Case B system with a $16\,M_\odot$ primary: the Case BB mass transfer occurs but stops before the major part of the helium envelope is removed. As it may have observational implications, we note that some of these objects explode *during* the mass transfer.

The Type Ib/c progenitors with initial masses above $\sim 25\,M_\odot$ are helium-poor due to strong stellar winds during a Wolf-Rayet phase. Fig. 6 shows that this result is not strongly affected by uncertainties in the assumed Wolf-Rayet mass loss rate. *Smaller* amounts of helium remain for the most massive progenitors when the mass loss rate is reduced by a factor of 2. The reason is that the lower Wolf-Rayet mass loss leads to larger convective cores in the advanced helium burning stages. The final masses of these stars is well above the Chandrasekhar mass.

Although the remaining amount of helium is similar for initial primary masses below $\sim 15\,M_\odot$ and above $\sim 25\,M_\odot$,

the envelope mass, i.e. the amount of mass above the CO-core, is much larger in the latter. While the stars from below $\sim 15\,M_\odot$ have a mantle of pure helium (plus 2% metals) on top of their CO-core, the envelope of the primaries from above $\sim 25\,M_\odot$ is strongly enriched with carbon and oxygen, as can be seen from the final surface abundances shown in Table 1.

We could now speculate that the Type Ic supernovae correspond to Case A/B primaries with initial masses below $\sim 15\,M_\odot$ and above $\sim 25\,M_\odot$. As single stars above $\sim 40\,M_\odot$ evolve into Wolf-Rayet stars with correspondingly low remaining amounts of helium in the pre-supernova stage, those, together with Case C primaries above $\sim 40\,M_\odot$, might as well contribute to the Type Ic supernova class. In fact, small amounts of helium might still be compatible with Type Ic supernovae (Filippenko et al. 1995). On the other hand, Case A/B primaries from the initial mass range $15\,M_\odot$...$25\,M_\odot$ as well as Case C primaries from initial masses below $\sim 40\,M_\odot$ might evolve into Type Ib supernovae.

On the other hand, Woosley & Eastman (1995) argued that the amount of helium seen in a Type Ib/c supernova (i.e., the helium line strengths) may not only depend on the amount of helium which is present. They conclude that it is essential whether radioactive ^{56}Ni is mixed close to or into the helium layer during the explosion, as the nickel decay can excite the helium line. Hachisu et al. (1991) have shown that more such mixing is expected in the explosions of lower mass helium stars.

In summary, close binary primaries with the largest initial masses ($\gtrsim 25\,M_\odot$ for the Case A/B) as well as single stars and wide binaries (denoted "Case C", although no mass transfer occurs; cf. Sect. 4.3) with initial masses above $40...50\,M_\odot$ are the best candidates for Type Ic supernova progenitors. In their pre-supernova stage, they contain low amounts of helium in their envelopes *and* they might not experience significant mixing of radioactive ^{56}Ni into the helium layer. This is interesting in context with the peculiar Type Ic supernova 1998bw and its associated weak γ-ray burst (Kulkarni et al. 1998). In the collapsar model of MacFadyen & Woosley (1999), γ-ray bursts may be formed in helium cores which evolve a sufficiently massive iron core to undergo a prompt collapse to a black hole, given that it has the right amount of angular momentum. Independent of the convection physics, a prompt black hole formation *and* a Type Ic supernova with small amounts of helium appear possible for Case C binaries and also for single stars with initial masses of $\sim 40\,M_\odot$ or above. It is thus consistent with our conclusions that SN 1998bw is a borderline case of a successful γ-ray burst produced according to the model of MacFadyen & Woosley (1999).

7. The overall picture

In Table 2, we summarize a possible overall picture for the outcome of massive close binary evolution through the various mass transfer cases, and for single star evolution. One can, however, *not* pick initial primary mass and period (i.e., mass transfer case) and then obtain the final answer at the corresponding position in the table. Due to uncertainties in the convection efficiency, the Wolf-Rayet mass loss rate, the post-main sequence radius evolution of massive stars, and the CO-core-compact remnant mass relation, the dividing lines between the various entries in Table 2 can not yet be completely determined.

Table 2. Type of remnant of primary components of massive close binaries, i.e., white dwarf (WD), neutron star (NS), low (LMBH) or high mass black hole (HMBH), and expected supernova type (if an explosion occurs, which is not secure for HMBHs) as function of the primary initial mass and the mass transfer type for a possible scenario of massive close binary evolution. The initial mass ranges are not to be taken too literally (see text).

$M_{1,i}$ $M_\odot$	Case A	Case B	Case C	single star
8...13	WD	WD	SN Ib NS	SN II NS
13...16	WD	SN Ib or Ic NS	SN Ib NS	SN II NS
16...25	SN Ib NS	SN Ib NS	SN Ib NS	SN II NS
25...40	SN Ic NS	SN Ic NS	SN Ib HMBH[a]	SN II HMBH[a]
> 40	SN Ic NS/LMBH	SN Ic NS/LMBH	SN Ic HMBH[b] NS/LMBH[c]	SN Ic HMBH[b] NS/LMBH[c]

[a] mass range depends on assumptions on convection; see text
[b] for models computed with the Ledoux criterion for convection
[c] for models computed with the Schwarzschild criterion and convective core overshooting

Table 2 should rather be regarded as a diagram with the initial binary period as the x-axis and the initial primary or stellar mass as y-axis. Several *qualitative* trends can be found in this "diagram", which should be taken more seriously than the exact location of the dividing lines.

Most important, we see that the dividing lines between equal final stages are not horizontal but sloped, with a positive slope (for larger initial masses having smaller y-values) for all of them. For example, the dividing line between white dwarf and neutron star formation is (roughly) at $16...13\,M_\odot$ for Case A binaries (cf. System No. 27 in Table 1) – it depends smoothly on the initial period for Case A as shown by Wellstein et al. (1999) –, at $\sim 13\,M_\odot$ for the Case B (cf. System No. 28 in Table 1), and somewhere between 8 and $10\,M_\odot$ for single stars and Case C binaries. Similarly, high mass black holes are preferentially produced for large initial masses *and* large initial periods. Similar trends can be found for the two dividing lines between Type Ib and Ic supernovae (where the one at smaller initial masses may or may not correspond to the Type Ib/Ic distinction; cf. Sect. 6).

This slope of the dividing lines between equal final stages are not small. For example, our models are consistent with an initial primary mass limit for black hole formation in Case A/B systems of well above $100\,M_\odot$, while in Case C systems and single stars we derive a value of $\sim 25\,M_\odot$. We thus emphasize that this effect should be included in population synthesis models which

predict X-ray binary or γ-ray burst frequencies. For the same reason, the neutron star or black hole mass functions derived from single star models can not simply be compared with mass functions of compact companions in X-ray binaries.

As discussed in Sect. 5.2, the predicted initial mass range for high mass black hole formation in Case C binaries and single stars is quite different for models using the Ledoux criterion for convection ($\gtrsim 30\,\mathrm{M}_\odot$) compared to models using the Schwarzschild criterion and overshooting (20...32 $\mathrm{M}_\odot$). In the latter case, the most massive single stars would evolve into low mass black holes or even neutron stars. This conclusion can be changed only if the Wolf-Rayet mass loss rate were smaller than one fourth of that in Eq. 1 (cf. Vanbeveren et al. 1998b).

Finally, we note that the orbital periods of the Case A,B,C binaries at the time when the primary has terminated its evolution occur in reverse order as the initial orbital periods (cf., Verbunt 1993). Early Case B systems end with shorter periods than the Case A systems because, for a given primary initial mass, less mass is transfered during a Case B mass transfer compared to the amount of mass which is transfered in a Case A and AB together. Furthermore, while the conservative Case A and B binaries evolve to periods of several weeks and months – our Wray 977/GX 301-2 progenitor model No. 8 with a final period of 46 days is a typical case – late Case B and Case C systems lose substantial amounts of mass and angular momentum and thus become short period binaries (if they do not merge). E.g., the system 4U 1700-37, a $\sim 30\,\mathrm{M}_\odot$ O star with a $2.6^{+2.3}_{-1.4}\,\mathrm{M}_\odot$ compact companion and a 3.4 day orbital period (Heap & Corcoran 1992, Rubin et al. 1996), must have gone through a non-conservative mass transfer. This implies that the progenitor mass of the compact object is likely to be larger than that of GX 301-2.

Consequently, conservative Case A and B systems, which are modeled in detail in the present work, are the best candidates for progenitors of close binaries consisting either of a helium star and a compact remnant or of two compact stellar remnants – i.e. for binary γ-ray burst progenitors (cf. Fryer et al. 1999, and references therein): Due to the large periods at the end of the primary's evolution the binding energy of the secondary's envelope is low when the reverse mass transfer occurs, which enhances the chance for the ejection of the envelope during the spiral-in of the compact remnant of the primary. In short period binaries like 4U 1700-37, a merging of both components is rather more likely (cf. Podsiadlowski et al. 1995).

The known black holes X-ray binaries which possibly all have high mass black hole companions (cf. Ergma & van den Heuvel 1998, Baylin et al. 1998, Brown et al. 1999) have such low periods that none of them could have undergone a conservative evolution. The fact that non-conservative evolution occurs for all Case C systems but not for all Case A or B systems is in agreement with the origin of high mass black holes in binaries as due to Case C mass transfer (cf. Table 2), as proposed by Brown et al. (1999). The predominance of short periods in massive black hole binaries may be due to selection effects. On the other hand, neutron star binaries with much longer periods, consistent with conservative evolution, have been found (e.g. Wray 977/GX 301-2)). This is again consistent with the evolutionary scenario depicted above.

It is important to note that Table 2 has been derived only for stars of about solar metallicity. The radius evolution of massive stars, and possibly also the Wolf-Rayet mass loss rates, depend strongly on metallicity. Also, we do not work out the relative frequencies with which the evolution through the various mass transfer channels occur. E.g., at solar metallicity, the Case C evolution may be relatively rare (cf. Sect. 4), which could be the reason why only one Galactic high mass X-ray binary is know to contain a high mass black hole (Cyg X-1), compared to two in the Large Magellanic Cloud. Furthermore, Wellstein et al. (1999) find that conservative evolution for Case B systems is restricted to initial primary masses below $\sim 25\,\mathrm{M}_\odot$, while Case A systems are more likely to avoid contact for initial primary masses above $\sim 15\,\mathrm{M}_\odot$. All this may change for different metallicities. To work this out has to be left to future investigations.

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