Constraints on the initial mass limit for black hole formation from the massive X-ray binary Wray 977

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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, 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 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 show that in binaries the critical initial mass limit for neutron star/black hole formation is very different from the corresponding value in single stars. This implies that 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.

1 Introduction

The evolution of stars is considerably complicated by the presence of a close companion (for a recent review and references see Vanbeveren 1998ab). But close binaries provide unique possibilities to test and to constrain uncertainties inherent in stellar evolution theories in general. For example Ergma & van den Heuvel (1998) showed that massive X-ray binaries can yield constraints for the initial mass limit for black hole formation $M_{\rm BH}$. In principle, a neutron star binary contains information on the initial mass of the neutron star progenitor, and thus provides a lower limit on $M_{\rm BH}$. The most massive X-ray binary containing a neutron star — Wray 977/GX 301-2 — is an ideal object for such a study, because it yields the largest neutron star progenitor mass. This system contains an X-ray pulsar (GX 301-2) and the B supergiant Wray 977 (BP Cru). The most resent determination of the stellar parameters of Wray 977 has been performed by Kaper & Najarro (2000). They found log T_{eff} [K] = 4.23...4.30, a radius of R = 60...70 $R_\odot$ and a lower mass limit from the absence of eclipses and from the mass function (cf. Kaper et al. 1995) of 39...40 $M_\odot$. An independent lower mass limit of $\approx 40\,{\rm M}_\odot$ for Wray 977 has been derived spectroscopically from the velocity amplitude by Kaper & Najarro (1999). Ergma & van den Heuvel (1998) concluded that the neutron star progenitor had a larger initial mass than the present mass of Wray 977, which results in a very massive neutron star progenitor. Here we present binary models from the zero age main sequence until beyond the death of the primary component which show the possibility of much smaller initial masses of the progenitor of GX 301-2. The computational methods and the complete grid of models can be found in Wellstein & Langer (1999).

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

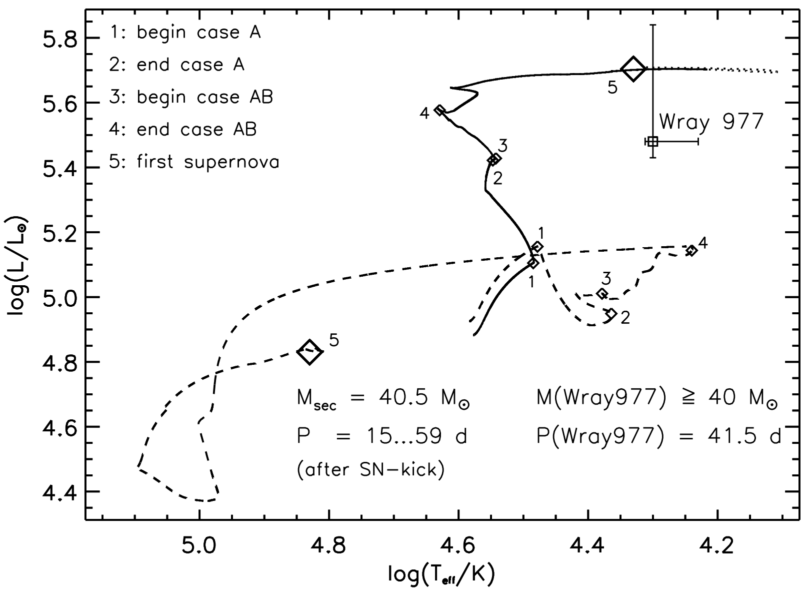

Fig. 1. Evolutionary tracks in the HR diagram of the primary component (initial mass 26 $M_\odot$, dashed line) and of the secondary component (initial mass 25 $M_\odot$, solid line) of our progenitor binary model for the massive X-ray binary Wray 977 (initial period 3.5 days). The diamonds mark the time of the supernova explosion of the primary on both tracks. The solid line of the secondary's track end when it fills its Roche lobe and mass transfer onto the neutron star would commence; the dotted continuation of the solid line shows its continued evolution as if it were in isolation. The square marks the observed position of the B supergiant Wray 977 and its error bars. In the lower part of the figure we show a comparison of mass an period of our model with empirical values (see Wellstein & Langer 1999).

Our binary model for Wray 977 consists of a conservative Case A evolution (mass transfer during central hydrogen burning) starting with a mass ratio near 1 — this systems yields the lowest achievable progenitor mass for the neutron star — and a mass close to the present system mass of $\approx 42\,M_\odot$.

I.e., our model system initially contains a 26 $M_\odot$ and a 25 $M_\odot$ star with a period of 3.5 days. The parameters of this model system after the supernova explosion of the primary agrees well with observations (cf. Fig. 1). Even the relative large period of Wray 977 is in agreement with a conservative model. We conclude that the progenitor of the neutron star GX 301-2 must have been born with at least 26 $M_\odot$.

3 M_{BH}: from binaries to single stars

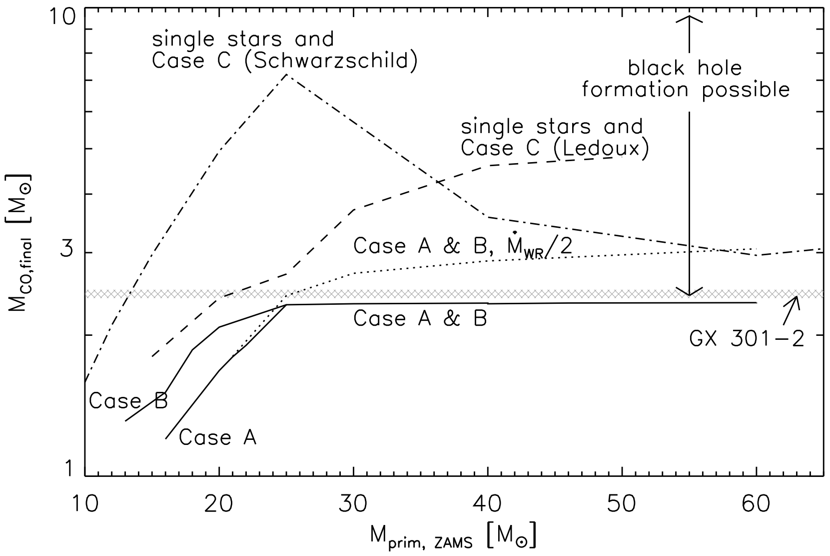

Fig. 2. Final CO-core masses of the primaries of close binaries as function of the initial mass (solid line, from Wellstein and Langer 1999). CO-core masses derived with a Wolf-Rayet-wind mass loss rate dived by a factor 2 are shown by the dotted line. The shaded horizontal line marks the CO-core mass of our progenitor of the neutron star GX 301-2 (cf. sect. 2). The dash-dotted line marks CO-core masses in single stars as derived by Maeder (1992), the dashed line as derived by Langer & Henkel (1995).

Since the mass loss imposed on the primary components of close binary systems is much larger than the mass loss of a single star of comparable initial mass, their final core masses can be significantly smaller, as shown in Fig. 2 for the final CO-core masses. Assuming that the final iron core mass depends monotonously on the final CO-core mass, this implies that, for example, a 26 $M_\odot$ star in a Case A binary may form a neutron star (cf. Sect. 2), while perhaps a 26 $M_\odot$ single star may form a black hole. In binaries, the initial mass limit for NS/BH formation is larger than 26 $M_\odot$ since the neutron star in Wray 977/GX 301-2 had an initial mass of at least 26 $M_\odot$. Therefore we can derive a lower initial mass limit for black hole formation in single stars of 13...21 $M_\odot$ from Fig. 2, the uncertainty being due to the uncertainty in the treatment of convection.

The fact that even the most massive primaries computed with the standard WR-wind mass loss rates form no larger CO-cores than the progenitor of Wray 977 leads to the question of whether Case A/B binaries can form black holes at all. Even assuming a WR-wind mass loss rate multiplicated by a factor 1/2 the CO-cores become only a little bit larger (cf. dotted line in Fig. 2), and they do not provide the required mass (their maximum mass is approximately 4 $M_\odot$) to form the observed black hole masses (e.g. Cyg X-1, LMC X-1, LMC X-3). We conclude that the black holes in massive X-ray binaries are likely to have formed via Case C mass transfer, as recently proposed by Brown et al. (1999). As can be seen in Fig. 2, only the Case C primaries, which are supposed to form CO-cores with approximately the same masses as single stars because they lose their hydrogen envelope very late, appear to be capable to provide enough mass. Also the generally small periods of all known black hole X-ray binaries, which are a clear indication of a non-conservative mass transfer stage, support the hypothesis that black hole binaries form predominantly in Case C systems.

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