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Evolution of low-mass X-ray binaries: dependence on the mass of the compact object *

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Abstract We perform numerical calculations to simulate the evolution of low-mass X-ray binary systems. For the accreting compact object we consider the initial mass of 1.4, 10, 20, 100, 200, 500 and 1000 $M_{\odot}$, corresponding to neutron stars (NSs), stellar-mass black holes (BHs) and intermediate-mass BHs. Mass transfer in these binaries is driven by nuclear evolution of the donors and/or orbital angular momentum loss due to magnetic braking and gravitational wave radiation. For the different systems, we determine their bifurcation periods $P_{\rm bif}$ that separate the formation of converging systems from the diverging ones, and show that $P_{\rm bif}$ changes from ~ 1 d to $\gtrsim 3$ d for a $1\,M_{\odot}$ donor star, with increasing initial accretor mass from 1.4 to 1000 $M_{\odot}$. This means that the dominant mechanism of orbital angular momentum loss changes from magnetic braking to gravitational radiation. As an illustration we compare the evolution of binaries consisting of a secondary star of $1\,M_{\odot}$ at a fixed initial period of 2 d. In the case of the NS or stellar-mass BH accretor, the system evolves to a well-detached He white dwarf-neutron star/black hole pair, but it evolves to an ultra-compact binary if the compact object is an intermediate-mass BH. Thus the binary evolution heavily depends upon the mass of the compact object. However, we show that the final orbital period-white dwarf mass relation found for NS low-mass X-ray binaries is fairly insensitive to the initial mass of the accreting star, even if it is an intermediate-mass BH.

Key words: binaries: close — stars: evolution — stars: neutron — X-ray: binaries

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) consist of a compact star, i.e. a black hole (BH) or a neutron star (NS), accreting from a low-mass ($\lesssim 1M_{\odot}$) companion via Roche-lobe overflow (White et al. 1995). The donor can be a main-sequence (MS) star, an evolved star (sub/red-giant), or a white dwarf (WD). There are ∼100 LMXBs known in the Galaxy (Liu et al. 2007), a small fraction of which have been discovered in globular clusters. Observations by the *Chandra X-ray Observatory* have revealed LMXBs in quite a few nearby galaxies (Fabbiano 1989, 2006).

The progenitors of the compact objects in LMXBs must have been massive stars. So short-period LMXBs should have undergone secular orbital angular momentum loss during their common

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envelope phase. However, a low-mass secondary star may not have enough energy to eject the envelope of the progenitor of the compact object during the common envelope phase, unless a significant fraction of the envelope has been previously lost through a very efficient stellar wind. Additionally, the binary is likely to be disrupted during the supernova explosion that produced the compact object (Justham et al. 2006; Li 2008). Alternatively, LMXBs may have evolved from binary systems with an intermediate-mass secondary (Podsiadlowski et al. 2002, 2003; Justham et al. 2006; Chen & Li 2006).

During the LMXB phase, mass transfer is driven either by the loss of orbital angular momentum due to magnetic braking (MB) and/or gravitational radiation (GR), or by nuclear evolution of the donor star. One interesting and important topic in the secular evolution of LMXBs is the so-called "bifurcation period" $P_{\rm bif}$. This period refers to the initial binary orbital period that seperates converging systems from diverging systems (Tutukov et al. 1985). The first systematic investigations on the bifurcation period were done by Pylyser & Savonije (1988, 1989). They found that for NS LMXBs the values of $P_{\rm bif}$, depending on the donor mass M_2 and the NS mass, are about 12 hours if the Verbunt & Zwaan (1981) MB law is adopted. The evolution of binary systems with orbital periods longer than $P_{\rm bif}$ is determined by the nuclear evolution of the donor star, and has been extensively investigated by Webbink et al. (1983) and Taam (1983). Systems with periods shorter than $P_{\rm bif}$ are captured by orbital angular momentum loss with decaying periods (Iben & Tutukov 1984). The final products of LMXBs are usually binary radio pulsars with white dwarf companions. It is well known that for diverging systems there exists a tight relation between the final orbital period P and the white dwarf mass $M_{\rm WD}$ (Rappaport et al. 1995; Tauris & Savonije 1999).

It is also noted that the value of $P_{\rm bif}$ depends on the mechanisms of mass and angular momentum losses during the mass transfer processes (e.g., Ergma et al. 1998; Podsiadlowski et al. 2002; van der Sluys et al. 2005; Ma & Li 2009). Recently De Vito & Benvenuto (2010) investigated the dependence of the evolution of NS LMXBs on the initial mass of the neutron star. These authors found that, in some cases varying the initial value of the NS mass at fixed initial orbital period may result in evolved congurations ranging from ultra-compact to widely separated binary systems. However, the final $P-M_{\rm WD}$ relation is fairly insensitive to the initial value of the NS mass.

There are few investigations on the bifurcation periods in BH LMXBs. In particular, recent observations suggested the possible existence of LMXBs with an intermediate-mass BH in globular clusters (Maccarone et al. 2011 and references therein). The formation processes of such bizarre objects are still unclear (Miller & Colbert 2004). It is expected that their evolution may be different from NS LMXBs because of the extremely high BH masses. In this paper, we will investigate the dependence of $P_{\rm bif}$ on the masses of the compact objects including NSs, and stellar-mass and intermediate-mass BHs. In order to approach this problem, we have carried out binary evolution calculations with the initial masses $M_{1,\rm i}$ of the accreting compact objects ranging from 1.4 $M_\odot$ to 1000 $M_\odot$. The organization of this paper is as follows. In Section 2, we briefly describe the stellar evolution code, the binary models, and the physical assumptions. In Section 3, we present our calculated results of the bifurcation periods, their dependence of binary evolution on $M_{1,\rm i}$, and the $P-M_{\rm WD}$ relation. In Section 4, we present the main conclusions of this work and their possible implications.

2 EVOLUTION CODE AND BINARY MODEL

We use an updated version of the stellar evolution code (Eggleton 1971, 1972) to calculate the evolutions of LMXBs consisting of an NS or BH (of mass M_1) and an MS secondary (of mass M_2). The effective radius of the Roche lobe for the secondary is taken from Eggleton (1983),

$$R_{\rm L,2} = \frac{0.49q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}a\,, \tag{1}$$

where $q = M_2/M_1$ is the mass ratio, and a is the orbital separation. Mass transfer rate via Roche lobe overflow (RLOF) is evaluated as

$$-\dot{M}_2 = \mathrm{RMT}\cdot\max\left[0, \left(\frac{R_2}{R_{\mathrm{L},2}} - 1\right)^3\right] M_\odot\ \mathrm{yr}^{-1}\,, \tag{2}$$

and we adopt RMT$= 10^3$ in the calculations (R_2 is the radius of the donor star).

Since the timescale of tidal synchronization in LMXBs is much shorter than the characteristic evolutionary timescale of the binary, we assume that the spin of the secondary star and the binary's orbital revolution are always synchronized. Assuming rigid body rotation for the secondary star and neglecting the spin angular momentum of the NS/BH, the total angular momentum of the binary system can be expressed as

$$J = I_2\omega + J_{\mathrm{orb}} = I_2\omega + G^{2/3}M_1M_2(M_1+M_2)^{-1/3}\omega^{-1/3}\,, \tag{3}$$

where I_2 is the moment of inertia of the secondary star, G is the gravitational constant, and ω is the angular velocity of the binary. We consider two kinds of mechanisms of angular momentum loss. The first is GR at a rate (Landau & Lifshitz 1975)

$$\frac{dJ_{\mathrm{GR}}}{dt} = -\frac{32}{5}\frac{G^{7/2}}{c^5}\frac{M_1^2M_2^2(M_1+M_2)^{1/2}}{a^{7/2}}\,, \tag{4}$$

where c is the speed of light. The second is MB. For a low-mass MS star with a deep convection zone, stellar winds which are magnetically coupled with the star can efficiently decelerate the stellar spin, thus carrying away the orbital angular momentum because of tidal synchronization. We adopt the saturated MB formula for a star of mass $\sim 0.1 - 1.1M_\odot$ suggested by Sills et al. (2000),

$$\frac{dJ_{\mathrm{MB}}}{dt} = \begin{cases} -K\omega^3(\frac{R_2}{R_\odot})^{1/2}(\frac{M_2}{M_\odot})^{-1/2}, & \omega \le \omega_{\mathrm{crit}} \\ -K\omega_{\mathrm{crit}}^2\omega(\frac{R_2}{R_\odot})^{1/2}(\frac{M_2}{M_\odot})^{-1/2}, & \omega > \omega_{\mathrm{crit}} \end{cases} \tag{5}$$

where $K = 2.7\times10^{47}$ g cm^2 (Andronov et al. 2003), and ω_{crit} is the critical angular velocity at which the angular momentum loss rate reaches a saturated state (Krishnamurthi et al. 1997),

$$\omega_{\mathrm{crit}}(t) = \omega_{\mathrm{crit},*}\frac{\tau_{t0,*}}{\tau_t}\,, \tag{6}$$

where $\omega_{\mathrm{crit},*} = 2.9\times10^{-5}$ Hz, $\tau_{t0,*}$ is the global turnover timescale for the convective envelope of the Sun at its current age; τ_t is for the secondary at age t, solved by integrating the inverse local convective velocity over the entire surface convective envelope (Kim & Demarque 1996).

Finally, we assume that the mass transfer is conservative. Mass loss from LMXBs tends to decrease the total mass and increase the binary separation (and hence the Roche lobe of the donor), resulting in mass transfer rates somewhat lower than in conservative mass transfer (Li & Wang 1998). It has already been shown that mass loss in NS LMXBs (e.g., outflows either from the L_1 Lagrangian point or from the vicinity of the NS) only influences the bifurcation period in a less important way compared with MB (Ma & Li 2009). For example, even if all of the transferred mass is assumed to be ejected from the binary, the values of P_{bif} only change by $\lesssim 3\%$ compared with the conservative case. For BH LMXBs, the effect of mass loss could be even lower because BHs are considerably more massive than NSs. This implies that (1) mass loss is less likely to occur, since the maximum Eddington accretion rate for a BH is higher than that for an NS, and (2) $\dot{J}/J$ due to mass loss in BH LMXBs is smaller than in NS LMXBs, because of the smaller mass ratio M_2/M_1 (see eqs. (4) and (5) in Ma & Li 2009).

3 NUMERICAL RESULTS

We take the initial secondary mass $M_{2,\mathrm{i}}$ to be 1 $M_\odot$ with a solar chemical composition ($X = 0.70$, $Y = 0.28$, and $Z = 0.02$) considering the following facts: (1) our focus here is how P_{bif} is influenced by the accretor mass with fixed donor mass, but LMXBs with intermediate-mass BHs are likely to only form in old, dense star clusters, in which most stars have low mass; (2) the chemical composition could only cause a small change in P_{bif} (Ergma et al. 1998). The initial masses of the accreting compact objects are taken to be $M_{1,\mathrm{i}} = 1.4$, 5, 10, 20, 100, 200, 500 and 1000 $M_\odot$, corresponding to NSs, stellar-mass and intermediate-mass BHs.

Throughout this paper we define the bifurcation period P_{bif} as the initial binary orbital period P_{i} with a zero-age main-sequence (ZAMS) companion star that separates converging from diverging systems.

The results of the bifurcation periods for different types of compact objects are summarized in Figure 1 and Table 1 (numbers are in boldface). It is noted that P_{bif} firstly decreases and then increases with increasing initial accretor mass from 1.4 $M_\odot$ to 1000 $M_\odot$, but P_{rlof} firstly increases and then decreases. The evolution of the binary separation a is determined by the following equation in the case of conservative mass transfer,

$$\frac{\dot{a}}{a} = -\frac{2\dot{M}_2}{M_2}(1-q) + \frac{2\dot{J}}{J}\,. \tag{7}$$

When the accreting star is an NS or stellar-mass BH, both GR and MB take effect with MB dominating the angular momentum loss, but the smaller mass ratio q in BH LMXBs implies a stronger tendency for orbit expansion, resulting from the first term on the right hand side of Equation (6). Consequently, P_{bif} becomes smaller. In intermediate-mass BH LMXBs, GR becomes comparable with or even more efficient than MB, because its angular momentum loss rate increases rapidly with the BH mass, $\dot{J}_{\mathrm{GR}} \propto M_1^{5/2}$, so the binary orbit is more likely to shrink with time.

To see this in more detail, let us compare the rates of angular momentum loss due to GR and MB. From Equations (4) and (5) we get

$$\frac{\dot{J}_{\mathrm{GR}}}{\dot{J}_{\mathrm{MB}}} = \begin{cases} \frac{4}{Kc^5}\left(\frac{R_2}{R_\odot}\right)^{-1/2}\left(\frac{M_2}{M_\odot}\right)^{1/2}\left(\frac{G^7}{\pi^2}\right)^{1/3}\frac{M_1^2M_2^2}{(M_1+M_2)^{2/3}}P^{2/3}\,, & \omega \le \omega_{\mathrm{crit}} \\ \frac{16}{Kc^5\omega_{\mathrm{crit}}^2}\left(\frac{R_2}{R_\odot}\right)^{-1/2}\left(\frac{M_2}{M_\odot}\right)^{1/2}(\pi^4G^7)^{1/3}\frac{M_1^2M_2^2}{(M_1+M_2)^{2/3}}P^{-4/3}\,, & \omega > \omega_{\mathrm{crit}} \end{cases} \tag{8}$$

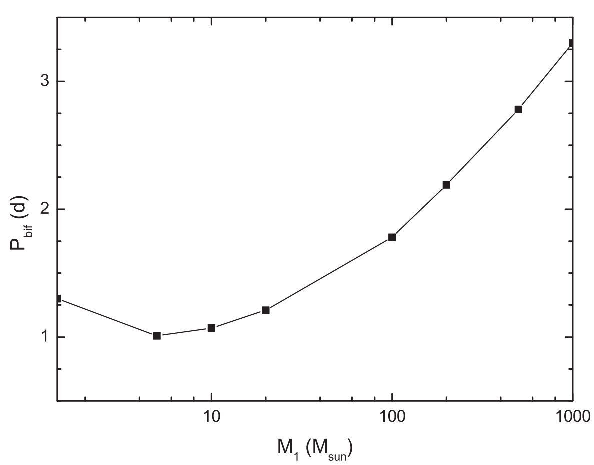

Fig. 1 The bifurcation period as a function of the accretor mass in an LMXB.

Table 1 The initial and final orbital periods of the LMXBs with different types of accretors. The donor mass is set to be 1 $M_\odot$. The bifurcation periods in each case are listed in boldface.

$M_{1,\rm i}$ ($M_\odot$)	$P_{\rm i}$ (d)	$P_{\rm f}$ (d)	$M_{1,\rm i}$ ($M_\odot$)	$P_{\rm i}$ (d)	$P_{\rm f}$ (d)
1.4	1.28	0.18	100	1.76	0.17
1.4	**1.30**	1.09	100	**1.78**	1.88
1.4	1.32	2.49	100	1.80	7.66
5	0.99	0.13	200	2.16	0.05
5	**1.01**	1.99	200	**2.18**	2.94
5	1.03	5.10	200	1.19	6.86
10	1.05	1.03	500	2.72	0.08
10	**1.07**	2.46	500	**2.74**	1.14
10	1.09	6.21	500	2.76	5.65
20	1.19	0.13	1000	3.19	0.16
20	**1.21**	1.72	1000	**3.29**	3.95
20	1.23	6.01	1000	3.33	17.14

or

$$\frac{\dot{J}_{\rm GR}}{\dot{J}_{\rm MB}} \simeq \begin{cases} 1.01\times10^{-3}(\frac{M_1}{M_\odot})^{4/3}(\frac{P}{\rm day})^{2/3}, & \omega\le\omega_{\rm crit} \\ 1.59\times10^{-3}(\frac{M_1}{M_\odot})^{4/3}(\frac{P}{\rm day})^{-4/3}, & \omega>\omega_{\rm crit} \end{cases} \tag{9}$$

where we adopt $\omega_{\rm crit}=2.9\times10^{-5}$ Hz (Sills et al. 2000), $M_2=1\,M_\odot$, and $R_2=1\,R_\odot$. Equation (8) indicates that, before MB reaches saturation, namely $\omega<\omega_{\rm crit}$, $\dot{J}_{\rm GR}/\dot{J}_{\rm MB}\sim1.1\times10^{-3}(P/{\rm day})^{2/3}$ with $M_{1,\rm i}=1.4\,M_\odot$, $\sim\,0.47(P/{\rm day})^{2/3}$ with $M_{1,\rm i}=100\,M_\odot$, and $\sim\,10.09(P/{\rm day})^{2/3}$ with $M_{1,\rm i}=10^3\,M_\odot$. So we can clearly see that with a fixed donor star, the more massive the accreting star, the greater is the dominance of GR over MB on the binary's evolution, and in the extreme case when $M_{1,\rm i}\gtrsim10^3\,M_\odot$, the effect of MB can almost be neglected.

As an illustration, we compare the evolution of LMXBs consisting of an NS/BH of different mass and a secondary star of 1 $M_\odot$ at an initial period of 2 d. In Table 2, we list the final orbital period $P_{\rm f}$ and the white dwarf mass $M_{\rm WD}$ after the mass transfer.

Figure 2 shows the evolutionary tracks of the secondary in the H-R diagram. Although mass transfer with $M_{1,\rm i}\le100\,M_\odot$ starts when the secondary evolves off the MS, the binary evolution with $M_{1,\rm i}\ge200\,M_\odot$ is controlled by angular momentum loss when the secondary is on the MS, so that the onset of mass transfer is earlier (see also Fig. 4).

Figure 3 compares the mass transfer rates when $M_{1,\rm i}=1.4$, 100, 200, and 1000 $M_\odot$. In the former two cases, the "bump-related" detachment at the time of the first dredge-up in the donor star is clearly seen, which occurs for a good fraction of the evolutionary paths leading to long-period binary millisecond pulsars (D'Antona et al. 2006). In the latter two cases, the mass transfer is always continuous, and the mass transfer rates finally increase when the donor becomes degenerate.

Figure 4 shows the evolution of the donor mass. At the same initial orbital period, the RL radius of the donor is the same, but the onset of RLOF occurs later when the accreting star is less massive. The evolution of the orbital periods is shown in Figure 5. When the compact object becomes more massive, the evolution is more likely to be captured early by angular momentum loss due to GR (especially for intermediate-mass BH binaries) and MB, so that systems with BHs of mass $\ge200\,M_\odot$ evolve to tighter configurations. These results show that the binary evolution strongly depends on the type of the compact accreting star.

We have performed evolution calculations for LMXBs with different initial orbital periods. For binary systems with initial orbital periods $>P_{\rm bif}$, mass transfer stops when the donor loses almost

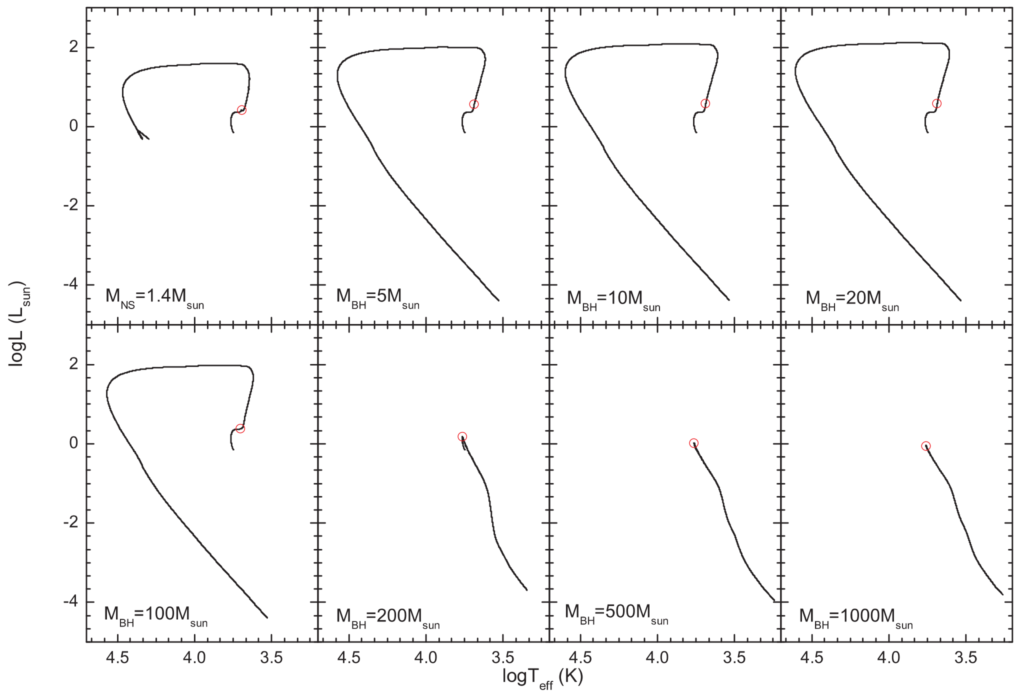

Fig. 2 The evolutionary tracks for a normal donor star with an initial mass of 1.0 $M_\odot$, evolving in binary systems with different initial accretor star masses. The initial orbital period is 2 d. The circle corresponds to the onset of RLOF.

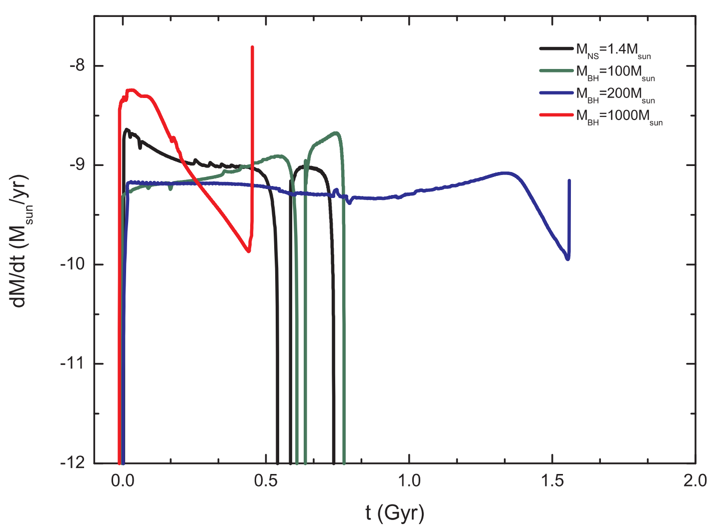

Fig. 3 Evolution of the mass transfer rates in an LMXB consisting of an NS/BH of different mass and a secondary star of 1 $M_\odot$ at an initial period of 2 d.

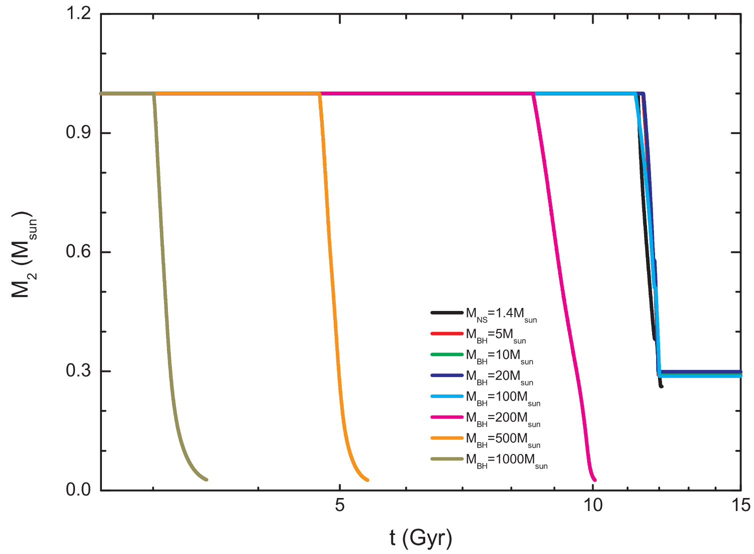

Fig. 4 Same as Fig. 3 but for the evolution of the donor mass.

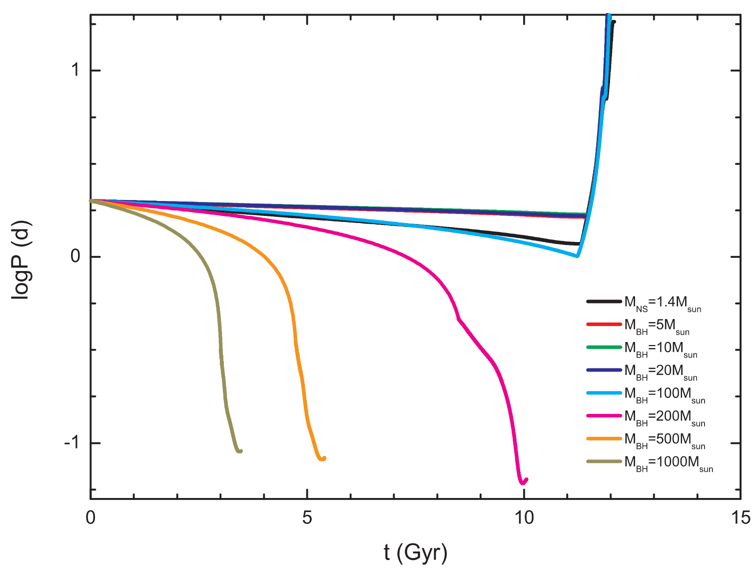

Fig. 5 Same as Fig. 3 but for the evolution of the orbital period.

Table 2 Final Orbital Periods and Donor Remnant Masses at the End of RLOF for LMXBs with an Initial Period of 2 d

$M_{1,\mathrm{i}}(M_\odot)$	1.4	5	10	20	100	200	500	1000
P_f (d)	18.34	44.72	52.54	55.49	40.03	0.064	0.084	0.091
$M_\mathrm{WD}(M_\odot)$	0.262	0.291	0.297	0.300	0.288	0.026	0.026	0.027

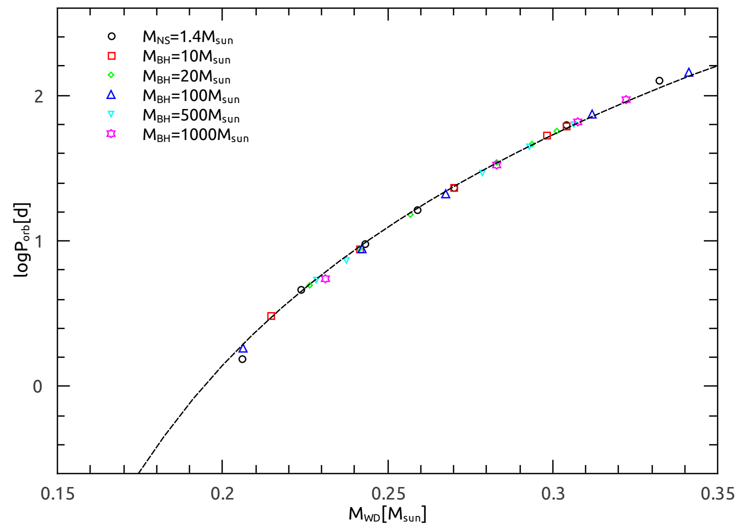

Fig. 6 The $P - M_{\rm WD}$ relation for the binary systems presented in this work. Circles, squares, diamonds, triangles, down triangles and stars depict systems with accreting stars with initial mass of 1.4, 10, 20, 100, 500 and 1000 $M_{\odot}$ respectively. In addition, we plot the relation given by Tauris & Savonije (1999) with a dashed line.

all of its envelope and becomes an He/CO WD. At this time we mark this core mass (as the WD mass) and the corresponding orbit period. Then altogether we can obtain the $P - M_{\rm WD}$ relation.

In Figure 6 we plot the $P - M_{\rm WD}$ relation for diverging systems from our calculations. In the figure we also include the relation obtained by Tauris & Savonije (1999). As can be seen, our evolutionary calculations agree with the prediction that in wide binaries the $P - M_{\rm WD}$ relation is fairly independent of the value of the initial mass of the accretor, no matter if it is an NS or a BH. Rappaport et al. (1995) claim that this relation should be fairly insensitive to changes in the initial NS mass. Our calculations validate their conclusion for compact objects ranging from NSs to intermediate-mass BHs.

4 DISCUSSION AND CONCLUSIONS

The concept of bifurcation period was firstly used in NS LMXBs. In this paper we extend it to BH LMXBs and present our calculated results of the $P_{\rm bif}$ for different types of LMXBs, to examine the dependence of binary evolution, with the accreting star ranging from NSs to intermediate-mass BHs, and the applicability of the relation between the final orbital period and the mass of the He WD remnant.

First, our calculations show that the value of $P_{\rm bif}$ varies with increasing initial accretor mass from 1.4 $M_{\odot}$ to 1000 $M_{\odot}$. The main reason is that the dominant mechanism of angular momentum loss in these systems is different. For a specific system, the value of $P_{\rm bif}$ is determined by the combined action of the nuclear expansion and orbital shrinkage due to angular momentum loss. Along with the increase of the accretor star mass, the efficiency of MB-induced angular momentum loss decreases, while GR becomes more and more important. We find that in LMXBs with a $1000\,M_{\odot}$ BH, GR dominates the angular momentum loss, giving a relatively large value of $P_{\rm bif}$.

This means that the LMXB evolution with a given orbital period and donor star dramatically diverge for different kinds of accreting star. For example, with an NS or stellar-mass BH, the system with fixed initial donor star mass ($1\,M_\odot$) and orbital period ($\gtrsim 1.0-1.3$ d) evolves to a well-detached He WD-NS/BH pair; if the compact object is more massive (e.g. intermediate-mass BH), it may contract down to an ultra-compact configuration.

This result may have interesting implications for intermediate-mass BH LMXBs in particular. These exotic objects may be formed in dense star clusters (e.g. globular clusters) where they form binary systems by dynamical interactions (tidal capture and exchange collisions) with normal low-mass stars in the cluster. Depending on the distribution of the initial binary's orbital period (which, unfortunately, is still unclear), the intermediate-mass BH LMXBs may have different characteristics. If $P > P_{\rm bif}$ initially, they may evolve to be transient X-ray sources in very wide orbits with ultra-luminous outbursts (Kalogera et al. 2004). If their initial orbits are narrow ($P < P_{\rm bif}$), they may shrink further, and some of them might contribute to the very faint X-ray transients discovered in the Galaxy, if the donor's hydrogen abundance is extremely low (King & Wijnands 2006).

Our investigation covers a broad range of the initial accretor star masses, from NSs to IMBHs, but the results suggest that the final orbital period - He WD mass relation is insensitive to the initial accreting star's mass, as claimed by Rappaport et al. (1995) for NS LMXBs (see also De Vito & Benvenuto 2010). Among the period - WD mass relations available in the literature, we find a good agreement between our results and those presented by Tauris & Savonije (1999).

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