Evolution of black-hole intermediate-mass X-ray binaries: the influence of a circumbinary disc

Wen-Cong Chen* and Xiang-Dong Li†

Department of Astronomy, Nanjing University, Nanjing 210093, China

ABSTRACT

Justham, Rappaport & Podsiadlowski (2006) recently suggested that black-hole low-mass X-ray binaries (BHLMXBs) with short orbital periods may have evolved from black-hole intermediate-mass X-ray binaries (BHIMXBs). In their model the secondaries in BHIMXBs are assumed to possess anomalously high magnetic fields, so that magnetic braking can lead to substantial loss of angular momentum. In this paper we propose an alternative mechanism for orbital angular momentum loss in BHIMXBs. We assume that a small fraction $\delta$ of the transferred mass from the donor star forms a circumbinary disc surrounding the binary system. The tidal torques exerted by the disc can effectively drain orbital angular momentum from the binary. We have numerically calculated the evolutionary sequences of BHIMXBs, to examine the influence of the circumbinary disc on the binary evolution. Our results indicate when $\delta \lesssim 0.01 - 0.1$ (depending on the initial orbital periods), the circumbinary disc can cause secular orbital shrinking, leading to the formation of compact BHLMXBs, otherwise the orbits always expand during the evolution. This scenario also suggests the possible existence of luminous, persistent BHLMXBs, but it suffers the same problem as in Justham, Rappaport & Podsiadlowski (2006) that, the predicted effective temperatures of the donor stars are significantly higher than those of the observed donor stars in BHLMXBs.

Key words: binaries: close – X-ray: binaries – circumstellar matter – infrared: stars.

1 INTRODUCTION

If the gravitational mass of a compact star exceeds the maximum value $\sim 2 - 3M_\odot$ of a neutron star (e.g. Rhoades & Ruffini 1974), this object should be taken as a black hole (BH) candidate. There exist currently around twenty stellar-mass BH candidates (see Lee, Brown & Wijers 2002; Orosz et al. 2002; Casares 2002), all of them are located in binary systems where their dynamical masses can be available estimated. Nine of these systems are defined as compact BH X-ray binaries (BHXBs) with short orbital periods ($\lesssim 0.5$ d) and low-mass donors ($< 1M_\odot$) (Lee, Brown & Wijers 2002; Ritter & Kolb 2003; Podsiadlowski, Rappaport & Han 2003). It was estimated that there may exist $\gtrsim 1000$ compact BHXBs in the Galaxy (Wijers 1996; Romani 1998).

The short orbital periods of BH low-mass X-ray binaries (BHLMXBs) imply that they must have undergone secular orbital angular momentum loss. If their progenitor systems contains a low-mass secondary initially, it is not clear whether the secondary star has enough energy to eject the envelope of the black hole progenitor during the common envelope evolution phase (Podsiadlowski, Rappaport & Han 2003; Justham, Rappaport & Podsiadlowski 2006). This difficulty can not be dealt with by assuming a intermediate-mass secondary, which have radiative envelope and are not expected to be subject to magnetic braking (Kawaler 1988), since the binary orbits will be widen when mass is transferred from the less massive secondary to the more massive BH (see Huang 1963). Eggleton & Verbunt (1986) suggested that these systems may be evolved from triple systems via the merging of the two massive components. Podsiadlowski, Cannon & Rees (1995) proposed that massive Thorne-Zytkow objects could lead to the birth of BHs with a low-mass donor star.

Justham, Rappaport & Podsiadlowski (2006) summarized the previous proposals for the formation of BHLMXBs. They instead suggested that BHXBs containing intermediate-mass Ap and Bp donor stars, which possess strong magnetic fields, may be driven to compact BHLMXBs via magnetic braking with an irradiation-driven wind from the donor star (see however, Yungelson et al. 2006).

Are there additional angular momentum loss mecha-
nisms for BHXBs besides magnetic braking? Here we explore an alternative possibility. It is well known that some fraction of the transferred matter from the donor star may leave the system in various ways during the mass exchange process (van den Heuvel 1994). In particular, for cataclysmic variables (CVs), Spruit & Taam (2001) and Taam & Spruit (2001) suggested that part of the outflow may be in the form of a circumbinary (CB) disc, and investigated the influence of the CB disc on the evolution of CVs. The similar idea was adopted by Meyer & Meyer-Hofmeister (2001) for BHXBs to regulate the mass transfer rates, in which the CB disc could result from the remnants of the previous common-envelope phase. In our previous works we have investigated the evolution of neutron star (NS) LMXBs and Algol type binaries with a CB disc (Chen, Li & Qian 2006; Chen, Li & Qian 2006). These works indicate that the presence of a CB disc can accelerate the evolution process of the binary systems, enhance the mass transfer rates, and lead to secular orbit shrinking under certain conditions.

The aim of this work is to study the influence of the CB disc on the evolution of BH intermediate-mass X-ray binaries (BHIMXBs), and explore the possibility of BHIMXBs being the progenitor systems of short period BHLMXBs. The structure of this paper is as follows. In section 2 we describe the adopted orbital angular momentum loss mechanisms in the evolution model of BHIMXBs. In section 3 we present the numerically calculated results for the evolutionary sequences. We summarize and discuss the uncertainties in our model in section 4.

2 DESCRIPTION OF THE MODEL

Although some BHXBs may form dynamically in globular clusters (Rappaport et al. 2001), we only consider those evolved from the primordial massive binary systems. We focus on the evolution of BHXBs consisting of an intermediate-mass donor star (of mass $M_d \sim 3-5 M_\odot$) and a black hole (of mass $M_{BH}$). Neglecting the spin angular momenta of both components, we consider three types of angular momentum loss from the binary system (in all calculations, magnetic braking mechanism is not included), which are described as follows.

2.1 Gravitational wave radiation

For a compact BHXBs gravitational wave radiation is able to carry away orbital angular momentum effectively and lead to mass transfer. The angular momentum loss rate due to gravitational radiation is given by (Landau & Lifshitz 1962):

$$J_{GR} = -\frac{32 G^{7/2}}{5} \frac{M_{d}^{2} M_{BH}^{2} M_{d}^{1/2}}{a^{5/2}},$$

where $G$ is the gravitational constant, $c$ the speed of light, $M = M_{BH} + M_d$ the total mass of the binary, $a$ the binary separation given by the Kepler’s third law $a = (GM/\Omega^2)^{1/3}$, where $\Omega$ is the orbital angular velocity of the binary system.

2.2 Isotropic winds

Mass and orbital angular momentum loss may occur during rapid mass transfer phase, since the mass accretion rate of a black hole is limited by Eddington mass-accretion rate $\dot{M}_{Edd}$. For spherical accretion, this maximum accretion rate can be derived from the equation that gravity can balance the radiation pressure:

$$\dot{M}_{Edd} = \frac{4\pi GM_{BH}}{\kappa c} \dot{\Omega},$$

where $\kappa = 0.2(1 + X) cm^2 g^{-1}$ is the electron scattering opacity for a composition with hydrogen mass fraction $X$ (Kippenhahn & Weigert 1994). The energy release efficiency $\eta_{\dot{M}}$ of disc accretion onto black hole can be approximately written as:

$$\eta_{\dot{M}} = 1 - (\frac{M_{BH}}{3M_{BH}})^2$$

as $M_{BH} < \sqrt{\frac{\kappa M_{BH}^9}{\pi}}$, where $M_{BH}^9$ is the initial mass of the BH (see, e.g. Bardeen 1970, King & Kolb 1997). From the above equations, Podsiadlowski, Rappaport & Han (2003) obtained the expression of the Eddington mass-accretion rate for a disc-fed BH:

$$\dot{M}_{Edd} \simeq 2.6 \times 10^{-7} M_{\odot}yr^{-1} \left(\frac{M_{BH}}{10 M_{\odot}}\right) \left(\frac{1}{\eta_{\dot{M}}}\right) \left(\frac{1.7}{1 + X}\right).$$

In our calculations we assume that the transferred matter in excess of the Eddington accretion rate is ejected in the vicinity of the BH in the form of isotropic winds, carrying away the specific orbital angular momentum of the BH. We introduce the parameter $f$ to describe the fraction of mass loss from the binary system, defined by the following relations:

$$\dot{M} = \dot{M}_{d} f,$$

and

$$\dot{M}_{BH} = \dot{M}_{d} (f - 1),$$

where $\dot{M}$ is the total mass-loss rate from the system, $\dot{M}_{d}$ is the mass transfer rate from the secondary, and $\dot{M}_{BH}$ is the mass accretion rate of the black hole, respectively. If the mass transfer rate $|\dot{M}_{d}| \leq \dot{M}_{Edd}$, $f = 0$, else $f = 1 + \dot{M}_{Edd}/\dot{M}_{d}$.

Based on the above equations and assumptions, the angular momentum loss rate via isotropic winds is

$$J_{IW} = f \frac{\dot{M}_{d} \dot{M}_{d}}{M_{BH}} J,$$

where

$$J = a^2 \mu \Omega$$

is the total orbital angular momentum and $\mu = M_{d} M_{BH}/M_{d}$ is the reduced mass of the binary system, respectively.

1 We do not consider mass and angular momentum loss due to the wind mass loss from the donor star, which is not important for intermediate-mass stars. Irradiation effect on the stellar winds is also not included.
2.3 CB disc

We further assume that a small fraction $\delta$ of the material overflowed from the donor star’s Roche-lobe always feeds into the CB disc rather accretes onto the BH. Then $M_d$ in Eqs. (5)-(7) should be replaced by $M_d(1-\delta)$, the BH mass accretion rate is $\dot{M}_{\text{BH}} = -(1-f)(1-\delta)M_i$, and the total mass loss rate $\dot{M} = M_d(f + \delta - f\delta)$. Tidal torques are then exerted on the CB disc extracting orbital angular momentum from the binary system (see Taam & Spruit 2001).

Similar as in Taam & Spruit (2001), Spruit & Taam (2001), and Chen, Li & Qian (2006), the viscous torque exerted at the inner edge $r_i$ of the CB disc can be shown to be:

$$T_i \equiv J_{\text{CB}} = \gamma a^2 \delta M_d \left( \frac{t}{\tau_{\text{vis}}} \right)^{1/3},$$

(9)

where $\gamma^2 = r_i/a$, $t$ is the time since the onset of Roche lobe overflow (RLOF). In the standard $\alpha$ viscosity prescription (Shakura & Sunyaev 1973), the viscous timescale $\tau_{\text{vis}}$ at the inner edge in the CB disc is given by:

$$\tau_{\text{vis}} = \frac{4\gamma^3}{3\alpha \Omega^2},$$

(10)

where $\beta = H_i/r_i$, $\alpha$ and $H_i$ are the viscosity parameter and the scale height of disc, respectively.

Combine Eqs. (9) and (10), the angular momentum loss rate via the CB disc can be written as:

$$\dot{J}_{\text{CB}} = \eta M_d \dot{M}_{\text{CB}},$$

(11)

where $\eta = \delta (t/\tau_{\text{vis}})^{1/3}$ and $\dot{J}_{\text{CB}} = \gamma J/\mu$ is the specific orbital angular momentum of the disc material at $r_i$ (e.g. Soberman, Phinney & van den Heuvel 1997).

The orbital evolution of BHXBs is governed by the change of the orbital angular momentum $J$ of the system caused by the above mentioned three mechanisms. Differentiating Eq. (8) we get:

$$\frac{\dot{J}}{J} = \frac{\dot{\Omega}}{\Omega} + \frac{\dot{M}_d}{M_d} \left[ 1 - (1-f-\delta) \frac{M_d}{M_{\text{BH}}} - (f+\delta) \frac{M_d}{3M} \right],$$

(12)

where we have neglected the terms of $f\delta$. Neglect the angular momentum loss due to gravitational wave radiation, the orbital evolution is governed by:

$$\frac{\dot{J}_{\text{CB}}}{J} = -\frac{\dot{\Omega}}{\Omega} + \frac{\dot{M}_d}{M_d} \left[ 1 - \frac{M_d}{M_{\text{BH}}} + \frac{2(f+\delta)M_d}{3M} \right].$$

(13)

Insert Eq. (11) into Eq. (13), orbit shrinking, i.e. $\dot{\Omega} > 0$, will occur when

$$\eta > \frac{M_{\text{BH}}}{\gamma M} \left[ 1 - \frac{M_d}{M_{\text{BH}}} + \frac{2(f+\delta)M_d}{3M} \right].$$

(14)

In this paper we take $r_i/a = \gamma^2 = 1.7$ (see Artymowicz & Lubow 1994, Muno & Maraner 2006), then $\eta > 0.77$ when $M_d \ll M_{\text{BH}}$, and $f, \delta \ll 1$ (see Fig. 1).

In Fig. 1 we plot the expected relation between $\eta$ and $M_d$ when the orbital period is constant for BH masses $M_{\text{BH}} = 7M_\odot, 10M_\odot$, and $20M_\odot$, respectively. Generally a larger $\eta$ is required for smaller $M_d$ and larger $M_{\text{BH}}$. This can be satisfied with an adequate mass input rate $\delta$ and sufficiently long time $t$ of RLOF.

2 In this subsection we use the subscript i to denote quantities evaluated at the inner edge $r_i$ of the CB disc.

3 NUMERICAL RESULTS

We have calculated the evolution of BHIMXBs adopting an updated version of the stellar evolution code developed by Egeleton (1971, 1972) (see also Han, Podsiadlowski & Egeleton 1994; Pols et al. 1995). In the calculations we set initial solar chemical compositions ($X = 0.7$, $Y = 0.28$, and $Z = 0.02$) for the donor stars, and take the ratio of the mixing length to the pressure scale height to be 2.0. We include the afore-mentioned three types of orbital angular momentum loss mechanisms during the binary evolution. For the CB disc, we take $\alpha = 0.01$ and $\beta = 0.03$ (Belle et al. 2004). Setting the initial mass of the BH $M_{\text{BH}}^0 = 10M_\odot$, we have performed the evolution calculations of BHIMXBs with an initial secondary of $M_i = 3, 4,$ and $5M_\odot$.

Figure 1. The critical $\eta = \delta (t/\tau_{\text{vis}})^{1/3}$ as a function of the mass $M_d$ of donor star for a constant binary orbit. The BH masses are taken to be 7 $M_\odot$ (dashed curve), 10 $M_\odot$ (solid curve), and 20 $M_\odot$ (dotted curve), respectively.
the orbits. But this tendency is held up when the angular momentum loss via the CB disc becomes sufficiently strong. The mass transfer drops into a “plateau” phase at a rate $\sim 10^{-9} M_\odot \text{yr}^{-1}$ for a few $10^8$ yr. These features are different from those in Podsiadlowski, Rappaport & Han (2003) for the standard evolution of BHIMXBs, in which the orbits always increase secularly. After that the mass transfer rates increase sharply as the secondary ascends the giant branch, but the final orbital evolution depends on the adopted value of $\delta$. With the higher value of $\delta$, a compact BHLMXB will be finally produced after a few $10^8$ yr mass transfer. If matter does not leave the CB disc, we can estimate from Fig. 2 the mass of CB disc $M_{\text{CB}} \sim 0.015, 0.028, 0.035 M_\odot$ with the initial donor mass of 3, 4, 5$ M_\odot$, respectively.

The calculated results for slightly wider initial orbital period of 3 d are presented in Fig. 3. Generally the mass transfer rates are higher for higher donor masses and wider initial orbits - the peaks of the mass transfer rates can reach $\gtrsim 10^{-5} M_\odot \text{yr}^{-1}$. Within less than 1 Myr the donor masses decrease to be $\lesssim 1 M_\odot$. Short orbital periods can also be attained, but generally a larger $\delta$ (up to $\lesssim 0.1$) is required compared with those in Fig. 2. In this case the the CB disc
believed that the transient behavior in X-ray binaries is due should be transient sources (Casares 2006). It is currently possible role in the evolution of NSLMXBs. In Fig. 4, we plot the X-ray lifetime can be considerably decreased. evolved donor star at the onset of mass transfer, so that the final orbital period, including the CB disc can allow a more the formation of the binary radio pulsar PSR J1713+0747 is also more massive, MCB ∼ 0.15, 0.28, 0.45M⊙ with the initial donor mass of 3, 4, 5M⊙, respectively.

One may expect that the CB disc may play a similar role in the evolution of NSLMXBs. In Fig. 4, we plot the evolutionary sequence of NSLMXBs with a donor star of Md = 1M⊙ and an initial orbital period of Porb = 1 d, to show the similar influence of changing δ on the final orbital evolution as in BH binaries. In our previous work on the formation of the binary radio pulsar PSR J1713+0747 (Chen, Li & Wang 2006) we have found that for a given final orbital period, including the CB disc can allow a more evolved donor star at the onset of mass transfer, so that the X-ray lifetime can be considerably decreased.

All of the BHLMXBs with an orbital period of ≤ 0.5 d should be transient sources (Casares 2006). It is currently believed that the transient behavior in X-ray binaries is due to the thermal-viscous instability of accretion discs, when the mass transfer rates lie below a critical value Mcr so that the surface temperature at the outer edge of accretion disc is lower than the hydrogen ionization temperature (King, Kolb & Burderi 1996). This critical mass transfer rate depends primarily on MBH, Md and Porb, and is given by (van Paradijs 1996; Dubus et al. 1999):

$$M_{cr} \approx 8.6 \times 10^{-9} \left( \frac{M_{BH}}{10M_{\odot}} \right)^{0.5} \left( \frac{M_d}{1M_{\odot}} \right)^{-0.2} \left( \frac{P_{orb}}{1d} \right)^{0.5} M_{\odot} yr^{-1}$$

In Fig. 2 the thick and thin curves correspond to stable and unstable mass transfer during the evolution of BHXBs. However, the mass transfer would be always stable for the wide orbit system with an initial orbital period of 3 d (see Fig. 3). It is interesting to see that the model BHLMXBs are likely to be persistent X-ray sources. This is not compatible with the observations of Galactic BHLMXBs, suggesting that δ does not need to be constant but changes during the evolution (see discussion below)

4 SUMMARY AND DISCUSSION

In this paper we have examined the influence of a CB disc on the evolution of BHLMXBs. Assuming that a fraction δ of the transferred material from the secondary forms a CB disc surrounding the binary system and extracts the orbital angular momentum from the binary, we have performed evolution calculations for BHXBs containing a donor star of mass in the range from 3 to 5M⊙ with an initial orbital period of 1 d and 3 d. The calculations show that the evolution of BHLMXB is sensitive to δ. Generally a larger δ is required for a wider initial orbit since the mass transfer itself during the evolution always causes orbital expansion. The results indicate that the orbits of BHXBs would show secular shrinkage when the values of δ lie in the range of a few 10^{-3} – 10^{-1}. Thus our CB disc scenario suggests a new evolutionary channel for the formation of BHLMXBs from BHIMXBs.

However, our results encounter the similar difficulty as in Justham, Rappaport & Podsiadlowski (2006), that the calculated effective temperatures T_{eff} are not consistent with those of the observed donor stars in BHLMXBs. We compare the calculated results of both BH-LMXBs and IMXBs with the observations in the T_{eff} - P_{orb} diagram in Fig. 5. One can see that the observed results seem to be more consistent with the evolutionary tracks of original BHLMXBs. Justham, Rappaport & Podsiadlowski (2006) have already pointed out that this temperature discrepancy seems to be a generic difficulty with any formation scenario that invokes primordially intermediate-mass donor stars. If this effective temperature problem can be solved, the CB disc mechanism may provide a plausible solution to the BHLMXB formation

3 Chandra observations of the 12.6 hr ultraluminous X-ray source in the elliptical galaxy NGC3379 suggest that the current on phase has lasted ∼ 10 yr (Fabian et al. 2006). This source could be a soft X-ray transient with long duration of outbursts. However, a persistent X-ray source as suggested by our calculations is an alternative possibility.
problem, without requiring anomalous magnetic fields in the donor stars.

The mechanism feeding the CB disc is still unclear. It has been argued that during mass exchange in binary systems, some of the lost matter which possesses high orbital angular momentum may form a disc surrounding the binary system (van den Heuvel 1994). This part of matter may come from the stellar wind from the donor star, wind and/or outflow from the accretion disc, or mass lost from the outer Lagrangian point. The values of $\delta$ adopted here seem to rule out stellar wind as the origin of the CB disc, which requires a unreasonably high wind mass loss rate in intermediate- and low-mass stars. We speculate that the disc wind/outflow may play a more important role in feeding the CB disc, as the X-ray irradiation on the accretion disc in BHXBs may evaporate the disc much more efficiently than in CVs. This may explain why the values of $\delta$ are about 2 – 3 orders of magnitude larger than those for CV evolution (Spruit & Taam 2001).

Dubus, Taam & Spruit (2002) investigated the structure and evolution of a geometrically thin CB disc to calculate its spectral energy distributions, and discussed the prospects for the detection of such discs in the infrared and submillimeter wavelength regions. Dubus et al. (2004) searched for excess mid-infrared emission due to CB disc material in CVs. But direct detection of the CB disc in CVs by infrared continuum studies has so far been elusive, partly because of the lack of accurate disc atmosphere models. Recently, Muno & Mauerhan (2006) studied the blackbody spectrum of BHLMXBs A 0620-00 and XTE J1118+480, and found that the inferred excess mid-infrared emitting areas are $\sim 2$ times larger than the binary orbital separations. Therefore, the detection of excess mid-infrared emission from these BHLMXBs provides evidence of the existence of CB disc around some BHLMXBs. These observations may set useful constraints on the evolution of the CB discs.

The masses of the model CB disc are significantly larger than those ($\sim 10^{-9}M_\odot$) estimated by Muno & Mauerhan (2006). Combined with the non-detection of discs in CVs by Dubus et al. (2004), this fact suggests that the presence of the CB disc may not always accompany the RLOF processes. For example, (X-ray) nova bursts may destroy the CB disc before it has developed to be massive enough. Or perhaps $\delta$ only needs to be high for a short time, while normal magnetic braking takes over the CB disc during the majority of the evolution. The latter may partly account for the discrepancy between the lifetimes of BHLMXBs in Fig. 3 ($\sim 0.5 - 1.5 \times 10^7$ yr) and those expected for observed BHLMXBs ($\sim 10^5 - 10^6$ yr). Since the CB disc can promote mass transfer very efficiently, BHLMXBs are more likely to be observed when the value of $\delta$ becomes extremely small.

ACKNOWLEDGMENTS

We thank the anonymous referee for his/her helpful comments that significantly improved the manuscript. This work was supported by the National Science Foundation of China (NSFC) under grant 10573010.

REFERENCES

Artyomowicz P., Lubow S. H., 1994, ApJ, 421, 651
Bardeen J. M., 1970, Nat, 226, 64
Belle K. E., Sanghi N., Howell S. B., Holberg J. B., Williams P. T., 2004, AJ, 128, 448
Casares J., 2006, in JENAM 2004 Astrophys. Rev., The Many Scales of the Universe, del Toro Iniesta J. C. et al., eds, Kluwer, Dordrecht, in press (astro-ph/0506071)
Chen W. -C., Li X. -D., Wang Z. -R., 2006, PASJ, 58, 153
Chen W. -C., Li X. -D., Qian S. -B., 2006, ApJ, in press (astro-ph/0606081)
Dubus G., Lasota J., Hamury J., Charles P., 1999, MNRAS, 303, 139
Dubus G., Taam R. E., Spruit H. C., 2002, ApJ, 569, 395
Dubus G., Campbell R., Kern B., Taam R. E., Spruit H. C., 2004, MNRAS, 349, 869
Eggleton P. J., 1971, MNRAS, 151, 351
Eggleton P. J., 1972, MNRAS, 156, 361
Eggleton P. J., Verbunt F., 1986, MNRAS, 220, 13
Fabiano G. et al., 2006, Apj preprint doi:10.1086/507018
Han Z., Podsiadlowski P., Eggelton P. P., 1994, MNRAS, 270, 121
Huang S. -S., 1963, ApJ, 138, 471
Justham S., Rappaport S., Podsiadlowski Ph., 2006, MNRAS, 366, 1415
Kawaler S. D., 1988, ApJ, 333, 236
King A. R., Kolb U., 1999, MNRAS, 305, 654
King A. R., Kolb U., Burderi L., 1996, ApJ, 464, L127
Kippenhahn R., Weigert A., 1990, Stellar Structure and Evolution. Springer, Berlin
Landau L. D, Lifshitz E. M., 1962, The Classical Theory of Fields.
Lee C. -H, Brown G. E., Wijers R. A. M. J., 2002, ApJ, 575, L996
Muno, M. P., Mauerhan, J. 2006, ApJ, submitted (astro-ph/0607083)
Meyer F., Meyer-Hofmeister E., 2001, in ASP Conf. Ser. 229, Evolution of Binary and Multiple Stars, ed. Ph. Podsiadlowski, S. Rappaport, A. R. King, F. D’Antona, and L. Burder, 167
Nelemans G. Tout C. A., 2005, MNRAS, 356,753
Orosz J. A. et al., 2002, ApJ, 568, 845
Podsiadlowski Ph., Cannon R. C., Rees M. J., 1995, MNRAS, 274, 485
Podsiadlowski Ph., Rappaport S., Han Z., 2003, MNRAS, 341, 385
Pols O., Tout C. A., Eggleton P. P., Han, Z., 1995, MNRAS, 274, 964
Rappaport S., Pfahl E., Rasio, F. A., Podsiadlowski Ph., 2001, in ASP Conf. Ser. 229, Evolution of Binary and Multiple Star Systems, ed. Ph. Podsiadlowski, S. Rappaport, A. R. King, F. D’Antona, and L. Burder, 409
Rhoades C. E., Ruffini R., 1974, Phys. Rev. Lett., 32, 324
Ritter H., Kolb U., 2003, A&A, 404, 301
Romani R. W., 1998, A&A, 333, 583
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Soberman G. E., Phinney E. S., van den Heuvel E. P. J., 1997, A&A, 327, 620
Spruit H. C., Taam R. E., 2001, ApJ, 548, 900
Taam R. E., Spruit H. C., 2001, ApJ, 561, 329
van den Heuvel E. P. J., 1994, in Interacting Binaries (Saas-
Evolution of BHIMXBs

Fee 22), Shore, S. N. et al. eds., p263
van Paradijs, J., 1996, ApJ, 464, L139
Warner B., 1987, MNRAS, 227, 23
Wijers R. A. M. J., 1996, in Wijers R. A. M. J., Davies M. B., Tout C. A., eds, Evolutionary Processes in Binary Stars. Kluwer, Dordrecht
Yungelson, L. R. et al. 2006, A&A, in press (astro-ph/0604434)

This paper has been typeset from a TeX/\LaTeX file prepared by the author.