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Evolutionary models of short-period soft X-ray transients: comparison with observations

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ABSTRACT

We consider evolutionary models for the population of short-period ($P_{\rm orb} \lesssim 10$ h) low-mass black-hole binaries (LMBHBs) and compare them with observations of soft X-ray transients (SXTs). We show that assuming strongly reduced magnetic braking (as suggested by us before for low-mass semidetached binaries) the calculated masses and effective temperatures of secondaries are encouragingly close to the observed masses and effective temperatures (as inferred from their spectra) of donor stars in short-period LMBHBs. Theoretical mass-transfer rates in SXTs are consistent with the observed ones if one assumes that accretion discs in these systems are truncated ("leaky"). We find that the population of short-period SXTs is formed mainly by systems which had unevolved or slightly evolved main-sequence donors ($M_2 \lesssim 1.2\ M_\odot$) with a hydrogen abundance in the center $X_c \gtrsim 0.35$ at the Roche-lobe overflow (RLOF). Longer period ($P_{\rm orb} \simeq (0.5-1)$ day) SXTs might descend from systems with initial donor masses of about 1 $M_\odot$ and $X_c \lesssim 0.35$. Thus, one can explain the origin of short period LMBHB without invoking donors with cores almost totally depleted of hydrogen. Our models suggest that, unless the currently accepted empirical estimates of mass-loss rates by winds for massive O-stars and Wolf-Rayet stars are significantly over-evaluated, a very high efficiency of common-envelope ejection is necessary to form short-period LMBHBs.

Key words. stars: binaries: close – stars: evolution – X-rays: binaries

1. Introduction

Soft X-ray transients (SXTs) are a sub-class of low-mass X-ray binaries most of which harbour black holes (see, e.g., Remillard & McClintock 2006). Their transient behaviour is commonly associated with the same thermal-viscous instability of accretion discs that drives outbursts of dwarf-novae (see, e.g., Dubus et al. 2001; Lasota 2001, and references therein). In this article we will be interested in black-hole systems with orbital periods shorter than ~0.5 day. Some observational data on these systems are summarised in Table 1. All known low-mass black-hole binaries (LMBHBs) are transient.

There are at least two major open questions concerning the origin and evolution of SXTs. First, the values of the parameters describing the common envelope phase, second the strength of the angular momentum loss through magnetic braking.

1.1. The common-envelope phase

As first suggested by McClintock & Remillard (1986) and de Kool et al. (1987) the progenitors of LMBHBs may be relatively wide binaries (but still "close" in an evolutionary sense) composed of a massive primary ($M_{10} \gtrsim (25-40)\ M_\odot$) and a low-mass companion ($M_{20} \lesssim 1\ M_\odot$). Such a binary avoids merging in the common envelope which is formed when a massive star overflows its critical lobe and survives the supernova explosion that produces the black hole. A black hole plus main-sequence star (henceforth, "bh+ms") binary is formed. As in cataclysmic variables, the further evolution of the system is controlled by the loss of angular momentum through gravitational radiation and/or magnetically coupled stellar winds (de Kool et al. 1987; Pylyser & Savonije 1989). This evolutionary path for LMBHBs has been challenged on the basis of computations which showed that envelopes of massive stars are very tightly bound to their cores. The "standard" equation for the variation of the orbital separation of components based on the balance between the binding energy of the mass-losing star and the orbital energy of the system (Webbink 1984; de Kool et al. 1987) implies a ratio of final $a_{\rm f}$ to initial a_i separations of components equal to

$$\frac{a_{\rm f}}{a_i} = \frac{M_{1,c}}{M_1}\left[1 + \left(\frac{2}{\alpha_{\rm CE}\lambda r_{1,L}}\right)\left(\frac{M_1 - M_{1,c}}{M_2}\right)\right]^{-1}, \quad (1)$$

where $\alpha_{\rm CE}$ is the common envelope ejection efficiency, λ the parameter of the binding energy of the stellar envelope, M_1 and $M_{1,c}$ are initial mass of mass-losing star and the mass of its remnant, $r_{1,L}$ is the dimensionless radius of the star at the beginning of mass transfer, M_2 is the mass of companion. Formally, applying Eq. (1) to the estimate of the outcome of the common envelope stage one finds that a low-mass secondary is unable to unbind the envelope of a massive primary (Podsiadlowski et al. 2003b; Kiel & Hurley 2006). Thus instead of forming a short-period binary, the components will merge. As found by Podsiadlowski et al. (2003b) and Justham et al. (2006), producing a population of LMBHBs in a "standard" scenario requires the product $\alpha_{\rm CE} \times \lambda$ to exceed ~0.1 which they consider as unrealistic. An alternative "anomalous magnetic braking scenario" (Justham et al. 2006) suggests that the progenitors of the donors of SXTs are intermediate-mass ($\gtrsim 2\ M_\odot$) Ap/Bp-stars

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Table 1. Estimates of spectral types, effective temperatures of donor-stars and mass ratios of components M_2/M_X in SXT.

	Object	P_0, hour	Sp	T_{eff}	q	Ref.	Comments
1	XTE J1118+480 (KV UMa)	4.104	K7V-M0.5V		0.083	1	
			K7V			2, 3	
			K5/K7V			4	
			K5-M0			5	
			K7-M0V			6	First IR-observartions
			mid to late K	4700 ± 100		7	
					~0.008	8	
			K5V-M1V		<0.1	9	
					0.044–0.035	10	
2	GRO J0422+32 (V518 Per)	5.088	M2 ± 2V			11	
			$M2^{+2}_{-1}$V		$0.116^{+0.079}_{-0.071}$	12	
			M1V			13	
			M1V			14	B5 to K7 from $(H-K)_0$ col. index
					0.313–0.076	10	
3	GRS 1009-45 (MM Vel)	6.840	later than G5V-K0V			15	
			K7V-M0V			16	possibly K6V
					0.159–0.125	10	
4	XTE J1650-500	7.680	K4 V		0.1	17	next best match G5V and K2III
5	A0620-00 (V616 Mon)	7.752	later than a K3V, most likely between K5V and K7V			18	
			K5 V			19	
			K3V			20	
				4900 ± 100		21	
					0.075–0.055	10	
6	GS 2000+25 (QZ Vul)	8.280	K5V			22	evolved
			K3-K6V			23	slightly evolved, but not a subgiant
			consistent with K5V			24	K4V is nearly identical, G5-K1 and K8-M0 also give very good correlations
					0.053–0.035	10	
7	XTE J1859+226 (V406 Vul)	9.120	G5-K0			25	G5V fits best
8	GRS 1124-68 (GU Mus)	10.392	K5V to K7V			26	
			K3 -K5V			27	slightly evolved, K7 features not observed
			K3-K4V			28	
			K3/5V			29	
					0.208–0.114	10	
9	H 1705-25 (V2107 Oph)	12.504	K7V			30	K3 to M0 also give good correlations
			K3V			31	
			K5V			32	
					<0.053	10	

References: 1 – Wagner et al. (2001), 2 – Zurita et al. (2002), 3 – Gelino et al. (2006), 4 – McClintock et al. (2003), 5 – Torres et al. (2004), 6 – Mikołajewska et al. (2005), 7 – González Hernández et al. (2006), 8 – Casares et al. (2001), 9 – McClintock et al. (2001), 10 – Orosz (2003), 11 – Casares et al. (1995), 12 – Harlaftis et al. (1999), 13 – Gelino & Harrison (2003), 14 – Reynolds et al. (2007), 15 – della Valle et al. (1997), 16 – Filippenko et al. (1999), 17 – Orosz et al. (2004), 18 – Froning et al. (2007), 19 – Harrison et al. (2007), 20 – Shahbaz et al. (1999), 21 – González Hernández et al. (2004), 22 – Ioannou et al. (2004), 23 – Harlaftis et al. (1996), 24 – Filippenko et al. (1995), 25 – Filippenko & Chornock (2001), 26 – King et al. (1996b), 27 – Orosz et al. (1996), 28 – Casares et al. (1997), 29 – Shahbaz et al. (1997), 30 – Filippenko et al. (1997), 31 – Remillard et al. (1996), 32 – Harlaftis et al. (1997).

with anomalously high magnetic field strength. In this case, after an initial high mass-loss rate stage of evolution, the secondary of the system turns into a low-mass star with a long evolutionary lifetime. This scenario explains the short orbital periods of SXTs. However, in such a scenario the effective temperatures of the descendants of the intermediate-mass stars significantly exceed the effective temperatures of the observed SXT donors. On the other hand Kiel & Hurley (2006) found that a population of black holes accompanied by low-mass secondaries may be formed if the rate of winds from WR stars is reduced ad hoc.

However, the estimates of both α_{CE} and λ remain uncertain. The estimate of $\alpha_{CE} \times \lambda$ is strongly influenced by the assumptions about the mass-loss by stellar winds and by the uncertainty about the role of the internal thermodynamic energy in unbinding the envelope of the donor (see for the first suggestion of this source of energy in the context of formation of planetary nebulae Lucy (1967) and e.g. Han et al. (1995); Tauris & Dewi (2001); Soker & Harpaz (2003); Podsiadlowski et al. (2003b); Webbink (2007) for further discussion of this issue applied to common envelopes).

De Marco et al. (2003) carried out 3D common envelope modelling for an 1.25 $M_{\odot}$ AGB star engulfing 0.1 and 0.2 $M_{\odot}$ companions that took into account both rotation and the interaction between the spiralling-in component and the donor star. If the ratios a_f/a_i obtained by De Marco et al. are inserted in Eq. (1), they correspond to $\alpha_{CE} \times \lambda$ up to ≃2. Regretfully, similar calculations are still absent for massive binaries and one has to rely on indirect methods for evaluation of $\alpha_{CE} \times \lambda$.

The attempts to find a plausible evolutionary scenario for the pulsar PSRJ 2145-0750 (van den Heuvel 1994) and the results of modelling of the population of binary pulsars (which also invokes high-mass stars) both favour $\alpha_{CE} \times \lambda \simeq 2$ (Portegies Zwart & Yungelson 1998)[1]. Kalogera (1999) in her study of evolutionary parameters of progenitors of donors in black-hole X-ray binaries found that the explanation of the origin of the latter systems suggests $\alpha_{CE} > 1$, implying that sources other than orbital energy release may be invoked in unbinding common envelopes. Hurley et al. (2002) in their model for the total Galactic population of interacting binaries obtained a subpopulation of transient low-mass black-hole binaries for $0.5 \leq \alpha_{CE} \times \lambda \leq 1.5$. On the other hand using supernova rates and empirical estimates of the compact object merger rate O'Shaughnessy et al. (2008) constrained $\alpha_{CE} \times \lambda$ to be in the range 0.15–0.5.

The issue of the sources of energy that may increase α_{CE} was discussed by Iben & Livio (1993). Referring the reader to the original paper, we mention only that, apart from recombination energy in ionization zones, Iben and Livio suggested, e.g., dynamo generation of magnetic fields that may contribute to matter ejection, enhanced nuclear burning due to injection of fresh matter into nuclear burning shells by circulation movements that develop in common envelopes and excitation of non-radial pulsations that may drive mass loss. None of these mechanism has been explored as yet.

All estimates of $\alpha_{CE} \times \lambda$ were obtained under different sets of assumptions on the evolution of massive stars that are consistent with our current knowledge of the stellar evolution. Thus it is still interesting to compare the predictions of various evolutionary models with observations. In this article we compare the Yungelson et al. (2006) model with the observed properties of secondary stars in SXTs (see also Yungelson & Lasota 2008).

1.2. Magnetic braking

Yet another problem, noted, e.g., by King et al. (1996a); Ergma & Fedorova (1998); Menou et al. (1999) and Ivanova & Kalogera (2006) is associated with the mechanism of AML by low donor-mass binaries. One finds that if, following Verbunt & Zwaan (1981), one assumes that the braking law for *single* field stars $\Omega \propto t^{-0.5}$ (Skumanich 1972) can be extrapolated over an order of magnitude in the rotational velocity v (from several 10 to several 100 km s^{-1}) to the case of close binary systems and if the spin-orbit coupling is efficient, the predicted mass-transfer rates for LMBHBs at orbital periods ≳2 h are sufficiently high for these systems to have stable hot discs. However, such a population of stable and bright low-mass black-hole X-ray binaries has not been observed. Also, the Skumanich (1972) "law" is apparently in conflict with observational data on rotation velocities in young open clusters (Collier Cameron 2002; Andronov et al. 2003). According to the latter study, the time-scale of rotational braking is two orders of magnitude longer than the one based on the Skumanich law. Also van Paradijs (1996) noted that the values of $\dot{M}$ in SXTs are close to those expected if gravitational wave emission is the sole sink of angular momentum. Also for cataclysmic variables mass transfer rates predicted by the Skumanich law based AML disagree with observations, see, e.g., Hameury et al. (1988) and Ivanova & Taam (2003).

In our previous work (Yungelson et al. 2006, henceforth, Paper I) we found that when the Verbunt & Zwaan AML mechanism is allowed to operate after the systems become semi-detached, one obtains a large number of bright, steady LMBHBs that clearly are not observed in reality (also Charles, private communication). Therefore we suggested, in line with observational evidence mentioned above, that in the semi-detached systems with black-hole accretors, magnetic braking operates on a much reduced scale (as compared with the Verbunt & Zwaan prescription), or that it does not operate at all. As a test of this hypothesis, we computed a population of LMBHBs under the assumption that MSW is not operating once the RLOF occurs and have shown that in this case there remains in the Galaxy about the same number of such systems as in the case with active MSW (≃10 000) but all of them are transient, according to the disc instability model (DIM) criterion of Dubus et al. (1999).

In the present paper we extend considerations of the "no-MSW after RLOF" model proposed in Paper I to the case of $\alpha_{CE} \times \lambda < 2$ and carry out a detailed comparison of the model with observations.

2. The model

For convenience we remind some basic information about our calculation of the LMBHB population.

The model of the LMXB population is obtained in two steps: (i) modelling time-dependent formation of the population of bh+ms binaries, (ii) tracing the subsequent evolution of each system. The Galactic ensemble of bh+ms binaries is computed with the population synthesis code SEBA (Portegies Zwart & Verbunt 1996; Portegies Zwart & Yungelson 1998; Nelemans et al. 2001; Nelemans et al. 2004) using 250 000 initial binaries with $M_{10} \geq 25\,M_{\odot}$. The time- and position-dependent Galactic star formation history in the code follows the model of Boissier & Prantzos (1999); for the inner 3 kpc of the Galaxy the star formation rate given in the latter study is doubled to mimic the Galactic bulge (see Figs. 1 and 2 of Nelemans et al. 2004). The assumed binarity rate is 50% (2/3 of the stars in binaries). The IMF follows Kroupa et al. (1993), the initial distribution of semi-major axes of binaries (a) is flat in $\log a$ between contact and $10^6\,R_{\odot}$. A flat mass ratio distribution, and an initial distribution of eccentricities of orbits $\Xi(e) = 2e$ are assumed.

For the common-envelope phase we used Eq. (1). We tested the combinations of common envelope ejection efficiency and stellar envelope binding energy parameters $\alpha_{CE} \times \lambda = 2, 0.5$, and 0.1 (see below).

Black hole progenitors have $M_{10} = 25{-}100\,M_{\odot}$. The relation between MS masses of stars and pre-SN masses generated by SEBA agrees well with the one obtained by the SSE-code of Hurley et al. (2000), despite differences in the treatment of stellar winds. The algorithm for the formation of black holes follows the fall-back scenario (Fryer & Kalogera 2001) with the assumption of a constant explosion energy of 10^{50} erg, which is within the expected range. Nascent black holes receive kicks at formation that follow the Paczyński (1990) velocity distribution with σ_v = 300 km s^{-1}, scaled down with the ratio of the black hole mass to neutron star mass.

[1] Though one cannot exclude that, because of the difference in the mass of progenitors of neutron stars and black holes, $\alpha_{CE} \times \lambda$ for them may be different.

In the next step of modelling, the population of bh+ms binaries born at different epochs is convolved with the grid of evolutionary tracks for low-mass components in the binaries with different combinations of masses of components and post-circularization (initial) orbital periods (see Fig. 3). All tracks used in the paper were computed by an appropriately modified TWIN version (September 2003) of the Eggleton (1971) evolutionary code. As mentioned in Sect. 1.2 the AML via magnetic stellar wind was taken into account following Verbunt & Zwaan (1981):

$$\dot{J} = -0.5 \times 10^{-28} f^{-2} k^2 \left(\frac{2\pi}{P}\right)^3 M_2 R_2^4, \quad (2)$$

where M_2 is mass of the secondary, R_2 – its radius, $k^2 \sim 0.1$ – its gyration radius, P – orbital period, $f \sim 1$ – a parameter derived from observations; it was set to 1. For momentum losses via gravitational wave radiation the standard Landau & Lifshitz (1971) formula was applied.

The evolution of each system was traced over a time span from formation to $T = 13.5$ Gyr or to the epoch when the mass ratio of the components of the system became $q = M_2/M_{\rm bh} = 0.02$. At $q \lesssim 0.02$ the circularization radius of the accretion stream becomes larger than the outer radius of the accretion disc, resonance phenomena in the disc become important and it remains unexplored as yet how mass transfer then proceeds. Model systems with $q < 0.02$ have $P_{\rm orb} \gtrsim 1.5$ h, mass-transfer rates $\lesssim 10^{-10}\ M_\odot\ {\rm yr}^{-1}$ and it remains to be observed if mass transfer occurs in them.

For a more detailed description of the input parameters we refer the reader to Paper I.

3. The population of progenitors

As discussed above, indirect estimates of the possible range of the product of common envelope equation parameters extend to $\alpha_{\rm CE} \times \lambda \lesssim 2$. We note that Tauris & Dewi (2001) have shown that, depending on the definition of the core of the star and the treatment of the role of internal thermodynamic energy, the binding energy parameter λ may vary by two orders of magnitude (from 0.02 to 3.50 for the same 20 $M_\odot$ star at the tip of red giant branch) and therefore we consider $\alpha_{\rm CE} \times \lambda > 1$ as an acceptable value. In Paper I we presented results of the modelling of the population of LMBHBs assuming a value of $\alpha_{\rm CE} \times \lambda = 2$. Here, we also discuss models with $\alpha_{\rm CE} \times \lambda = 0.1$ and 0.5.

A run of SEBA-code with $\alpha_{\rm CE} \times \lambda = 0.1$ produced about 3400 zero-age bh+ms binaries formed in a Hubble time. However, all $M_2 \lesssim 1.5\,M_\odot$ secondaries (i.e., stars subject to magnetic braking) were paired with $\gtrsim 14\,M_\odot$ primaries, exceeding the largest estimate of black hole mass in a known LMBHB (9.7 ± 0.6 for A0620-500, Froning et al. 2007) – and often exceeding the largest dynamically evaluated mass of black hole in binaries in the Galaxy (15.65 ± 1.45 $M_\odot$ Orosz et al. 2007)[2]. Since this model contradicts observations, we do not consider it further.

The model with $\alpha_{\rm CE} \times \lambda = 0.5$ and AML via MSW implies the presence in the Galaxy of about 1700 semidetached bh+ms binaries with $q \geq 0.02$, 220 of which are bright and stable. Based on arguments presented in Paper I we conclude that, as in the $\alpha_{\rm CE} \times \lambda = 2$ case, in conflict with observations, up to several dozen persistent LMBHBs then would be observed in the Galaxy above the *RXTE All Sky Monitor* sensitivity limit, thus implying the need for a reduced MSW. The luminosities of these persistent LMBHBs are not high enough to correspond to the bright steady X-ray sources observed in elliptical galaxies (Irwin 2006; Sivakoff et al. 2007).

Table 2. Numbers of Galactic detached bh+ms systems with $M_{\rm bh} \leq 12\,M_\odot$, $M_{20} \leq 1.2\,M_\odot$, $P_{\rm orb} < 1.2$ day formed in Hubble time, systems that reached RLOF, and current number of semidetached LMBHB with $q \geq 0.02$.

	$\alpha_{\rm CE} \times \lambda = 2$	$\alpha_{\rm CE} \times \lambda = 0.5$
Total number of systems	25685	10910
Systems that reached RLOF	12150	6150
Systems currently at $q \geq 0.02$	5080	2980

Thus, we consider results for models in which AML via MSW does not act upon RLOF. Both for $\alpha_{\rm CE} \times \lambda = 2$ and 0.5, almost all semidetached bh+ms binaries descend from systems with $M_{\rm bh} \leq 12\,M_\odot$ and $M_2 \leq 1.2\,M_\odot$. Table 2 compares the number of systems for two cases[3]. The total numbers of systems differs by a factor ~2 and apparently neither contradicts observation–based estimates of several hundred to several thousand objects (Chen et al. 1997; Romani 1998), though an $\alpha_{\rm CE} \times \lambda = 0.5$ model may be more attractive.

In the $M_{10} = (25{-}40)\,M_\odot$ range to which most of the precursors of black holes in bh+ms binaries belong, $M_{10} \gg M_{20}$ and the second term in the brackets in Eq. (1) is $\gg$1. Then, roughly, after the common envelope stage one obtains the relation: $a_f/a_0 \propto \alpha_{\rm CE} \times \lambda$. Thus, the transformation law for component separation may be written, approximately, as $f(a_{\rm f})\Delta a_{\rm f} = C \times h(a_0)\Delta a_0$, where $h(a_0)$ and $f(a_{\rm f})$ are, respectively, the distribution of systems over orbital separations prior to and after the common envelope stage. By virtue of this relation, functions f and h must be similar. This is illustrated in Figs. 1 and 2.

For lower $\alpha_{\rm CE}$, initially wider progenitor systems are sampled, as shown in the upper panel of Fig. 1. Initially too "close" systems merge, but they are replaced by initially wider systems. The rate of AML given by Eq. (2) is a function of orbital separation ($\dot{J} \propto a^{-0.5}$) and as a result post-common-envelope separations of components in progenitors of bh+ms systems that evolve into contact may descend only from a very narrow range of a, given a limited time-span from formation to the Hubble- or MS-evolution times. In this range of a the systems are distributed similarly irrespective of $\alpha_{\rm CE} \times \lambda$ (Fig. 1, lower panel).

Figure 2 shows that, while for $\alpha_{\rm CE} \times \lambda = 2$ initial systems with low M_2 dominate, "successful" progenitors of LMBHB have similar distributions over M_2 both for $\alpha_{\rm CE} \times \lambda = 0.5$ and 2, since $\dot{J} \propto M_2 R_2^4$. Masses of black holes in the two $\alpha_{\rm CE} \times \lambda$ cases also have similar distributions, since for (25–40) $M_\odot$ stars that are typical of most of the progenitors of black holes in LMBHB, the masses of their He-cores do not change significantly in the hydrogen-shell burning stage that preceeds RLOF. As a combined effect of similar distributions of detached bh+ms progenitors of LMBHB over $M_{\rm bh}$, M_2 and a, scatter diagrams (e.g., $M_2 - P$) for populations of LMBHB are similar both for $\alpha_{\rm CE} \times \lambda = 0.5$ and 2 and differ only in the number of systems per "unit area" (by factor ~2), since initial systems were sampled from different ranges in a_0 and our assumed initial distribution over separations is $\propto 1/a_0$. For consistency with Paper I we further consider the model for $\alpha_{\rm CE} \times \lambda = 2$.

[2] The 34 h binary X-1 in the starburst galaxy IC 10 contains a $\gtrsim 23\,M_\odot$ black hole (Silverman & Filippenko 2008).

[3] Since we present one random realization of each model, all numbers given are subject to Poisson noise.

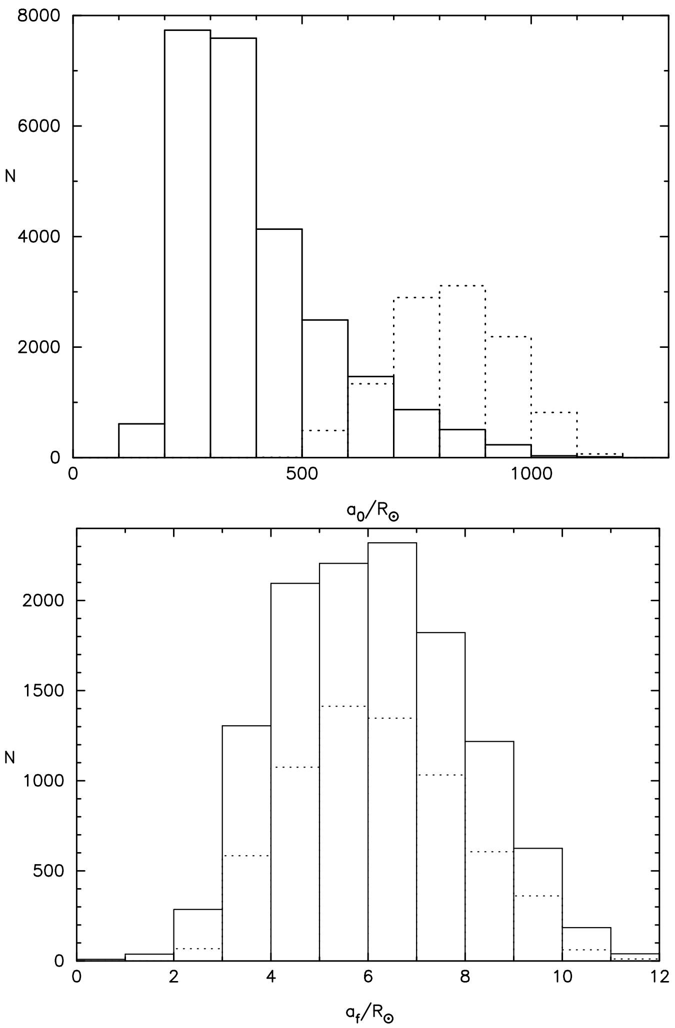

Fig. 1. Model distributions over separation of components in the population of precursors of bh+ms binaries with $M_{\rm bh} \leq 12\,M_{\odot}$, $M_{20} \leq 1.2\,M_{\odot}$, $P_{\rm orb} < 1.2$ day after circularisation of the orbits (*upper panel*) and in the ensemble of bh+ms binaries that produce LMXB (*lower panel*). Solid line – $\alpha_{\rm CE} \times \lambda = 2$, dotted line – $\alpha_{\rm CE} \times \lambda = 0.5$.

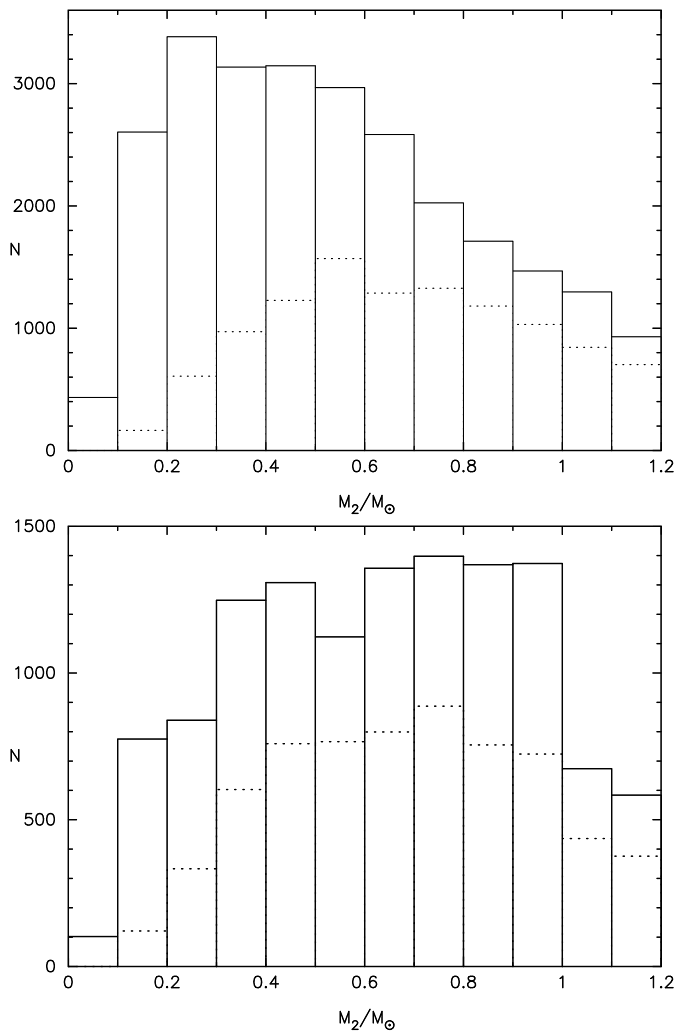

Fig. 2. Model distributions of initial masses of secondary components in the population of precursors of bh+ms binaries with $M_{\rm bh} \leq 12\,M_{\odot}$, $M_{20} \leq 1.2\,M_{\odot}$, $P_{\rm orb} < 1.2$ day after circularisation of the orbits (*upper panel*) and in the ensemble of bh+ms binaries that produce LMXB (*lower panel*). Solid line – $\alpha_{\rm CE} \times \lambda = 2$, dotted line – $\alpha_{\rm CE} \times \lambda = 0.5$.

Figure 3 shows the distribution of zero-age ms+bh binaries in the initial-mass-of-the-donor M_{20} – initial (post-circularisation of the orbit) period P_0 plane[4]. If a bh+ms system reached contact, its further time-dependent behaviour was determined by interpolaton in the grid of pre-computed evolutionary tracks. The borders of this grid are outlined in Fig. 3. The initial systems with masses larger than the rhs side border of the outlined range or periods longer than the upper border of this region evolve to longer periods upon RLOF and have unstable discs unless their mass is $\gtrsim 4\,M_{\odot}$. Evolution of the latter systems is illustrated by some evolutionary tracks in Figs. 4 and 6. Low-donor-mass systems, if their periods are not short enough, never evolve to contact. There is, however, a contribution to the population of LMBHBs from stars with $M_{20} < 0.4\,M_{\odot}$ and initial orbital period $P_0 < 0.8$ day and these systems were evolved analytically. In binaries with $M_{20} \lesssim 0.6\,M_{\odot}$ and $P_0 \gtrsim 0.8$ day the donors do not fill their Roche lobes in the Hubble time. The initial masses of the progenitors of the donors are typically $\lesssim 1\,M_{\odot}$ and this means that most of the donors have to be unevolved or slightly evolved at the instant of RLOF.

[4] Each dot in the plot represents several systems that have similar M_{10}, M_{20}, P_0 but were born at different epochs in the history of the Galaxy. Thus, some of the systems shown in the plot do not have time to evolve into contact.

4. Observational parameters of short-period LMBHBs

4.1. Effective temperatures

As noted by Justham et al. (2006), any formation scenario for LMBHBs has to explain the spectral types of black-hole low-mass companions. The determination of spectral types is a challenging task since the emission of the cool star is contaminated by the radiation from the accretion disc and the hot spot where the accretion stream hits the disc's edge (Charles & Coe 2006). Moreover, contamination by the disc may vary with time if the system did not reach quiescence. The published methods of spectral type determination vary in sophistication from naked eye estimates to using χ^2 statistics after subtracting template spectra from Doppler-corrected averaged spectra (see, e.g., Harlaftis et al. 1996); sometimes spectral types are inferred from colours, absolute magnitudes, SED and in many cases are subjective. For this reason, estimates of the donor's spectral

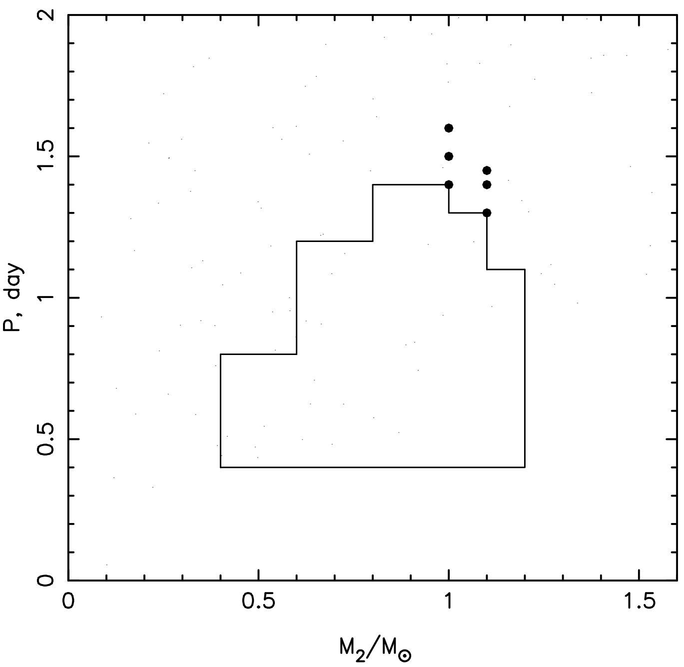

Fig. 3. Galactic zero-age population of low-mass black hole binaries (dots). The evolution of the systems that form LMBHB is determined by interpolation in the grid of evolutionary tracks with the border outlined by the polygon or analytically, if $M_{20} < 0.4\,M_{\odot}$ and $P_0 < 0.8$ day. Heavy dots mark initial parameters of the tracks listed in Table 3 and shown as examples in Figs. 4–6.

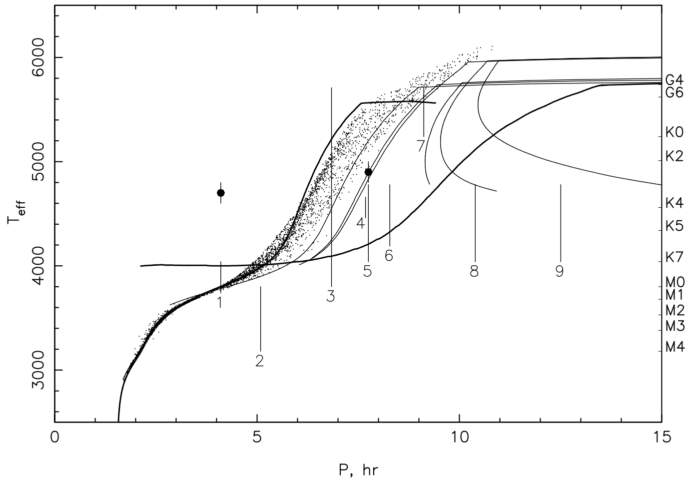

Fig. 4. Model population vs. observational estimates of the ranges of effective temperatures of donors in SXTs (dots). Vertical lines mark the ranges of effective temperatures of donor-stars in observed SXTs corresponding to the ranges of the estimates of their spectral types (Table 1). Systems are annotated according to their number in Table 1. Large filled circles give $T_{\rm eff}$ of donors derived from the fits to synthetic spectra. Heavy solid lines to the left and right show "limiting" tracks for a (1+12) $M_{\odot}$, $P_0 = 0.4$ day system in which MB does not operate after RLOF and a (1+4) $M_{\odot}$, $P_0 = 1.9$ day system with MB operating after RLOF (see Sect. 4.1 for discussion). Thin solid lines are evolutionary tracks for $M_0 = 1.0$ and $1.1\,M_{\odot}$ donors with $4\,M_{\odot}$ accretors listed in Table 3. The $Sp - T_{\rm eff}$ relation used in the paper is shown at the right border of the coordinate box.

Table 3. Parameters of tracks shown in the figures (from left to right in each figure). The columns list the initial mass of the star, initial orbital period of the system, period at RLOF, central hydrogen abundance at RLOF, the age of star at RLOF. In system 1 the initial mass of the accretor is 12 $M_{\odot}$, in systems 2–8 the initial mass of the accretor is 4 $M_{\odot}$.

No.	$M_0/M_{\odot}$	P_0, day	P_c, day	X_c	T_c Gyr
1	1.0	0.4	0.316	0.696	0.07
2	1.0	1.4	0.375	0.403	4.33
3	1.0	1.5	0.395	0.324	5.30
4	1.0	1.6	0.420	0.231	6.33
5	1.1	1.3	0.425	0.447	2.59
6	1.1	1.4	0.446	0.369	3.22
7	1.1	1.45	0.460	0.325	3.51
8	1.0	1.9	1.772	8×10^{-5}	9.17

type for the same system may differ by several subtypes (see Table 1 where we summarised the published spectral types for LMBHBs).

The effective temperature of the donor is available in the literature for XTE J1118+480 (KV UMa) and A0620-00 (V616 Mon) only. They were derived as a by-product of abundance determinations that used synthetic spectra and χ^2-minimisation techniques[5]. For other systems we were forced to apply the $Sp - T_{\rm eff}$ relation for zero-age main-sequence stars. We used the relation given by Tokunaga in Cox (2000). This relation is accepted by the authors of the catalogue of Hipparcos spectroscopic standards. For A0-M6 spectra the approximate uncertainty of this scale (one standard deviation) is ±100 K.

A caveat has to be entered concerning observers assigning "nonexistent" spectral subtypes to their objects. The modern MK classification system is devised in such a way that subsequent subtypes represent approximately equal differences in the spectra and some original decimal subdivisions were dropped. For instance, some subtypes between K5 and M0 are absent: "K7 is considered as half a subtype later than K5 and earlier than M0" (Keenan 1985). For spectral types absent in the spectral classification (e.g., K3V) we applied a linear interpolation in $\log T_{\rm eff}$.

In Fig. 4 we plot the distribution of our model population in the $P_{\rm orb} - T_{\rm eff}$ plane and compare it with the $T_{\rm eff}$ of particular systems. In the absence of objective criteria for the discrimination of reliable vs. non-reliable spectral type determinations, we plot for each system the complete range of the effective temperature for the range of spectral types assigned to it by different observers. Within the uncertainties of the spectral type determinations and conversion $Sp - T_{\rm eff}$ the model satisfactorily reproduces $T_{\rm eff}$ of the donors in the LMBHBs with $P_{\rm orb} \lesssim 9$ h.

Podsiadlowski et al. (2003a) noticed that for $T_{\rm eff} \lesssim 4500$ K stellar models with grey atmosphere boundary conditions tend to overestimate the effective temperatures of stars, compared to models with more realistic non-grey atmospheres. Using unevolved models of low-mass stars, Podsiadlowski et al. estimated that the correction in temperature may amount to about 350 K. However, (i) they used a different stellar structure code; (ii) the correction may be different if the comparison is made for non-grey atmosphere models of out-of-thermal-equilibrium mass-losing stars. However, models of the latter kind have not yet been computed and for the moment the difference between our models and the non-grey atmosphere models cannot be estimated.

[5] Froning et al. (2007) cast doubt upon the temperature determination for A0620-00 by González Hernández et al. (2004), claiming that the latter authors used an insufficient set of spectral lines in their study and overestimated $T_{\rm eff}$.

Some systems – GRS 1009-45, XTE 1650-500, A0620-00, and GS 2000+25 – are apparently located below the "populated" area. However, we restricted the initial periods of bh+ms binaries and masses of donors with the limits shown by the solid line in Fig. 3 so that interpolation between pre-computed tracks that upon RLOF evolve continuously to shorter periods and tracks that immediately go to longer periods (or change the direction of evolution in $P_{\rm orb}$) is avoided. As can be seen from the tracks plotted in Fig. 4 and from Table 3 (tracks 2–7), for a system with a given M_{10} and M_{20} the direction of evolution changes quite abruptly over a narrow range of initial $\Delta P_{\rm orb} \lesssim 0.1$ day. For a given combination of M_{10} and M_{20} a "gap" between tracks evolving in different directions forms. But since there is a continuity in the initial parameters of the systems, the "gap" in reality is filled. This is clearly shown by the tracks plotted in Fig. 4. Initial parameters of these additional tracks belong to a well populated area in the M_{20}–P_0 diagram (Fig. 3). We did not pursue the goal of finding the precise parameters of the initial system(s) that may fit the parameters of a particular observed system and the precise borders of the progenitor space, since the accuracy to which the parameters of SXT are known and the uncertainty in the efficiency of magnetic braking do not justify this time-consuming and computationally expensive task.

Nevertheless it is clear, at least qualitatively, that the origin of short-period LMBHBs may be explained within the paradigm of the strongly reduced magnetic braking in systems with donors overflowing Roche lobes.

In Paper I we reduced the AML by magnetic braking (MB) to 0. This might be excessive and in reality some amount of MB can be still operating. (But we found that reducing the MB by a factor of 2 still leaves some ~100 bright steady sources.) We plot in Fig. 4 two "limiting" tracks: for $(1 + 12)\,M_\odot$, $P_{\rm orb0} = 0.4$ day in which the donor is almost unevolved at RLOF and MB is absent after RLOF and for $(1 + 4)\,M_\odot$, $P_{\rm orb0} = 1.9$ day in which the donor has $X_{\rm c} \simeq 10^{-4}$ at RLOF and MB continues to operate (tracks 1 and 8 in Table 3). Crudely, model populations with MB and without MB have to be located between these two limiting curves. Of course there will be a contribution from lower and higher mass systems, as we plotted only the 1 $M_\odot$ tracks for simplicity. Therefore adding some MB to our model will shift the population to the right, reaching a better agreement with observations while still not producing stable luminous sources. From Fig. 5 in Paper I one can see that such an addition of MB mainly will influence the long-period systems.

From Table 3 and Fig. 4 one can see that stars turn to longer periods if $X_c \lesssim 0.35$ at RLOF. For instance a 1.1 $M_\odot$ donor with $P_{\rm orb0} = 1.4$ (second to the right line) spends almost 10 Gyr in the RLOF-state, out of which during about 5 Gyr it evolves to longer periods. This provides the possibility of explaining SXTs with periods >9–10 h. However, it is then necessary to compute a new grid of tracks for stars that evolve to longer periods and a very dense grid of tracks to cover the space between tracks evolving to shorter and longer $P_{\rm orb}$. This will be the topic of a dedicated paper.

4.2. Mass transfer rates

There is no secure method of mass transfer rate determination for transient LMXBHs. One can obtain an estimate of this parameter by dividing the mass accreted during outburst by the recurrence time. However, this approach has several weaknesses. First, recurrence times are known only for a few systems. Second, it is not sure that the rate calculated in this way represents the secular value (this is the general drawback of mass-transfer rate estimates) and third, it assumes that during the "refill", accretion onto black hole does not occur. This last assumption is put in doubt both by observations (see e.g. Done et al. 2007, and references therein) and models (see Lasota 2008, and references therein) which suggest that quiescent discs are truncated and therefore leaky. In such a case one can estimate the upper limit to the mass transfer rate which cannot be larger than the critical-for-stability accretion rate at the truncation radius (see Paper I for details). The actual mass transfer rate should be somewhere between the values estimated by the two methods.

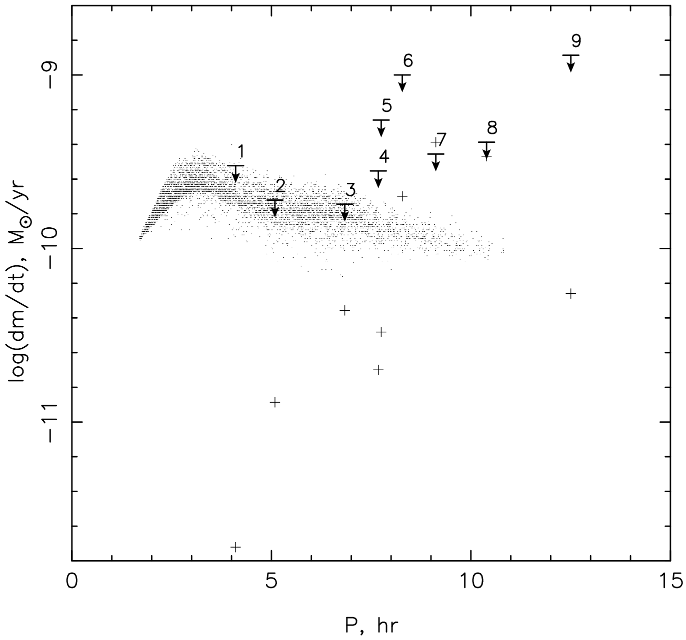

Fig. 5. Mass transfer rates in model LMBHB as a function of their orbital periods (dots). Arrows mark upper limits to the estimates of mass-transfer rates in observed SXTs as given by Eq. (3). Crosses are estimates of mass-transfer rates in SXTs based on recurrence times.

Figure 5 compares the model mass transfer rates with observational estimates of $\dot M$. We present two estimates of the latter. We show $\dot M$ estimates from recurrence times and mass accreted during the outburst and estimates of the upper limit of the accretion rate at the truncated disc inner edge. In the latter case, we get:

$$\dot M_{\rm max} \lesssim 2.5\times10^{-7}\left[(1+q)^{1/3}\,(0.5-0.227\log q)\right]^{10.32} \times P_d^{1.72} f_t^{2.58}\ M_\odot\ {\rm yr}^{-1}. \quad (3)$$

In Eq. (3) $P_{\rm d}$ is the orbital period in days, and $f_{\rm t} \lesssim 0.48$ is the fractional disc truncation radius. We used the revised version of the critical accretion rate (Lasota et al. 2008):

$$\dot M^-_{\rm crit} = 2.64\times10^{15}\ \alpha_{0.1}^{0.01}\ R_{10}^{2.58}\ M_1^{-0.85}\ {\rm g\,s^{-1}}. \quad (4)$$

The estimates of mass-transfer rates for leaky discs differ slightly from the ones given in Table 3 of Paper I, since in the present study we used in the equation for $\dot M_{\rm max}$ the lower limit of q as given in Table 1 instead of assuming a similar $q = 0.1$ for all systems. For V406 Vul we estimated q by using the value of the mass function and the mass of the secondary as obtained from its spectral type.

The estimates of $\dot M_{\rm max}$ for XTE J1118+480, GRO J0422+32, and GRS 1009-45 strongly suggest that the AML in short-period LMBHB might be defined by GWR only.

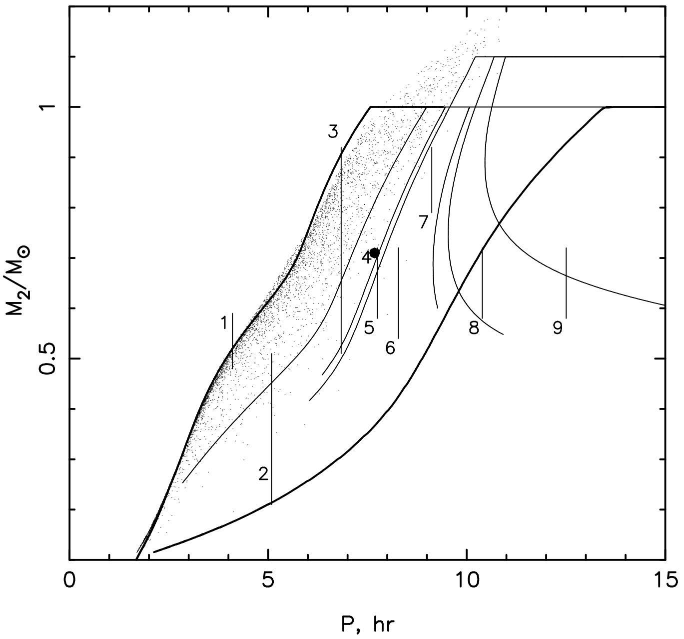

Fig. 6. Masses of donor-stars in modelled population. Vertical lines show the ranges of M_2 corresponding to the uncertainty in the determination of spectral types (Table 1). Heavy solid lines show "limiting" tracks as in Fig. 4. Thin solid lines are evolutionary tracks for 1.0 and 1.1 $M_\odot$ donors with 4 $M_\odot$ accretors like in Fig. 4. For XTE J1650-500 (at $P_{\rm orb}$=7.88 h) there is only one determination of spectrum – K4V, but the same authors (Orosz et al. 2004) mention that the next best fits are G5V and K2III; for this reason we show the lower limit for M_2 in this system.

H1705-25 (system 9) may, as noted in the previous subsection, belong to the population in which donors fill Roche lobes when their central hydrogen abundance $X_{\rm c}$ is reduced by $\gtrsim$50%.

4.3. Masses of secondaries

Figure 6 compares the ranges of the masses of donors in observed SXTs corresponding to the ranges of the estimates of their spectral types with the masses of donors in the model. The spectrum-mass scale is adopted after Schmidt-Kaler, as given in Cox (2000).

The situation with M_2 is similar to that with $T_{\rm eff}$: our model population well covers the masses of the four shortest period systems, but to explain longer period ones we need to apply tracks for more evolved systems that we did not include in our grid of tracks. Adding some AML due to MB also would improve the agreement with observations. Figure 6, like Fig. 4, suggests that the origin of LMBHBs with orbital periods of 10–12 h may be associated with systems in which RLOF occurred when $X_{\rm c} \lesssim 0.35$.

5. Discussion and conclusion

We have shown above that assuming the product of the stellar-envelope binding-energy parameter and the common-envelope expulsion efficiency parameter $\alpha_{\rm CE} \times \lambda = 2$, it is possible to reproduce, (within the uncertainty of observations) the number of LMBHBs in the Galaxy, the effective temperatures and masses of the donors in these systems (as inferred from the spectra of the latter) and their mass-transfer rates. This result is maintained for $\alpha_{\rm CE} \times \lambda = 0.5$ but further reduction of $\alpha_{\rm CE} \times \lambda$ to 0.1 results in models whose parameters are not compatible with the currently available data on observed systems. Also we reiterate that (as found in Paper I) a substantial reduction of the strength of magnetic braking as compared to the "standard" (Verbunt & Zwaan 1981) makes all calculated systems transient, in agreement with observations.

The common envelope phase remains the most enigmatic phase of binary star evolution. As long as the processes of interaction of the companion star with the envelope it is penetrating is not understood, the use of simple conservation-law based equations will remain the necessary, albeit approximate, approach. However, the evolution of massive stars strongly depends also on stellar winds. The mass of the black-hole progenitor and the mass of its envelope, and the radius of the star that define the outcome of the common envelope stage, are interrelated via mass loss in the pre-common-envelope stage, which is not well constrained. The survival of a binary in a supernova explosion depends on the mass-loss in the Wolf-Rayet star phase, the possible kick imparted to the nascent black hole and the fraction of the mass of the exploding star that forms the black hole. None of these parameters are well constrained.

The situation concerning mass-loss by massive stars is controversial. It became a recognized fact that stellar winds of both O-stars and WR-stars are clumped (e.g., Owocki et al. 1988; Smith 2007; Moffat et al. 1988; Hamann & Koesterke 1998) and empirical estimates of mass-loss rates that depend quadratically on the density have to be revised downward by a factor of several. In particular, downward revision of empirical $\dot{M}$ values would bring them into agreement with modern theoretical (Vink et al. 2001) rates for OB-stars (Mokiem et al. 2007; Vink 2007; Vink et al. 2007). It is also claimed that the widely accepted Nugis & Lamers (2000) rates for WR-stars, which already are clumping-corrected, have to be revised further downward (Hamann et al. 2006). A decrease of $\dot{M}$ would mean more massive stellar envelopes and, generally, more energy would be needed for the ejection of common envelopes. This may be interpreted as a need for higher $\alpha_{\rm CE}$.

On the other hand, based on results of extensive analysis of the ratios of blue to red supergiants, of Wolf-Rayet stars to O supergiants, of red supergiants to Wolf-Rayet stars and of the relative number of Wolf-Rayet subtypes, WC to WN stars, Eldridge et al. (2008) suggested that the total amount of mass lost by stars has to be increased. In the latter study both single and binary evolutionary models were considered and the mass-loss rates of Vink et al. (2001) and Nugis & Lamers (2000) were used.

In such a controversial situation we may only claim, based on our results, that for the parameters of stellar evolution implemented in our evolutionary and population synthesis codes, which are consistent with state-of-the art stellar evolution theory, an agreement between the properties of the observed population of short-period LMBHBs and the model suggests a high efficiency of expulsion of common envelopes.

Above, we have shown that the number and properties of observed short-period LMBHB may be explained by the model that assumes a strongly reduced strength of magnetic braking. But we recall the existence of the alternative model of Menou et al. (1999) which suggests that most LMBHB might have truncated discs that are secularly in a cold and stable equilibrium with transiency due to random variability in the properties of discs and/or mass transfer rates. Within this model most of the systems we modeled and classified as transients may appear as faint and stable. At the moment there are no theoretical arguments against the Menou et al. model and observations that may serve as selection criterion between the two models still have not been defined. Thus, both models remain possible.

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