THE FORMATION, EVOLUTION AND PARAMETERS OF SHORT-PERIOD LOW-MASS X-RAY BINARIES WITH BLACK-HOLE COMPONENTS

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Abstract. We discuss the formation, evolution and observational parameters of the population of short-period ($\lesssim 10 \text{ hr}$) low-mass black-hole binaries (LMBHB). Their evolution is determined by the orbital angular momentum loss and/or nuclear evolution of the donors. All observed semidetached LMBHB are observed as soft X-ray transients (SXTs). The absence of observed short-period stable luminous X-ray sources with black holes and low-mass optical components suggests that upon RLOF by the donor, the angular-momentum losses are substantially reduced. The model with reduced angular-momentum loss reasonably well reproduces the masses and effective temperatures of the observed secondaries of SXTs. Theoretical mass-transfer rates in SXTs are consistent with those deduced from observations only if the accretion discs in LMBHB are truncated. The population of short-period LMBHB is formed mainly by systems which at RLOF had unevolved or slightly evolved donors (abundance of hydrogen in the center $X_c \gtrsim 0.35$). Our models suggest that a very high efficiency of common envelopes ejection is necessary to form LMBHB.

1. Introduction

Currently, ten Galactic dynamically-confirmed black-hole candidate X-ray binaries with K/M spectral type secondaries and orbital periods $\lesssim 1 \text{ day}$ have been observed (McClintock & Remillard 2006). All these objects are SXTs. Their X-ray luminosity may vary by 5–8 orders of magnitude between quiescence and the peak of the outburst. Recurrence times spread from a about a year to tens or years and could be even longer. Their variability is interpreted as resulting from a thermal-viscous instability of irradiated accretion discs around black holes in semidetached binaries (see Lasota 2001, and references therein). The estimated number of low-mass black-hole binaries (LMBHB) in the Galaxy ranges from several hundred to several thousand (Chen et al. 1997; Romani 1998). The list of short-period black-hole SXTs and some of their observed and inferred parameters are rendered in Table 1. Observational data presented in Table 1 is based on the survey of the literature (see Yungelson & Lasota 2008).

Below, we consider the formation, evolution and some observational properties of LMBHBs.
Table 1. Known short-period black-hole SXTs.

| No. | Name                  | $P_{\text{orb}}$, hr | Sp   | $\langle \dot{M}_{\text{recc}} \rangle$ M$_{\odot}$ yr$^{-1}$ | $\dot{M}_{\text{in}}$, M$_{\odot}$ yr$^{-1}$ |
|-----|-----------------------|----------------------|------|---------------------------------------------------------------|-----------------------------------------------|
| 1.  | XTE J1118+480 (KV UMa)| 4.10                 | K5-M1| 1.9 $\times$ 10$^{-12}$                                      | 3.0 $\times$ 10$^{-10}$                      |
| 2.  | GRO J0422+32 (V518 Per)| 5.09                 | M2-M4| 1.3 $\times$ 10$^{-11}$                                      | 1.9 $\times$ 10$^{-10}$                      |
| 3.  | GRS 1009-45 (MM Vel)  | 6.84                 | K7-M0.5| 4.4 $\times$ 10$^{-11}$                                      | 1.8 $\times$ 10$^{-10}$                      |
| 4.  | XTE J1650-500         | 7.68                 | K4   | 2.0 $\times$ 10$^{-11}$                                      | 2.8 $\times$ 10$^{-10}$                      |
| 5.  | A0620-00 (V616 Mon)   | 7.75                 | K3-K7| 3.3 $\times$ 10$^{-11}$                                      | 2.8 $\times$ 10$^{-10}$                      |
| 6.  | GS 2000+25 (QZ Vul)   | 8.28                 | K3-K6| 2.0 $\times$ 10$^{-10}$                                      | 5.5 $\times$ 10$^{-10}$                      |
| 7.  | XTE J1859+226 (V406 Vul)| 9.12                  | G5-K0| 4.1 $\times$ 10$^{-10}$                                      | 1.0 $\times$ 10$^{-9}$                       |
| 8.  | GRS 1124-68 (GU Mus)  | 10.39                | K3-K7| 3.4 $\times$ 10$^{-10}$                                      | 3.5 $\times$ 10$^{-10}$                      |
| 9.  | H 1705-25 (V2107 Oph) | 12.50                | K3-K7| 5.5 $\times$ 10$^{-11}$                                      | 4.1 $\times$ 10$^{-10}$                      |
| 10. | 4U 1543-47 (IL Lup)   | 27.0                 | A2   | 4.2 $\times$ 10$^{-10}$                                      | 1.3 $\times$ 10$^{-9}$                       |

Note: $\langle \dot{M}_{\text{recc}} \rangle$ – mass-transfer rate estimate based on recurrence times, $\dot{M}_{\text{in}}$ – upper limit to mass-transfer rate based on assumption of maximal truncation of accretion discs in SXTs.

2. The model

To obtain a model of the population of LMBHBs one needs to follow two steps: (i) the time-dependent formation of the population of detached “black-hole + main-sequence star” binaries and (ii) the subsequent evolution of every binary till the Hubble time.

The threshold for the masses of black-hole producing binary components is (20 – 25)M$_{\odot}$ (e.g., Ergma & van den Heuvel 1998). The masses of the secondaries in SXTs suggested by their spectral types are $\sim$1.5M$_{\odot}$. Therefore the sequence of transformations of a binary which results in the formation of a LMBHB may be the following:

(a) the primary component evolves off main-sequence and becomes a supergiant,
(b) the supergiant overflows Roche lobe and forms a common envelope, since mass ratio of components $q \gg 1$; if the components do not merge, the primary becomes a Wolf-Rayet (WR) star,
(c) the WR star explodes as a supernova and forms a black hole.

If the binary is not disrupted by the supernova explosion, a system with a black hole accompanied by a low-mass main-sequence star, i. e., a LMBHB, is formed. If the separation of components is sufficiently small ($\lesssim$10R$_{\odot}$), the orbital angular momentum loss (AML) via magnetic braking (MB) and/or gravitational wave radiation (GWR) may bring secondary component of the system to the Roche-lobe overflow (RLOF).

The range of post-common-envelope binary separations which allow the formation of semidetached LMBHBs is very narrow. Hence the probability of formation of a SXT depends very strongly on the physical processes that determine the semi-major axis of the binary, i.e. the stellar winds at all stages of evolution and, especially, the efficiency of ejection of the common envelope. For the latter, the ratio of final $a_f$ to initial $a_i$ separations of components is equal.
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where $\alpha_{ce}$ is the common envelope ejection efficiency, $\lambda$ – the parameter of the binding energy of the stellar envelope, $M_1$ and $M_{1,c}$ are the initial mass of the 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. If $M_1 \gg M_2$, then, crudely, $a_f/a_i \propto \alpha_{ce}\lambda$. Both terms in the latter expression are highly uncertain (see discussion in Podsiadlowski et al. 2003; Kiel & Hurley 2006; Yungelson & Lasota 2008). Indirect estimates involving formation scenarios for binaries with neutron-star or black-hole components suggest $\alpha_{ce}\lambda \lesssim 2$. This might mean that sources other than the orbital energy are involved in the ejection of the common envelope, though, the nature of these sources is still not fully understood. In practice, $\alpha_{ce}\lambda$ remains a parameter, tuning of which allows reproducing the properties of specific systems or stellar populations.

In the second step of modeling, the evolution of every system is followed taking into account the AML via gravitational wave radiation and/or magnetic stellar wind (MSW) and, if necessary, nuclear evolution of the main-sequence star.

3. The galactic population of LMBHBs

In Yungelson et al. (2006) and Yungelson & Lasota (2008) was carried out the population synthesis for galactic LMBHBs for three values of $\alpha_{ce}\lambda$: 0.1, 0.5 and 2. We refer the reader to these papers for the details of the computations. Two main conclusions were drawn from the models computed in these studies.

First, the model for $\alpha_{ce}\lambda = 0.1$ is not compatible with observations of SXTs since in this case the overwhelming majority of black holes has masses $\gtrsim 14 M_\odot$, exceeding the largest estimated black hole mass in known SXTs ($9.7 \pm 0.6$ for A0620-500, see Froning et al. 2007).

Second, if the AML via MB for LMBHBs is treated in a “standard” way, assuming after Verbunt & Zwaan (1981) that for components of close binaries the braking law for single field stars (Skumanich 1972) can be extrapolated over the range of rotational velocities from several 10 to several 100 km/s and that the spin-orbit coupling is efficient, model mass-transfer rates for LMBHBs at $P_{\text{orb}} \gtrsim 2$ hr are so high that these systems might have stable hot discs according to the disc instability model (DIM) criterion of Dubus et al. (1999). But such stable and bright LMBHBs have not been observed.

A strong reduction of the magnetic braking efficiency in close binaries as compared to single stars is suggested also by the data on stellar rotation in young open clusters (Collier Cameron 2002; Andronov et al. 2003) and the mass transfer rates in cataclysmic variables (e.g., Hameury et al. 1988; Ivanova & Taam 2003). In Yungelson et al. (2006) and Yungelson & Lasota (2008) we computed a population model of LMBHBs assuming that MB stops operating once the RLOF occurs (“no-MB” model). We found that the number of galactic LMBHBs remains of the same order of magnitude as in the case with active MB (several 1000) but all systems are transient.
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Figure 1. Left panel: Model population (dots) vs. observational estimates of the ranges of effective temperatures of donors in SXTs inferred from their spectral types (vertical lines). The latter are annotated according to their number in Table 1. Large filled circles give $T_{\text{eff}}$ of donors derived from the fits to synthetic spectra. Heavy solid lines to the left and right, respectively, show the approximate limits of the region which may be occupied by LMB-HBs, while thin solid lines show tracks for the donors in $(1.1 + 4)M_\odot$ systems which have at RLOF $X_c = 0.45$ and 0.37, respectively (see the text for discussion). The $Sp - T_{\text{eff}}$ relation used in the paper is shown at the right border of the coordinate box. Right panel: Masses of donor-stars in modeled population. Vertical lines show the ranges of $M_2$ inferred from their spectral types (annotation like in the left panel). Heavy and thin solid lines – the same tracks as in the left panel.

In Yungelson et al. (2006) and Yungelson & Lasota (2008) we compared the $\alpha_{\text{ce}}\lambda = 2$ “no-MB” model with observations. Below, we present the model for $\alpha_{\text{ce}}\lambda = 0.5$. In this case, the number of LMBHBs that reach contact in Hubble time and evolve to $P_{\text{orb}} \lesssim 10 \, \text{hr}$ is $\approx 6000$ and $\approx 3000$ of them have currently $P_{\text{orb}} \gtrsim 1.5 \, \text{hr}$\footnote{Systems with shorter $P_{\text{orb}}$ have $q \gtrsim 0.02$ and the character of mass exchange in them is unclear because of the effect of resonances, see Yungelson et al. (2006) for details.}. For comparison, in the model for $\alpha_{\text{ce}}\lambda = 2$ these numbers are about $12000$ and $5000$, respectively.

3.1. Effective temperatures and masses of secondaries in LMBHBs

When spectral types of the secondaries in observed SXTs are known, one can evaluate their effective temperatures and masses and to compare them with model predictions. Inevitably, such a comparison may be only crude, since the spectra of the secondaries are contaminated by the radiation of accretion disks and hot spots and we have at our disposal $Sp - T_{\text{eff}}$ and $Sp - T_{\text{eff}}$ relations for main-sequence stars only (relations from Cox 2000, were used). In the left panel of Fig. 1 we plot the effective temperatures of donor-stars in modeled systems as a function of orbital period and compare them with the ranges of $T_{\text{eff}}$ inferred
from the spectral types of donors in SXTs. Having in mind uncertainties in the spectral type determinations and $Sp - T_{\text{eff}}$ scale, we find that the model satisfactorily reproduces $T_{\text{eff}}$ of the donors in the LMBHBs with $P_{\text{orb}} \lesssim 9$ hr.

In our models the efficiency of magnetic braking is 0. In reality some MB might be acting as, probably, in the case of cataclysmic variables (see, for instance, [Ivanova & Taam 2003, but also 3.2 below). We show in Fig. 1 two “limiting” tracks: for the system with initial masses of components 1 and 12 $M_\odot$ and post-circularization period $P_{\text{orb},0} = 0.4$ day in which the donor is almost unevolved at RLOF and MB does not act after RLOF and for a $(1+4) M_\odot$, $P_{\text{orb},0} = 1.9$ day system in which at RLOF donor has hydrogen abundance in the center $X_c \approx 10^{-4}$ and the MB continues to operate during mass-transfer with an efficiency corresponding to [Verbunt & Zwaan (1981) law. Crudely, if the efficiency of MB is not 0, the model population must be located between these two limiting curves. Of course there will be a contribution from lower and higher mass systems, as we plotted the $1 M_\odot$ tracks for simplicity only. Adding some MB to our model will shift the population to the right, providing a better agreement with observations. Adding moderate MB will influence mainly the long-period systems, without producing stable systems.

A similar satisfactory agreement of model populations with observations is found for the masses of secondaries of SXTs (Fig. 1 right panel).

We note that, since for large initial $q$ the transformation of separation of components in common envelopes depends linearly on $\alpha_{cc} \lambda$, the distributions of model populations in $P - T_{\text{eff}}$ and $P - M_2$ plots are similar for $\alpha_{cc} \lambda = 0.5$ and 2, and only differ by the density of points per unit area of the diagrams.

There are SXTs with $P_{\text{orb}} \approx (8-12)$ hr – GRS 1009-45, XTE 1650-500, A0620-00, and GS 2000+25, which, apparently, are located below the “populated” area in Fig. 1. However, we should note that in our modeling we tried to avoid the effect of bifurcation of evolutionary tracks – evolution of systems to shorter or longer periods upon RLOF, depending on the extent of hydrogen depletion in the cores of the models. For this reason we restricted ourselves to systems evolving to shorter $P_{\text{orb}}$ only. However, our computations show that, if GWR is the sole sink of angular momentum, binaries with $M_1 \approx (4-12) M_\odot$ and $M_2 \lesssim 1 M_\odot$ evolve to longer periods if at the instant of RLOF their secondaries have $X_c \lesssim 0.4$. This is illustrated in Fig. 1 by evolutionary tracks for initially $(1.1+4) M_\odot$ systems in which secondaries have, respectively, $X_c \approx 0.45$ and 0.37 at the RLOF. The latter binary spends several Gyr evolving to longer periods. Initial (post-circularization of the binary after supernova explosion) orbital periods of these two binaries $P_0$ differ by 0.1 day only. Since the distribution of the binaries over $P_0$ is continuous, this proximity of initial parameters of the binaries and striking difference in their evolutionary behavior suggests a possibility of explaining the origin and parameters of SXTs with $P_{\text{orb}} \approx (8-12)$ hr. This conjecture has yet to be confirmed by detailed modeling.

### 3.2. Mass-transfer rates in LMBHBs

An estimate of mass-transfer rate in an SXTs may be obtained by dividing the mass accreted during outburst by the recurrence time. However, (i) recurrence times are known for A0620-00 (about 60 yr) and 4U 1543-47 (about 10 yr) only; (ii) it is not evident that the rate calculated this way represents the secular
value, and (iii) this method of estimate assumes that between outbursts, when accretion disc is “refilled”, accretion onto black hole does not occur. The 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 in SXTs are truncated and therefore leaky. In the latter case, mass-transfer rate cannot be larger than the critical-for-stability accretion rate at the truncation radius (see Yungelson et al. 2006, for details). The actual mass-transfer rate should be between the values estimated by the two methods.

Using the expression for the critical accretion rate Lasota et al. (2008):

$$\dot{M}_{\text{crit}} = 2.64 \cdot 10^{15} \alpha_{0.1}^{0.01} R_{10}^{2.58} M_1^{-0.85},$$

(2)

where $\alpha$ is viscosity parameter and $R_{10}$ is disc radius in units of $10^{10}$ cm, we obtain for the upper limit of mass-transfer rate

$$\dot{M}_{\text{max}} \lesssim 2.5 \cdot 10^{-7} \left[ (1 + q)^{1/3} (0.5 - 0.227 \log q) \right]^{10.32} P_d^{1.72} f_t^{2.58} M_\odot \text{ yr}^{-1},$$

(3)

where $P_d$ – orbital period in days, $f_t \lesssim 0.48$ – fractional disc truncation radius.

In Fig. 2 we compare the model mass-transfer rates with the estimates obtained by the two above mentioned methods. The “leaky disc” estimates of $\dot{M}_{\text{max}}$ for XTE J1118+480, GRO J0422+32, and GRS 1009-45 strongly suggest that the AML in short-period LMBHBs might be really defined by GWR only.

4. Conclusion

We calculated models of the Galactic population of short-period low-mass black-hole binaries which are identified with soft X-ray transients. We found that
using the values of the common-envelope parameter $\alpha_{ce}\lambda$ between $\approx (0.5 - 2)$ and assuming a strongly reduced magnetic braking it is possible to reproduce, (within the uncertainty of observations) the number of the LMBHBs in the Galaxy and the effective temperatures and masses of the donors in these systems (as inferred from the spectra of the stars). The above mentioned values of $\alpha_{ce}\lambda$ imply that the common-envelope expulsion in the progenitors of SXTs has to be very efficient and that sources other than orbital energy may be required in this process.

In our model, all short-period LMBHB systems are transient in agreement with observations.

Model mass-transfer rates in LMBHBs are consistent with the upper limits derived from observations under assumption that accretion discs in SXTs are leaky.

**Acknowledgments.** We thank G. Nelemans for providing models of zero-age populations of LMBHBs and G. Dubus for the analysis of stability of accretion disks. Both of them are acknowledged for numerous discussions. LRY acknowledges organizers of the conference for financial support. This study was supported by RFBR grant 07-02-00454 and Russian Academy of Sciences Basic Research Program “Origin and Evolution of Stars and Galaxies”.

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