

# Evolution of black hole low-mass binaries

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**Abstract.** Several evolutionary sequences with low mass secondaries as donors and black holes as accretors are calculated. Adopting a simple estimate for the efficiency of magnetic braking we have determined the bifurcation period  $P_{bif}$ , separating converging from diverging binary systems, to be  $\sim 1$  day. It is shown that in converging binary systems, similar to neutron star binaries with low-mass secondaries, evolution proceeds towards very short orbital periods with continuous accretion or it ends by formation of system with a low mass helium white dwarf and a black hole. If the final orbital period of the latter system is less than 10 hours, it is possible that the system will reappear as a persistent X-ray source with ultra-short orbital period. For systems which evolve towards very short orbital periods there always is a phase in which the mass accretion rate exceeds a certain  $\dot{M}_{crit}^{irr}$  above which the system is a persistent X-ray source. By comparing evolutionary sequences for different black hole masses it is shown that for a more massive black hole as accretor the range in which mass transfer is unstable is larger than for a less massive black hole.

It is shown that after the common envelope (CE) phase, during the extensive high-velocity wind stage (before the collapse to a black hole) only helium stars of rather low mass end up with orbital periods lower than  $P_{bif}$  which enables them to evolve towards the short orbital period range where the majority of the low-mass X-ray binaries (LMXB) with black holes as accretors are observed. This implies that the pre-CE progenitors of black holes in these systems had masses  $\leq 25 M_{\odot}$ .

**Key words:** stars: evolution – black hole physics – X-rays: stars

## 1. Introduction

During recent years about half a dozen of black hole candidates (BHC) with low mass companion stars have been identified as the so-called X-ray transients. From the mass function the minimum mass of unseen companion exceeds the canonical neutron star maximum mass value of  $3 M_{\odot}$ . The total number in the Galaxy of such systems is estimated to be between a few hundred and a few thousand and at any moment only a small fraction

is X-ray active ( see reviews, Tanaka & Lewin, 1995, Tanaka & Shibazaki, 1996).

The origin of low-mass X-ray binaries (LMXBs) is not very clear. The most popular scenario proposes as starting point a relatively wide binary system with extreme mass ratio (van den Heuvel 1983). After filling its Roche lobe, the massive primary engulfs its low-mass companion. The low-mass companion will spiral-in in the massive star's envelope. In a finely tuned spiral-in scenario (van den Heuvel & Habets, 1984, De Kool et al. 1987, Portegies Zwart et al. 1997) if the spiral-in ceases before the low-mass secondary coalesces with the helium core of the primary a close binary forms. In this it is assumed that stars exceeding  $50 M_{\odot}$  evolve into black holes. Recent population synthesis calculations by Portegies Zwart et al. (1997) concerning the formation rates of low-mass X-ray binaries with black holes shows that with such a mass limit the standard scenario predicts formation rates of black-hole LMXBs two orders of magnitudes lower what is derived from observations. They show that in order to obtain agreement between theoretical predictions and with observations all stars with a mass in exceeding of  $20 M_{\odot}$  must finish their evolution as a black hole, or that stellar winds from the binary components cause much larger loss of angular momentum than assumed. The first possibility raises the question how the neutron star in the massive X-ray binary 4U 1223-62 (Wray 977) originated? It is shown that the initial mass of the progenitor of the neutron star in this system was exceeding  $50 M_{\odot}$  (Kaper et al. 1995).

To resolve both problems, Ergma & van den Heuvel (1998) have suggested that in a certain mass range, probably between  $20 M_{\odot}$  and  $50 M_{\odot}$ , the outcome of the collapse is either a neutron star or a black hole depending not on the initial main-sequence mass value (as has been assumed before) but depending on the magnetic field strength and rotation rate of the collapsing core.

Eggleton & Verbunt (1986) have involved triple system to produce low-mass X-ray binary (with a neutron star or a black hole as the compact object). Van den Heuvel (1994) showed, however, that although this model may produce LMXBs with neutron stars, it is unlikely to explain LMXBs with black holes, as the formation of a Thorne-Zytkow star with a black hole in its center is highly unlikely to occur. Because of the latter argument, the scenario proposed by Podsiadlowski et al (1995) for LMXBs with black holes is also unlikely to occur.

In the past, not much attention has been paid to the evolution of low-mass binary system with massive accretors (black holes). Pylyser & Savonije (1988) have calculated nine evolutionary sequences for combinations ( $M_d/M_\odot$ ,  $M_{BH}/M_\odot$ ) (1,4), (1.5,4) and (1.5,12) to explain the evolutionary stage of A0620-00 ( $M_d$  and  $M_{BH}$  are the secondary and black hole masses respectively). King et al. (1996) computed two evolutionary sequences for a binary with a black hole as accretor.

We describe the evolution of eleven systems with different donor and black hole masses. Particular emphasis is given to exploring the evolution of systems in which the secondary fills its Roche lobe near the so-called bifurcation period  $P_{bif}$  (sf. Pylyser&Savonije, 1988). Especially if the period while the secondary fills the Roche lobe is smaller than  $P_{bif}$  the system appears to reach very short orbital periods, and provide important information on the initial mass range of progenitors of black holes.

## 2. Assumptions

For evolutionary calculations we used a modified version of Paczynski's evolutionary code (Fedorova & Ergma 1989). Our code contains the mass transfer description by Kolb&Ritter (1990). For  $R_d \leq R_{RL}$  (optically thin mass transfer) formulae A1-A9 from this paper and for  $R_d \geq R_{RL}$  (optically thick mass transfer) formulae A10-A18 have been used accordingly ( $R_d$  and  $R_{RL}$  are the secondary and Roche lobe radii respectively). In model calculations the mass accretion rate was iterated and for each iteration the stellar envelope has been recalculated. We assume the mixing length equal to 1.8 of pressure scale heights and the initial abundances  $X=0.7$  and  $Z=0.02$ . The heating of the secondary by X-ray radiation from the accretion disk is not included. We assumed the so-called "conservative evolution" i.e. no matter is lost from the system. We have used the dwarf nova instability criterion adapted to account for X-ray heating of the disk to understand the distribution of soft X-ray transients (with a black hole as the accretor) in the ( $P_{orb} - M$ ) diagram (Van Paradijs, 1996). Recently, King et al (1997) have realized that heating by irradiation is much weaker if the accreting object is a black hole rather than a neutron star, since the black hole has no hard surface and cannot act as a point source for irradiation. For black hole binaries King et al (1997) have obtained the following formula for the critical accretion rate:

$$\dot{M}_{crit}^{irr} \approx 2.86 \times 10^{-11} M_{BH}^{5/6} M_d^{-1/6} \left( \frac{P_{orb}}{hrs} \right)^{4/3} [M_\odot / yr] \quad (1)$$

where  $M_{BH}$  and  $M_d$  are masses of the black hole and the secondary in solar units. For  $M < \dot{M}_{crit}^{irr}$  mass-transfer is unstable and the source will show transient outbursts.

### 2.1. Orbital evolution

We assume that the evolution of binaries is determined by three factors:

1. The rate of decrease of the orbital separation  $A$  due to gravitational wave radiation losses (Landau&Lifshitz, 1962)

$$\frac{dA}{dt} = -1.65 \times 10^{-9} \frac{M_d M_{BH} (M_d + M_{BH})}{A^3} \quad (2)$$

(the mass and  $A$  are in solar units and time in yr)

2. Mass transfer between the components after the secondary fills its Roche lobe (with  $\dot{M}_d < 0$ )

$$\frac{dA}{dt} = 2 \times A \frac{M_d - M_{BH}}{M_d M_{BH}} \dot{M}_d \quad (3)$$

3. By magnetic braking due to the tidal coupling of the donor star to the orbital period based on Skumanich law (Skumanich, 1972)  $v = 10^{14} \lambda t^{-1/2}$ , where  $\lambda \approx 0.7 - 1.8$  (from observation)

$$\left( \frac{d \ln J}{dt} \right)_{MB} = -5 \times 10^{-29} k^2 \left( \frac{2\pi}{P_{orb}} \right)^{10/3} \frac{(M_{BH} + M_d)^{1/3} R_d^4}{G^{2/3} M_{BH} \lambda^2} \quad (4)$$

$$\left( \frac{dA}{dt} \right) = -6.06 \times 10^{-7} \left( \frac{M_{BH} + M_d}{M_{BH}} \right)^2 \left( \frac{R_d}{A} \right)^4 \quad (5)$$

$k$  is the gyroradius of the secondary (Verbunt&Zwaan, 1981). We considered black holes with masses 4 or 12  $M_\odot$  since, it is evident from Tab.1 that the majority of measured black hole masses fall in this range.

It was also assumed that the spin angular momenta of both components could be neglected and that tidal interaction in the binary was sufficiently effective to keep the (magnetically braked) rotation of the donor star synchronous with the orbit. Tidal mass transfer was started when the radius of the secondary became larger than the critical Roche-lobe radius given by Paczynski (1971) as

$$R_{RL} = 0.46224 \times \left( \frac{M_d}{M_{BH} + M_d} \right)^{1/3} \quad (6)$$

To describe the binary evolution it is informative to introduce several timescales: thermal readjustment time of the secondary is

$$\tau_{K-H} = \frac{GM_d^2}{R_d L_d} \quad (7)$$

The timescale for angular momentum loss due to magnetic braking of the donor star is

$$\tau_{MB} = - \left( \frac{d \ln J}{dt} \right)_{MB}^{-1} \quad (8)$$

The timescale of the tidal mass loss from the donor star is

$$\tau_{ML} = - \frac{M_d}{\dot{M}_d} \quad (9)$$

For our evolutionary picture, magnetic braking is the most efficient mechanism to remove angular momentum. Gravitational

**Table 1.** Observational data for BHC low-mass X-ray binaries

Source	Mass function	$\frac{P_{orb}}{hrs}$	$M_{BH}/M_{\odot}$	$M_s/M_{\odot}$	References
Nova Muscae 1991	$3.1 \pm 0.4$	10.4	$>4.45 \pm .46$	0.7	RMB
A0620-003	$3.18 \pm .16$	7.75	3.3-4.24	.15-.38	MRW
GS2000+25 (QZ Vul)	$4.97 \pm .1$	8.3	6.04-13.9	.26-.59	HHF
GS2023+338 (V404Cyg)	$6.3 \pm .3$	155.3	12	0.6	SRZ
Nova Oph 1977	$4.0 \pm .8$	16.8	$6 \pm 1$	0.7	ROM
GRO J0422+32	$1.21 \pm .06$	5.08	$3.57 \pm .34$	$.39 \pm .02$	FMH
GRO J1655-40	$3.24 \pm .09$	62.4	$7.02 \pm .22$	$2.34 \pm .12$	OB
GRS1009-45(Nova Vela 1993)		6.86			SHC
GX339-4		14.8			TL
1755-338		4.4			TL
1957+115		9.3			TL

wave radiation turns out to be ineffective if the orbital period exceeds 12 hours.

In Table 1 we have also presented data for four suspected black hole systems with known orbital periods. The characteristics used (without mass determination of the compact object) in evaluating the possibility that binary contains a black hole are: 1) ultrasoft spectra, 2) high-energy power-law tail  $> 20$  keV, 3) two spectral states, 4) millisecond variability in the hard state (Tanaka & Lewin, 1995).

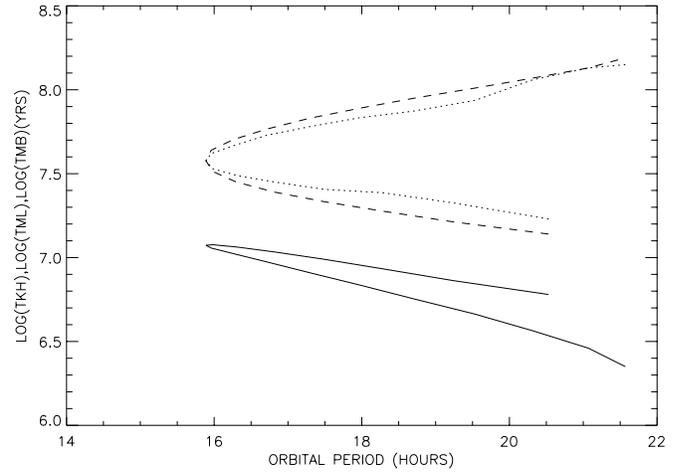
### 3. Results

Results of our calculations are presented in Table 2 and are shown in Figs 1-6.

It is known from the results of numerical calculations that simulate the evolution of low mass close binary systems, in which a low mass ( $< 2.0 M_{\odot}$ ) star transfers mass to a compact object that for slightly evolved secondaries a certain critical bifurcation orbital period  $P_{bif}$  exists (Pylyser & Savonije, 1988). If at RLOF (RLOF - stage of the Roche lobe overflow)  $P_i > P_{bif}$  where  $P_i$  is the initial orbital period of the binary at the instant of RLOF the binary evolves with increasing orbital period until the mass losing star has lost its envelope and a wide detached binary is formed. In the opposite case, if  $P_i < P_{bif}$  the binary evolves with decreasing orbital period until the mass-losing component becomes degenerate and an ultra-compact binary is formed (Tutukov et al., 1985)

In systems where RLOF occurs very close to the bifurcation period that in our investigation is one day, the mass transfer timescale  $\tau_{ML}$  is very close to  $\tau_{MB}$  (Fig. 1). This explains why the orbital period is almost not changing during the evolution of these systems (Fig. 2). This value of the bifurcation period for LMXB with a black holes as accretor is very important in connection with the formation mechanism of black holes in low-mass X-ray binaries (Ergma & van den Heuvel 1998 ; see Discussion).

In Fig. 2 the mass accretion rate versus orbital period or evolutionary time for three evolutionary models 1,4,6 is shown. Here model 1 represents the so called converging evolutionary sequence, model 4 represents the case when RLOF occurs very



**Fig. 1.** Evolution of timescales  $\tau_{K-H}$  (full curve),  $\tau_{MB}$  (dashed curve) and  $\tau_{ML}$  (dotted curve) as a function of orbital period for model (4)

close to the bifurcation period and model 6 is typical diverging evolutionary sequence.

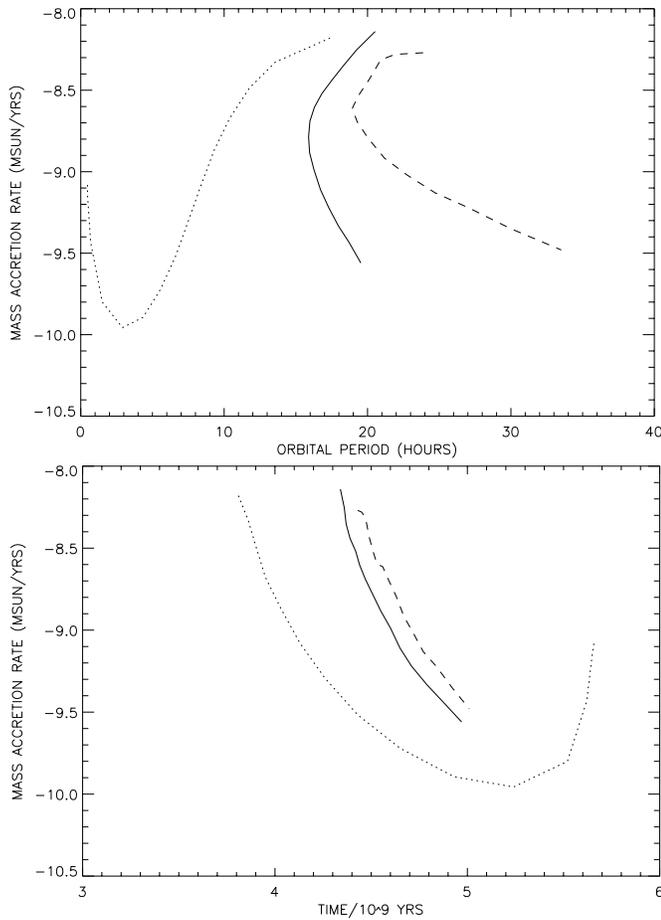
Five of our systems evolve to very short orbital periods. After reaching a minimum orbital period, due to the change of the mass-radius relation of the secondary ( from Main Sequence to a degenerate ) the sign of the orbital period variation changes. In these cases the evolution of the orbital separation is increasing and mass loss rate is decreasing. In Fig. 3 we present the mass accretion rate versus orbital period for two evolutionary models 1 and 9. In both cases RLOF starts at same evolutionary stage of the donor but the mass of the black hole differs. From Fig. 3 it is clearly seen that in the system with higher black hole mass conditions for a disk instability are more favorable (e.g.  $\dot{M} < \dot{M}_{crit}^{irr}$ ). This can be explained by two reasons: 1) a larger  $M_{BH}$  increases the orbital angular momentum of the binary and reduces the mass transfer rate as,  $\propto M_{BH}^{-2/3}$  (King, 1988).

2) On the other hand, the critical mass accretion rate increases as  $\propto M_{BH}^{5/6}$  [Eq. (4)]. Both effects lead to more favorable conditions for the occurrence of disk instability in binaries with a more massive black hole and soft X-ray transient event.

**Table 2.** Parameters of the calculated models

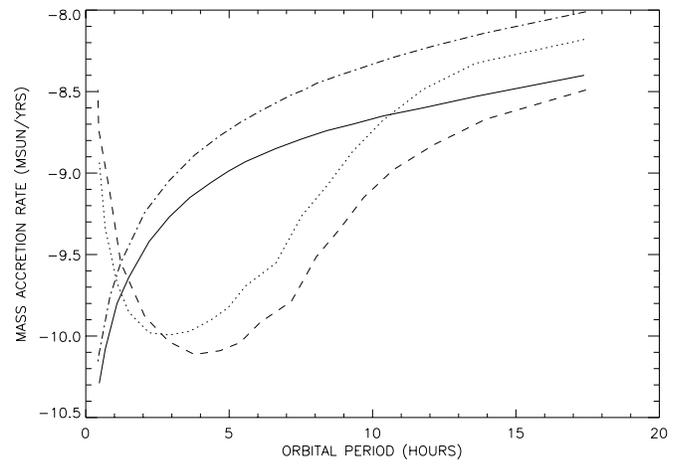
Model	$M_{BH}/M_{\odot}$	$M_d/M_{\odot}$	$t_i/10^9 yrs$	$X_{c,i}, M_{He,i}/M_d$	$P_i$	$P_{min}$	$P_f$	$M_{He,f}/M_d$	$M_f/M_{\odot}$	$t_f/10^9 yrs$
1	4	1.25	3.806	$6.42 \times 10^{-5*}$	17.75	0.469	$0.469^a$	0.025	0.05	5.65
2	4	1.25	4.117	0.007	19.95	0.289	$0.289^a$	0.87	0.08	6.13
3	4	1.25	4.319	0.026	22.18	0.137	$0.137^a$	0.97	0.13	6.97
4	4	1.25	4.323	0.026	22.24	15.57	15.57	0.97	0.18	6.06
5	4	1.25	4.328	0.026	22.31	7.92	7.92	0.97	0.17	6.49
6	4	1.25	4.432	0.033	23.90	18.94	46.96	0.93	0.20	6.22
7	4	1.25	4.569	0.049	27.11	3.93	151.36	0.97	0.24	5.58
8	4	1	10.14	0.042	19.22	11.75	11.75	0.97	0.17	12.02
9	12	1.25	3.806	$6.42 \times 10^{-5*}$	17.68	0.42	$0.42^a$	0.97	0.06	6.60
10	12	1.25	4.117	0.007	19.87	0.15	$0.15^a$	0.97	0.13	8.17
11	12	1.25	4.323	0.026	22.15	18.41	84.2	0.97	0.22	6.17

In Table 2  $t_i$  is the initial age at (RLOF),  $X_{c,i}$  is the initial core hydrogen abundance,  $M_{He,i(f)}$  is the mass of initial or final helium core,  $P_{i,min,f}$  is the initial, minimal or final period of the system (hours),  $t_f$  is the final age at the beginning of detachment or at the end of the calculations if mass transfer is not finished.  $M_f$  is the final mass of the donor. <sup>a</sup> Mass transfer is not finished at the end of computations.



**Fig. 2.** Evolution of mass accretion rate as a function of the orbital period (upper figure) and the time (lower figure) for models: dotted curve - model 1; full curve -model 4; dashed curve -model 6

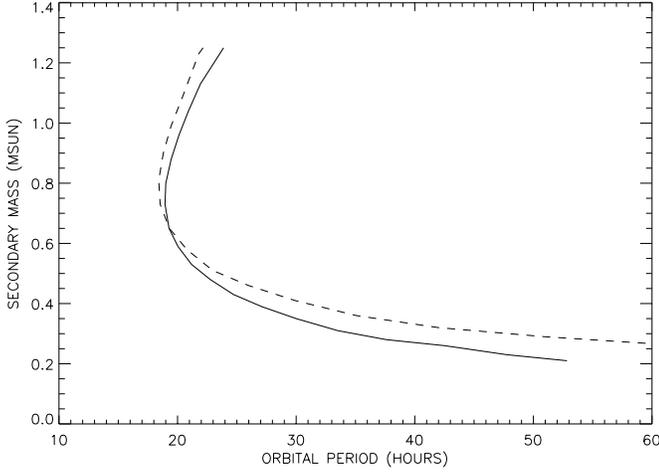
For all calculated sequences (1-3,9,10) for which the orbital evolution is towards very short orbital periods a persistent X-ray source phase with short orbital periods ( $P_{orb} < 2$  hours) must



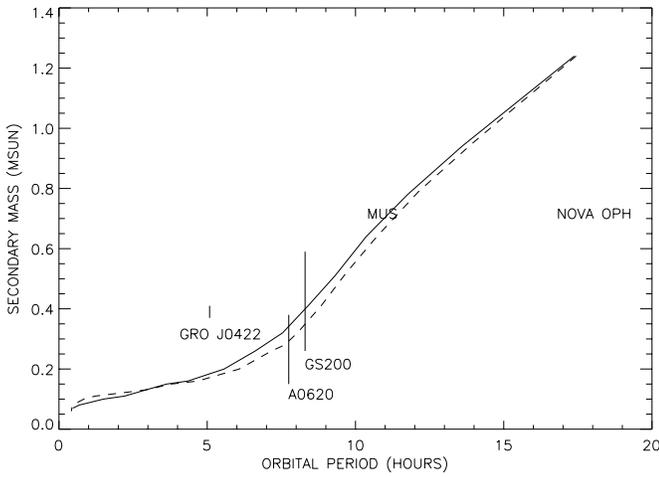
**Fig. 3.** Mass accretion rate vs. orbital period for two evolutionary sequences: dotted curve - model 1; dashed curve - model 9 The critical mass accretion rate computed from Eq. (1) is shown for  $M_{BH}=4$  (full curve) and  $12 M_{\odot}$  (dash-dotted curve)

exist since  $\dot{M} > \dot{M}_{crit}^{irr}$  (independent of the black hole mass). According to the results of our computations if at RLOF the helium core mass of the secondary is less than  $\sim 9 \times 10^{-3}$  and with a low mass black holes ( $4 M_{\odot}$ ) as accretor for longer orbital periods ( $P_{orb} > 10$  hours) there is a phase with the accretion rate higher than  $\dot{M}_{crit}^{irr}$ . This indicates that here also a persistent X-ray source may be observed. Currently one persistent low mass X-ray binary, namely GX339-4 (Fender et al 1997), is suspected to have a black hole. We have found that our model 1 may explain persistent X-ray radiation in GX 339-4 since for  $P_{orb} > 10$  hours  $\dot{M} > \dot{M}_{crit}^{irr}$  (Fig. 3)

In Fig 4,5 we have shown the secondary mass versus orbital period for sequences 6,11 and 1,9 respectively. From Fig 5. we see that the information concerning observed secondary masses (Table 1) may help to choose the possible evolutionary history for the observed system. Computed evolutionary sequences 1,9 for example well reproduce the orbital period, secondary masses



**Fig. 4.** Evolution of the mass of the secondary as a function of orbital period for diverging sequences: full curve - 6, dashed curve - model 11



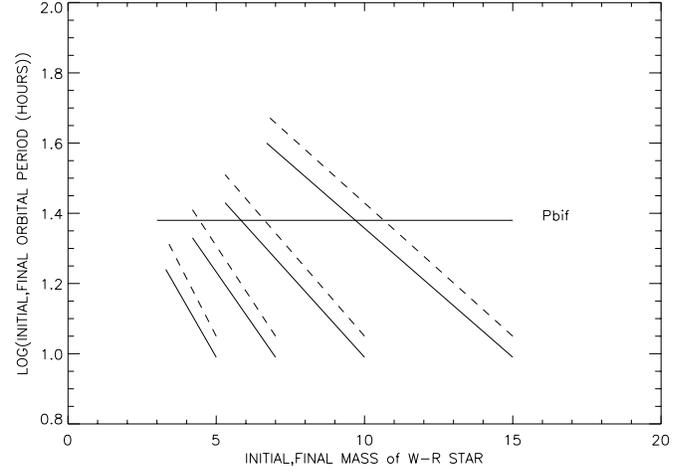
**Fig. 5.** Evolution of the mass of the secondary as a function of orbital period for model 1 (full curve) and model 9 (dashed curve) The observed secondary masses (Table 1) are also shown

and the accretion rate for Nova Muscae 1991, A0620-003 and GS2000+25. But agreement with observed and calculated secondary mass values for Nova Oph system is poor (see Fig 5).

#### 4. Discussion

For the study of the origin of these systems knowledge of the bifurcation period value found here is important for the following reasons. The progenitors of black holes in these systems (after the common envelope phase) were Wolf-Rayet stars with very strong stellar winds (see, Portegies Zwart et al.1997, Ergma&van den Heuvel, 1998). If mass leaves the system by an isotropic, high - velocity wind, carrying the specific angular momentum of the primary, then the orbital separation will increase as

$$\frac{\dot{A}}{A} = \frac{\dot{M}_{WR}}{M_{WR}} \left[ \frac{2M_2 + M_{WR}}{M_{WR} + M_2} - 2 \right] \quad (10)$$



**Fig. 6.** Evolution of orbital periods in the WR wind loss phase. Full curves (systems with  $M_2=1.5 M_\odot$ , dashed curves (systems with  $M_2=1.25 M_\odot$ ). Systems with final orbital periods above  $P_{bif}$  can never evolve into short period binaries with a black hole (LMXBs)

where  $\dot{M}_{WR}$ ,  $M_{WR}$  and  $M_2$  are the mass loss rate of the Wolf-Rayet stars, the mass of the Wolf-Rayet star and the mass of the secondary respectively. During the helium burning stage we have integrated this semi-major axis variation using mass loss rates of Wolf-Rayet stars given by Langer (1989);

$$\dot{M}_{WR} = 6 \times 10^{-8} (M_{WR}/M_\odot)^{2.5} M_\odot/\text{yr}$$

and assuming helium burning time in the core of a WR star, for which the fit to the Iben&Tutukov (1985) data gives:

$$\log t_{He} \approx 7.15 - 3.7y + 2.23y^{1.37} \text{yr}, \quad (11)$$

where  $y = \log(M_{WR}/M_\odot)$ . The computations have been done for  $M_{WR}=5, 7, 10, 15 M_\odot$  (20, 25, 32, 41  $M_\odot$  ZAMS progenitors, respectively) and  $M_2=1.25$  and  $1.5 M_\odot$ . We started from minimum values of the orbital period equal to those when the secondary filled its Roche lobe (immediately after the common-envelope phase). Results of the integrations are given in Fig. 6 showing that, only for low mass Wolf- Rayet stars ( $<7 M_\odot$ ) after the wind mass-loss phase the orbital separation is favorable for future orbital evolution towards shorter orbital periods ( e.g.  $P_i < P_{bif}$ ). Thus, to explain the short orbital periods of the LMXB with black hole accretors, one needs to produce black holes from stars that are much less massive than was assumed previously. The same argument excludes formation of short-period low-mass black hole systems with unevolved main-sequence companions as suggested by King et al. (1997), since after the wind phase the orbital periods of all systems are longer than 10 hours ( see Fig. 6), and only after a long evolution (billions of years) with magnetic braking, periods of about 8 hrs can be reached.

The results obtained by Pylyser&Savonije (1988) in computing the evolution of systems with massive accretors show absence of converging systems with  $M_{BH}=4 M_\odot$  for initial donor masses  $\geq 1.7 M_\odot$ . They note that for any given initial accretor mass a maximum initial donor mass can be found for

which no convergent systems can be formed. This conclusion is very important for restriction of the initial donor mass since the majority of the soft X-ray transients have short orbital periods ( $< \text{one day}$ ) e.g. they must be converging systems. For several evolutionary sequences (4-8, 11) the accretion phase ends with the formation of a low mass helium white dwarf with a black hole companion. Except for sequence (5) in all other cases the orbital separation is so large that these systems will never contact. Only for sequence (5) the orbital period is so short that after  $\sim 4 \times 10^9$  years the low-mass helium white dwarf could fill its Roche lobe at  $P_{orb} \sim 5$  min and a new very bright persistent X-ray phase will follow with decreasing mass transfer rate and increasing orbital period. Such a system would be very similar to the famous ultra-short LMXB MXB 1820-30 with the only difference that there will be no X-ray bursts. Unfortunately detection of such exotic systems (low mass white dwarf with black hole) is very difficult, contrary to systems with a neutron star (like PSR J0751+18) where the neutron star appears as a millisecond pulsar.

## 5. Conclusions

We have computed several evolutionary sequences with low-mass secondaries as donors and a black hole as accretors. Adopting simple estimates for the efficiency of magnetic braking (Verbunt & Zwaan, 1981) we determined the bifurcation period to be  $P_{bif} \sim 1$  day, that separates converging binaries from diverging. We have shown that for converging binaries the orbital evolution evolves either towards very short orbital periods by accretion, or ends up with the formation of a low mass helium white dwarf + black hole binary system. This is similar to the results obtained for low mass secondary + neutron star binary evolution (Ergma et al. 1998). If in such a system the final orbital period is less than 10 hours, it is possible that the system will reappear as a persistent X-ray source with ultra-short orbital period. For systems that evolve towards very short orbital periods there always is a phase in which the mass accretion rate is larger than  $M_{crit}^{irr}$ . These systems therefore, always have a persistent X-ray phase. By comparing the evolutionary sequences with different black hole masses it is shown that for more massive black holes the period range for unstable mass transfer is larger than it is for less massive black holes.

Finally we show, that after the common envelope phase and before collapse to a black hole, only helium stars with a relatively small mass end up with orbital periods less than the  $P_{bif}$ . These systems can evolve towards short orbital periods that are characteristic for the majority of the observed LMXB with black holes as accretors. This implies that the progenitors of the black holes in these systems were stars initially less massive than  $25 M_{\odot}$

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