HIGH MASS X-RAY BINARIES: FUTURE EVOLUTION AND FATE

Krzysztof Belczynski[1,2], Tomasz Bulik[1], Chris L. Fryer[3,4,5]

[1] Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
[2] Center for Gravitational Wave Astronomy, University of Texas at Brownsville, Brownsville, TX 78520, USA
[3] Computational Computer Science Division, Los Alamos National Laboratory, Los Alamos, NM, USA
[4] Department of Physics, The University of Arizona, Tucson, AZ, USA
[5] Department of Physics and Astronomy, The University of New Mexico, Albuquerque, NM, USA

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ABSTRACT

BH-NS and BH-BH systems are among the most promising gravitational wave sources detectable by advanced LIGO/VIRGO and the Einstein Telescope. Although the rates of these systems may be above those of NS-NS mergers, BH-NS and BH-BH systems are difficult to detect, and thusfar none have been observed. But the progenitors of BH-NS and BH-BH binary systems may have been observed, in the form of High-Mass X-ray Binaries (HMXBs). In this paper, we continue work studying these potential progenitors of these important gravitational wave sources. In the first two papers of the series, we have demonstrated that IC10 X-1 and NGC300 X-1 are direct progenitors of BH-BH systems and that Cyg X-1 may form, alas with a very low probability, a BH-NS system. Here, we analyze the Galactic binaries GX 301-2, Vela X-1, XTEJ1855-026, 4U1907+09, Cir X-1 and extra-galactic LMC X-1, LMC X-3, M33 X-1. In each case, we find that the future evolution will not allow the formation of a BH-NS nor a BH-BH system. Most of these binaries will soon merge in the common envelope phase, with a compact object sinking into a helium-rich core of a stellar companion. This "helium-merger" may be a progenitor for long duration gamma-ray bursts (GRBs). Based on the observed HMXB population, the rate of helium-mergers may make up a sizable fraction of long-duration GRBs. Due to this high number of potential GRB progenitors, a chance that a Galactic HMXB has caused one of the recent major mass extinction events is significant ($\sim 10 - 20\%$).

Subject headings: binaries: close — stars: evolution, neutron — gravitation

1. INTRODUCTION

Binary compact mergers are the most promising sources for ground-based gravitational wave detectors such as LIGO or VIRGO. These observatories are currently being upgraded and are scheduled to begin operating in the 2015 time frame. With the heightened sensitivity of these upgraded detectors, the questions surrounding gravitational wave detection are evolving from "will we detect gravitational waves?" to "when will we detect gravitational waves?" and "what type of merging remnant will dominate the detections?". So far, astronomers have only observed double neutron stars (NS-NS), detecting the pulsar in radio frequencies of electromagnetic spectrum (e.g., Lorimer 2008). Kim, Kalogera & Lorimer (2010) assessed empirical NS-NS inpiral rates and it appears that the detection of these events in gravitational radiation is unavoidable once the advanced instruments reach their design sensitivity. But the upgraded LIGO and VIRGO systems should also be sensitive to other types of double compact objects, namely black hole neutron star systems (BH-NS) and double black holes (BH-BH). Unlike NS-NS binaries, these binary systems have yet to be observed. In principle, these types of double compact objects are within reach of radio and microlensing surveys. Dong et al. (2007) reported the first potential detection of BH-BH system, but allowed for an alternative interpretation of the `OGLE-2005-SMC-001` lensing event. Population synthesis results based on theoretical evolutionary considerations indicate that BH-NS and BH-BH systems are expected to form and populate the local universe (e.g., Lipunov, Post-

nov & Prokhorov 1997; Bethe & Brown 1998; De Donder & Vanbeveren 1998; Bloom, Sigurdsson & Pols 1999; Fryer, Woosley & Hartmann 1999; Nelemans, Yungelson & Portegies Zwart 2001, Belczynski, Kalogera & Bulik 2002, Voss & Tauris 2003). In particular, it was recently argued that BH-BH systems will dominate the gravitational radiation inspirals (Belczynski et al. 2010b).

At *Warsaw Observatory* we have undertaken a program to provide empirical constraints on the existence of these undetected classes of compact binary systems. Bulik, Belczynski & Prestwich (2011) studied the future evolution of two extra-galactic X-ray binaries hosting massive black holes with Wolf-Rayet companions: IC10 X-1 and NGC300 X-1. It was argued that these binaries will produce massive BH-BH systems. Based on a simple rate estimate, it was shown that the detection of such massive BH-BH inspirals by gravitational detectors is likely even in the existing data of the initial LIGO and VIRGO. Belczynski, Bulik & Bailyn (2011) have studied the famous Galactic binary Cyg X-1 hosting a massive black hole and an O type companion. It was found that the most likely fate of this binary is disruption during the supernova explosion that forms a neutron star out of the O type companion. Cyg X-1 has only a small chance of forming a close BH-NS system. The rate of BH-NS systems inferred from Cyg X-1 is too low to make them likely sources for advanced gravitational radiation detectors. However, it was noted that this finding represents only a lower limit on the detection of BH-NS systems as these objects may form along channels that do not involve Cyg X-1 like stage.

In this study we discuss the remaining Galactic and extra-galactic high mass X-ray binaries (HMXBs) that are putative progenitors for the BH-NS or BH-BH systems. The binaries under consideration host already one compact object, a neutron star or a black hole, and a massive companion that can in principle form the second compact object. We chose only those binaries that have rather well established system parameters. We do not have any strict definition for our sample as we have chosen (rather subjectively) binaries that either appear to have a chance to form BH-NS or BH-BH system, or were brought to our attention by someone from the compact object community. In some cases, we had to perform detailed calculations to establish the fate of a given system. However, in other cases it was enough to search literature for a better parameter estimate or just to reiterate the previously presented arguments to confirm already proposed conclusions. As we will show, it appears that besides considered earlier binaries IC10 X-1, NGC300 X-1 and Cyg X-1, none other is likely to form BH-NS nor BH-BH system.

In §2, we review the fates of each system individually. In many cases, the binary system is expected to merge. This merger of a compact remnant with a massive companion has been proposed as a progenitor of long-duration GRBs (Fryer & Woosley 1998). We discuss the implications of these systems on the GRB population in §3.

2. CASE STUDY

2.1. *GX 301-2/BP Cru: CE merger*

This system consists of a neutron star (NS) and a very massive companion. The orbital period was measured at $P_{orb} = 41.5$d, the orbit is eccentric $e = 0.46$, the NS was estimated to have high mass $M_{NS} = 1.85$ M$_\odot$ and a very massive companion star was found $M_{opt} = 43$ M$_\odot$ (Kaper et al. 2006). Since this is a non-eclipsing system, a constraint may be put on the system inclination resulting in the minimum mass of the optical companion at $M_{opt} = 39$ M$_\odot$. We will use this lower limit as it provides the best chance for the system survival (see below). This system is a potential progenitor of BH-NS binary. Since the NS is already in place, the only requirement is that the companion forms a black hole (BH) and the companion mass appears sufficient for BH formation. Although, not well established, the transition from the NS to BH formation may be argued to be anywhere in the range of the zero age main sequence star mass $M_{zams} = 20 - 40$ M$_\odot$ for solar metallicity appropriate for this Galactic system. Following the recent calculations of compact object masses with the updated wind mass loss we employ the transition at $M_{zams} = 20$ M$_\odot$ (Belczynski et al. 2010a; Fryer et al. 2011). Therefore, if the companion was a single star it would form a BH. However, this is a secondary component in a binary that has not yet finished its evolution. The primary, that obviously was initially a more massive star in the binary, has already finished its evolution and formed a NS. The claim that the secondary will form a BH seems counter-intuitive. Yet, typical binary evolution leading to the formation of X-ray binaries can easily explain such a system.

If initially this system hosted $40 + 30$ M$_\odot$ stars on a close orbit, the 40 M$_\odot$ star initiated Roche lobe overflow (RLOF) while still on Main Sequence. Since the mass ratio of both stars was close to unity, the RLOF was dynamically stable and did not lead to the development of a common envelope. If this star lost more than 20 M$_\odot$ and if de-rejuvenation was effective, the star transitioned from the BH to NS formation zone, and became the currently observed NS. The formation of a NS has set the current orbital parameters including the high eccentricity as a result of natal kick the NS received in an asymmetric supernova explosion (Hobbs et al. 2005). If part of the transferred material, say 10 M$_\odot$ was successfully accreted onto the companion it increased its mass to 40 M$_\odot$, becoming the currently observed optical star in GX 301-2. It is not our intention to provide the detailed evolutionary history of this system as we are much more interested in its future. However, we outlined the likely formation scenario of this binary as it may seem curious to form first a NS and then a BH. More detailed calculations and discussion of similar processes are given by Wellstein & Langer (1999) and Belczynski & Taam (2008b).

At the current orbital period the semi-major axis is $a = 175$ M$_\odot$, while the closest encounter at periastron is $a_p = 95$ R$_\odot$. The Roche lobe radius of the optical companion at periastron is $R_{lobe} = 60$ R$_\odot$. The radius evolution of 30, 40 and 50 M$_\odot$ stars is shown in Figure 1. It is apparent that the optical star will eventually overfill its Roche lobe. From Figure 1 it becomes clear that the RLOF will start shortly after the star leaves its main sequence and begins crossing the Hertzsprung gap (HG). At the onset of RLOF, the system is still highly eccentric as tidal forces are very weak for such massive stars (e.g., Claret 2007). Although the treatment of the mass transfer on an eccentric orbit is complicated (e.g., Sepinsky et al. 2010), we can neglect this stage in the case of GX 301-2. The expansion of the massive companion is so rapid that within about 2000 yr the star expands from 60 to 200 R$_\odot$ engulfing entire system with its envelope (e.g., Hurley, Pols & Tout 2000), initiating a common envelope phase (e.g., Webbink 1984). Once the NS is within the stellar atmosphere of the companion the orbit should rapidly circularize due to the increasing dynamical friction. Since the entry into the atmosphere will occur somewhere around periastron, it is natural to assume that the orbit will circularize to a new separation equal to the size of pre-CE periastron distance or maybe even smaller $a_{pre,CE} \lesssim 95$ R$_\odot$. As an upper upper limit (albeit unphysical), we also consider the much larger pre-CE orbit $a_{pre,CE} \lesssim 175$ R$_\odot$. To calculate the post CE separation, we use energy balance between the orbital energy and the envelope binding energy. The binding energy is given by $E_{bind} = -(GM_{opt}M_{env})/(\lambda R_{opt})$, where $M_{env} = 25$ M$_\odot$ for a $M_{opt} = 40$ M$_\odot$ Hertzsprung gap star and λ is the parameter characterizing the mass distribution within the star. The lower the λ the harder it is for a companion to eject the envelope. We have adopted $\lambda = 0.2$ from Xu & Li (2010) that is appropriate for massive Hertzsprung gap star[1] of the relevant radius.

The final, post-CE, separation is determined by how much orbital energy is required to eject the envelope. If we assume all of the orbital energy goes into unbinding the envelope, the post-CE separations are found

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[1]We have obtained additional models from Xu & Li as massive stars ($M > 20$ M$_\odot$) were not included in their original study.

to be $a_{\rm post,CE} = 0.28, 0.17$ R$_\odot$ for initial separations of $a_{\rm pre,CE} = 175, 95$ R$_\odot$, respectively. Since the exposed core of the massive post main sequence star is a massive helium star or Wolfe-Rayet star ($M_{\rm WR} = 15$ M$_\odot$) its radius is $R_{\rm WR} \gtrsim 1$ R$_\odot$ (e.g., Petrovic, Pols & Langer 2006). That means that the CE phase ended up with the NS sinking into the helium core of the companion star, i.e. a merger. In a number of population synthesis calculations, the parameter λ denoting the binding energy of the envelope is fixed (non-physically) to one particular value for all stars of all masses and radii. Typically, $\lambda = 1.0$ was adopted due to lack of availability of more physical values. If we use $\lambda = 1.0$ instead of using calculated binding energies, we effectively decrease the binding energy. Nonetheless, this system with $\lambda = 1.0$ would still end up in a merger. Massive stars like the optical companion of GX 301-2 are not expected to have $\lambda \gtrsim 1.0$ at any point during Hertzsprung gap (Xu & Li 2010), although it was recently claimed that the actual lambda value may be $\sim 3 - 5$ times higher than currently estimated (Ivanova & Chaichenets 2011).

For all the above estimates, we have assumed that all orbital energy goes into unbinding the envelope (CE efficiency of 100%) thus maximizing the survival chances of this system. Additionally, we have neglected the internal structure of the companion star. Belczynski et al. (2007) argued that since the Hertzsprung gap stars have not yet developed clear core-envelope structure the CE phase always leads to a merger if such a star is a donor independent of amount of orbital energy available for the envelope ejection. Even if some stars may develop core-envelope structure later in the Hertzsprung gap and survive CE, this is not likely in the case of GX 301-2 donor that will initiate CE right after entering Hertzsprung gap (see Fig. 1).

Despite a number of very optimistic assumptions we have made to allow for the formation of BH-NS binary, GX 301-2 will most likely end its evolution as a single peculiar object formed in CE merger (a so-called helium merger). Several systems that we will discuss in the subsequent sections will face a very similar fate, and we will provide only basic information without the full description as it was done here for GX 301-2.

2.2. Vela X-1/GP Vel: CE merger

This system consists of a heavy NS ($M_{\rm NS} = 2.0$ M$_\odot$) orbiting ($P_{\rm orb} = 8.96$d) a massive companion ($M_{\rm opt} = 23.8$ M$_\odot$; e.g. Barziv et al. 2001) on a slightly eccentric orbit ($e = 0.09$; e.g., Tomsick & Muterspaugh 2010). It is clearly seen from Figure 2 that the RLOF will start right after the optical component enters Hertzsprung gap and it expands to reach its Roche lobe radius of $R_{\rm lobe} = 32$ R$_\odot$. Due to the extreme mass ratio of donor to accretor (23.8 : 2), the RLOF initiates a CE phase. The current orbital separation is not subject to any strong changes (small changes due to wind mass loss and tides) and we assume that the orbital separation at the onset of CE is the same as it is today $a_{\rm pre,CE} = 53$ R$_\odot$. A 23.8 M$_\odot$ star at the onset of Hertzsprung gap has a core of about 7 M$_\odot$ and massive 17 M$_\odot$ envelope. We optimistically assume that core-envelope structure is well developed and system can survive CE phase provided that there is enough orbital energy to expel the envelope. The energy balance is calculated for two values of $\lambda = 0.65, 1.0$: the first is a physical value

corresponding to the stellar structure of the donor and the second is an upper limit on lambda for such a donor on the Hertzsprung gap (Xu & Li 2010). The corresponding post-CE separations are $a_{\rm post,CE} = 0.4, 0.6$ R$_\odot$. Since the core of the donor is a massive helium star $M_{\rm WR} = 7$ R$_\odot$, its radius ($R_{\rm WR} \gtrsim 1$ R$_\odot$; Petrovic et al. 2006) is larger than the post-CE separation indicating that this system has not survived the CE phase, forming another helium-merger.

2.3. XTE J1855-026: CE merger

This system is a $P_{\rm orb} = 6.07$d eclipsing binary with a typical NS ($M_{\rm NS} = 1.4$ M$_\odot$) and a massive companion ($M_{\rm opt} = 25$ M$_\odot$) with a negligibly small eccentricity ($e \lesssim 0.04$; Corbet & Mukai 2002, Tomsick & Muterspaugh 2010). The corresponding orbital separation is $a = 42$ R$_\odot$ and the Roche lobe of the optical companion $R_{\rm lobe} = 26$ R$_\odot$. The radius of the optical component will reach its Roche lobe radius either at the very end of the main sequence or at the very onset of Hertzsprung gap (similarity of Vela X-1 optical component allows to use Fig. 2 to demonstrate this point). The RLOF will lead to the development of the CE phase (note the extreme mass ratio of donor to accretor 25 : 1.4). If the star is on main sequence during the onset of the CE phase, the binary components will most certainly merge because, at this evolutionary stage, there is no clear core-envelope structure. We assume that the optical star in XTE J1855-026 is on the Hertzsprung gap while initiating CE and that the system at least have a chance of survival. However, the solution of energy balance leads to very small post-CE separations: $a_{\rm post,CE} = 0.2, 0.3$ R$_\odot$ for the realistic and limiting values of $\lambda = 0.7, 1.0$ respectively. The massive helium core ($M_{\rm WR} = 7$ R$_\odot$) have radius ($R_{\rm WR} \gtrsim 1$ R$_\odot$; Petrovic et al. 2006) exceeding the size of post-CE orbit. This system will merge in CE event, barring further binary evolution and potential double compact object formation.

2.4. 4U 1907+09: CE merger

This system hosts a typical NS ($M_{\rm NS} = 1.4$ M$_\odot$) and a massive companion ($M_{\rm opt} = 27$ M$_\odot$) on a rather close $P_{\rm orb} = 8.38$d and eccentric $e = 0.28$ orbit (Cox et al. 2005). Cox et al. (2005) estimated the companion radius at $R_{\rm opt} = 26$ R$_\odot$ and provided arguments that the system is in wind-fed configuration typical of HMXBs: (i) increase of X-ray luminosity at the periastron passage and (ii) the radius of optical companion is well within its Roche lobe even at periastron $R_{\rm lobe} = 31$ R$_\odot$. However, they made an error in the Roche lobe radius estimate as the radius at the periastron for this particular binary configuration is actually much smaller $R_{\rm lobe} = 24.4$ R$_\odot$ (e.g., Eggleton 1983; Cox et al. (2005) made a typo in converting the Eggleton formula and their factor $q^{3/2}$ should actually read $q^{2/3}$). Therefore, if the radius estimate is correct, the donor overflows its Roche lobe at periastron passages and the increased periastron X-ray luminosity is due to a cyclic RLOF in addition to the wind accretion. If the companion radius is somewhat overestimated by Cox et al. (2005) then companion may not be filling its Roche lobe, but it is very close to RLOF at periastron.

At solar metallicity, the radius of such a massive star reaches ~ 27 R$_\odot$ at the end of the main sequence (MS), and expands to ~ 1100 R$_\odot$ in the HG (e.g., Hurley et al.

2000). Whether currently the system is going through a cyclic and moderate RLOF at periastron passage or not, the companion star is still in its MS because it has not yet expanded to large post-MS evolution radii. The expected near future expansion of the companion on the HG will engulf the system in common envelope. Note the extreme mass ratio (27:1.4). If the CE phase starts while the star is still in its MS phase, the fate of the system is set and the binary will merge. If the star initiates a CE phase while already on the HG, the system is still most likely to end up in a merger (Belczynski et al. 2007). However, we will ignore this fact for the sake of argument, and we will show that simple energy balance estimation does not allow this system survival in any case.

The CE starts once the optical companion begins its rapid expansion at the onset of the HG phase. Whether we assume the periastron distance as the initial CE separation or actual (most likely overestimated) binary separation $a_{\mathrm{pre,CE}} = 39, 54 \, \mathrm{R_\odot}$, the system merges during CE. The post-CE separation obtained from the energy balance is calculated to be $a_{\mathrm{post,CE}} = 0.20, 0.26 \, \mathrm{R_\odot}$, resulting in $R_{\mathrm{lobe}} = 0.10, 0.14 \, \mathrm{R_\odot}$ while the massive WR star (8 $\mathrm{M_\odot}$ He core of the optical companion) radius is $R_{\mathrm{WR}} = 0.8 \, \mathrm{R_\odot}$ for both initial separation cases, respectively. Again we have used realistic $\lambda = 0.7$ appropriate for such massive star at its given radius, and we have assumed conservatively the 100% efficiency of orbital energy conversion into unbinding the envelope.

In all cases, this system will end in a CE merger.

2.5. Cir X-1: CE merger

This binary was at first believed to host a BH due to the presence of jets. However, the discovery and then later confirmation of thermonuclear bursts has shown beyond a doubt that the compact object is a NS (Lineares et al. 2010). The orbital period ($P_{\mathrm{orb}} = 16.6$d) and eccentricity are well established ($e = 0.45$). However, due to the high extinction toward Cir X-1 and potential large contribution of a disk emission in UV, optical and IR the mass and evolutionary status of a companion are not well constrained. Estimates range from $3 - 5 \, \mathrm{M_\odot}$ subgiant (Johnston, Fender & Wu 1999) to 10 $\mathrm{M_\odot}$ suprgiant (Jonker, Nelemans & Bassa 2007).

If Cir X-1 were hosting a BH as it was originally suspected and if the companion was massive enough to form a NS (e.g., $\sim 10 \, \mathrm{M_\odot}$) then it would be a potential progenitor of BH-NS system. However, this option is no longer supported. This peculiar XRB is a potential progenitor of either a NS-WD system (low mass $3 - 5 \, \mathrm{M_\odot}$ companion) or NS-NS system (high mass companion 10 $\mathrm{M_\odot}$). In the following estimates we assume a canonical NS mass of 1.4 $\mathrm{M_\odot}$ for the compact star in Cir X-1, and adopt either a low or high mass companion $M_{\mathrm{opt}} = 4, 10 \, \mathrm{M_\odot}$.

For the low mass companion, the RLOF commences when the star is on HG and leads most likely to CE evolution (mass ratio of 4:1.4) that ends up in a merger with a NS. The orbital separation just prior RLOF is $a = 48 \, \mathrm{R_\odot}$ with companion radius $R_{\mathrm{opt}} = 12 \, \mathrm{R_\odot}$. We adopt the periastron distance for the onset of CE $a_{\mathrm{pre,CE}} = 26 \, \mathrm{R_\odot}$ with $e = 0.45$ as the tidal forces were not able to circularize the system for this (radiative) companion (e.g., Claret 2007). We calculate CE with $\lambda = 0.5$ (Xu & Li 2010) and obtain a final orbital separation $a_{\mathrm{post,CE}} = 0.21 \, \mathrm{R_\odot}$. The com-

panion lost its entire envelope and will become a low mass helium star $M_{\mathrm{WR}} = 0.6 \, \mathrm{M_\odot}$ with radius $R_{\mathrm{WR}} = 0.14 \, \mathrm{R_\odot}$ and thus it exceeds its new Roche lobe $R_{\mathrm{lobe}} = 0.07 \, \mathrm{R_\odot}$. The NS has inspiraled into He core of the 4 $\mathrm{M_\odot}$ HG companion.

For the high mass companion, the RLOF will start much earlier, but again when the donor star is crossing HG. The initial periastron separation is $a_{\mathrm{pre,CE}} = 63 \, \mathrm{R_\odot}$ with $e = 0.45$ and the donor radius $R_{\mathrm{opt}} = 19 \, \mathrm{R_\odot}$. We use $\lambda = 0.7$ appropriate for this given donor and we calculate the final orbital separation $a_{\mathrm{post,CE}} = 0.26 \, \mathrm{R_\odot}$. The companion became a helium star with mass $M_{\mathrm{WR}} = 2.1 \, \mathrm{M_\odot}$ and with radius $R_{\mathrm{WR}} = 0.35 \, \mathrm{R_\odot}$ and thus it exceeds its new Roche lobe $R_{\mathrm{lobe}} = 0.11 \, \mathrm{R_\odot}$. The NS has inspiraled into He core of the 10 $\mathrm{M_\odot}$ HG companion.

2.6. LMC X-1: CE merger

This is the first XRB discovered in the Large Magellanic Cloud (LMC). The system parameters are relatively well established (Orosz et al. 2009; Ziolkowski 2011). The compact object is a BH with mass $M_{\mathrm{BH}} = 10.9 \, \mathrm{M_\odot}$ in an orbit around a main sequence star with mass $M_{\mathrm{opt}} = 31.8 \, \mathrm{M_\odot}$ and radius $R_{\mathrm{opt}} = 17.0 \, \mathrm{R_\odot}$. The orbit is circular or if there is any eccentricity it is negligibly small ($e \lesssim 0.03$). The orbital period is found to be $P_{\mathrm{orb}} = 3.91$d corresponding to an orbital separation $a = 36.5 \, \mathrm{R_\odot}$. This indicates that the optical star almost fills its Roche lobe ($R_{\mathrm{lobe}} = 17.3 \, \mathrm{R_\odot}$). Since the mass of a optical star is above the BH formation limit for single stellar models and for our adopted evolutionary scenario (Belczynski et al. 2002; 2008a), this system is a candidate progenitor of BH-BH system. If binary interactions can remove a significant part of the MS star mass, it could also potentially form BH-NS system.

The initial mass of the optical companion was estimated at about $M_{\mathrm{opt,zams}} = 35 \, \mathrm{M_\odot}$ (Orosz et al. 2009; Ziolkowski 2011). The radius evolution of a $M_{\mathrm{zams}} = 35 \, \mathrm{M_\odot}$ star at $Z = 0.3 \, \mathrm{Z_\odot}$ metallicity typical of the LMC is shown in Figure 3. For $M_{\mathrm{zams}} = 35 \, \mathrm{M_\odot}$ we see that the radius of the star reaches its Roche lobe at about 5 Myr of MS evolution. For this given set of orbital parameters, evolutionary stage of a donor and high mass ratio of the binary, (31.8:10.9) the RLOF will develop into a CE phase. The CE evolution is bound to lead to the merger (MS donor) and the BH will sink into the He enriched core of MS star. At the time of merger, the donor should have evolved through about 90% of its MS lifetime. The core mass at the end of MS is similar to that at the beginning of HG: $\sim 11 \, \mathrm{M_\odot}$ for the optical star in LMC X-1.

2.7. LMC X-3: BH-WD Binary

This system is another black hole binary in the LMC. The optical companion was established to be a BV star with mass $4 - 8 \, \mathrm{M_\odot}$ and radial velocity curve with $P_{\mathrm{orb}} = 1.7$d and potential small eccentricity $e = 0 - 0.1$ was obtained by Cowley et al. (1983). The lack of eclipses ($i < 70 \deg$) places a lower limit only on the mass of compact object, but it is high enough to indicate a black hole binary. If the maximum mass of the companion (8 $\mathrm{M_\odot}$) is confirmed, this system is a potential BH-NS system progenitor. However, recent estimates indicate that LMC X-3 will face a different fate.

Soria et al. (2001) study included effects of irradiation, and they estimated that the companion is a subgiant star

filling its Roche lobe B5 IV ($M_{\rm opt} = 4.7~{\rm M_\odot}$) and obtained limit for the mass of a black hole $M_{\rm BH} > 5.8~{\rm M_\odot}$. This system is already at RLOF and a companion star is losing mass ($R_{\rm lobe} = 4.7~{\rm R_\odot}$ if we adopt a BH mass $M_{\rm BH} = 5.8~{\rm M_\odot}$). The evolutionary state of the companion to put it at a right size to commence RLOF at the observed orbital period is either late MS or early HG. The helium core of such a donor will be found at $0.5 - 0.7~{\rm M_\odot}$. The RLOF will continue through HG, Red Giant Branch to stop finally at Core Helium Burning at which stage the companion will contract. The remaining envelope of companion will be lost in stellar wind exposing $0.6 - 0.8~{\rm M_\odot}$ CO white dwarf. The orbit, due to mass transfer (from less massive companion to more massive BH) will expand to over 100 days forming a wide (non-coalescing) BH-WD binary.

2.8. *M33 X-7: CE Merger*

This system is a massive binary consisting of a black hole $M_{\rm BH} = 15.65~{\rm M_\odot}$ and an O7-8 III companion $M_{\rm opt} = 70~{\rm M_\odot}$ on a close and almost circular orbit: $P_{\rm orb} = 3.45$d, $e = 0.0185$ (Orosz et al. 2007). Following Valsecchi et al. (2010) we adopt M33 metallicity of $Z = 0.01$ or 50% solar.

The radius of the optical component is estimated to be 19.6 ${\rm R_\odot}$ (Orosz et al. 2007). The orbital separation is found to be $a = 42.4~{\rm R_\odot}$ and the Roche lobe radius at periastron for the optical component is $R_{\rm lobe} = 21.3~{\rm R_\odot}$. The companion is still in its MS and almost fills its Roche lobe. It will take only about ~ 0.2 Myr for such a massive star to expand and overfill its Roche lobe. Due to the extreme mass ratio (70 : 15.65), the system will enter the common envelope phase that will lead to a merger (MS donor). The massive BH will sink into the core of the companion: at this point the companion has evolved through about $60 - 70\%$ of its MS lifetime and the core will mostly consist of helium nuclei.

3. DISCUSSION

Including our previous studies we have shown that out of 11 very massive HMXB with reasonably known binary parameters: 2 (IC10 X-1, NGC300 X-1) will form close BH-BH systems, 1 (Cyg X-1) will have a 30% chance to form a BH-NS system (with 1% probability of this being a close system), 1 (LMC X-3) will form a wide BH-WD system, and the remaining 7 binaries will merge in common envelope (GX 301-2, Vela X-1, XTE J1855-026, 4U 1907+09, Cir X-1, LMC X-1, M33 X-1). The summary of our results is given in Table 1.

In the helium merger model of long-duration gamma-ray bursts (GRBs) the compact object, either a NS or a BH, sinks into the helium rich core of its companion. A compact object accretes at a high rate $\gtrsim 0.01~{\rm M_\odot~s^{-1}}$ (Fryer & Woosley 1998, Zhang & Fryer 2001) and, in the NS case, a BH forms. The helium core as it accretes onto a BH forms a transient torus (Barkov & Komissarov 2011) leading to a standard scenario for a GRB engine (Popham, Woosley & Fryer 1999). Helium merger configuration is most easily provided in the common envelope merger of HMXBs in which an optical companion is already an evolved star beyond main sequence (He core) or at the end of main sequence (high concentration of He in the core). In the merger, part of a companion star is ejected (but not fully)

away from the system, and the compact object sinks into helium-rich core. The so-called "Christmas burst" (GRB 121225) may be potentially the first identifiable example of a helium merger GRB, with indication of an inner compact source and a surrounding shell (Thone et al. 2011).

Fryer, Belczynski & Thone (2013) have employed theoretical population synthesis predictions for common envelope mergers and estimated the characteristic observational features of helium merger GRBs. Their model calculates a GRB luminosity based on a helium core mass (required to be typically larger than 4 ${\rm M_\odot}$) and establishes the position of the shell surrounding the central GRB engine based on the radius of the companion star (CE donor). Here we use our empirically based estimates and employ Fryer et al. (2013) model to estimate typical luminosities of helium merger GRBs.

In the case of GX 301-2, we expect a NS to sink into a 60 ${\rm R_\odot}$ Hertzsprung gap star with 15 ${\rm M_\odot}$ helium core and GRB luminosity of $L_{\rm grb} = 10^{49}, 10^{51}~{\rm erg~s^{-1}}$ for neutrino annihilation and Blandford-Znajek emission model respectively (for each system, we will provide two values for $L_{\rm grb}$ corresponding to these two emission mechanisms). For Vela X-1 a NS will enter a 32 ${\rm R_\odot}$ Hertzsprung gap star with 7 ${\rm M_\odot}$ helium core and $L_{\rm grb} = 10^{46}, 10^{50}~{\rm erg~s^{-1}}$. In binary XTE J1855-026 a NS will merge into 26 ${\rm R_\odot}$ Hertzsprung gap star with 7 ${\rm M_\odot}$ helium core and $L_{\rm grb} = 10^{46}, 10^{50}~{\rm erg~s^{-1}}$. In case of 4U 1907+09 we predict a merger of a NS and a 26 ${\rm R_\odot}$ late main sequence or early Hertzsprung gap star with 8 ${\rm M_\odot}$ helium-rich core and $L_{\rm grb} = 10^{47}, 5 \times 10^{50}~{\rm erg~s^{-1}}$. For Cir X-1 a NS will sink into a $12 - 19~{\rm R_\odot}$ Hertzsprung gap star with $0.6 - 2.1~{\rm M_\odot}$ helium core. For this case, a GRB is not expected but such mergers may account for some subset of ultraluminous supernovae (Fryer et al. 2013). For LMC X-1 a BH will merge into a $\sim 11~{\rm M_\odot}$ helium-rich core of a 17.3 ${\rm R_\odot}$ star at the end of its main sequence evolution with a potential GRB at $L_{\rm grb} = 10^{48}, 10^{51}~{\rm erg~s^{-1}}$. A BH in M33 X-1 will sink into a 21.3 ${\rm R_\odot}$ main sequence companion that has evolved through about $60 - 70\%$ of its central hydrogen burning. Since the optical companion has mass of $\sim 70~{\rm M_\odot}$ its helium-rich core is also very massive $\sim 20~{\rm M_\odot}$ and potential GRB luminosity is very high $L_{\rm grb} = 10^{51}, 5 \times 10^{51}~{\rm erg~s^{-1}}$.

There are at least 4 HMXB binaries in our Galaxy with very massive donors ($M_{\rm opt} > 20~{\rm M_\odot}$; required for a GRB) that will merge in the soon-to-come common envelope phase (see Tab. 1). As discussed above the merger will be followed shortly by a gamma ray burst (Fryer & Woosley 1998; Thone et al. 2011). The HMXB lifetime may be estimated from the lifetime of an optical component. For the considered binaries (GX 301-2, Vela X-1, XTE J1855-026, 4U 1907+09) the HMXB lifetime can be roughly estimated as the difference between the lifetime of the companion star and the minimum time required to form a NS i.e. 5 Myr (Belczynski & Taam 2008). The companion lifetime depends on its mass and it is 5.3 Myr for a 43 ${\rm M_\odot}$ star (GX 301-2), 8 Myr for 24 ${\rm M_\odot}$ star (Vela X-1), 7.8 Myr for 25 ${\rm M_\odot}$ star (XTE J1855-026), and 7.3 Myr for 27 ${\rm M_\odot}$ star (4U 1907+09). This leads to the X-ray lifetime estimates of $\tau = 0.3$, 3, 2.8 and 2 Myr, respectively. The expected formation rate of such X-ray binaries is $R = \sum \tau_i^{-1} = 4.5$ Myr^{-1}. Since the HMXB lifetimes are very short, this is

also the estimate of the helium merger Galactic GRB rate. The rate estimate is formally dominated by the contribution of GX 301-2 and in this case this system deserves a few more comments. The companion in GX 301-2 might have gained up to 20 $M_\odot$ from the NS progenitor, and the rejuvenation might not have been complete. Thus it is quite likely that the expected lifetime of GX 301-2 as an HMXB is longer, up to 3 Myr. If we adopt such long lifetime the formation rate of helium merger GRBs drops to 1.5 Myr^{-1}. These rates have been calculated assuming that the entire Galaxy has been searched for HMXB and our observational sample is complete. In reality HMXBs have been found only in about 25% of the volume of the disk (e.g., Ozel et al. 2010). Thus the estimated rates have to be corrected for that and are in the range $R_{\rm Galactic} = 6-18$ Myr^{-1}.

The star formation in the Galactic disk is approximately constant and at the level of 3.5 $M_\odot$ yr^{-1} (e.g., O'Shaughnessy et al. 2006). The rate of helium merger GRBs may be translated into $\mathcal{R}_{grb} \approx 1.6-5.1 \times 10^{-6}$ $M_\odot^{-1}$ and is expressed per unit of star forming mass. This value can be used to estimate the GRB rate in other galaxies or in cosmological population studies. Since the delay of helium CE merger events is rather short ($\lesssim 10$ Myr), these particular GRBs are expected in any galaxy with ongoing star formation.

It must be noted that our estimate provides only a lower limit on the helium merger GRB rate. There are a number of HMXBs in our Galaxy without fully established orbital/component parameters (Liu, van Paradijs & van den Heuvel 2006), some of which may be potential GRB progenitors. There may be ways to produce a helium merger GRB without a HMXB phase, for example NS ejection into a companion via supernova natal kick (e.g., Fryer et al. 2013).

Nevertheless, our estimate provides a rather signifi-

cant number of GRBs in the history of the Galactic disk $\sim 60,000 - 180,000$ (for 10 Gyr of constant star formation) and we check whether such a GRB may have affected life on Earth. The extent of the disk, where most of star formation is taking place, may be approximated by radius of 18 kpc and vertical extent of 0.60 kpc (Paczynski 1990) and that gives disk volume of $V_{\rm disk} \approx 610$ kpc^3. Long GRBs with their maximum energy output of 5×10^{51} erg/s lasting ~ 10s may have a big impact or are claimed to be lethal for Earth biosphere if exploding within 2 kpc (Nakar 2010). The volume of impact sphere within the disk is then about $V_{\rm impact} \approx 7.5$ kpc^3. And therefore the Galactic rate needs to be reduced by factor of ~ 80 ($V_{\rm disk}/V_{\rm impact}$) to provide the rate estimate of GRBs in the impact zone: $0.073 - 0.22$ Myr^{-1}. The long GRB power is collimated in a relativistic jet with beaming of $\sim 5°$ (e.g., Frail et al. 2001; Soderberg et al. 2006). Since only a direct hit on the Earth biosphere may be lethal or cause a major mass extinction, this leads to further reduction by factor of ~ 500. Finally, we obtain the rate of direct GRB hits coming from the impact zone at the level $0.15 - 0.45$ Gyr^{-1}. Over a 4.5 Gyr of Earth history the expected number of direct nearby hits is in the range $0.65 - 2.0$. There are at least five major mass extinction events noted in the last 0.5 Gyr in the marine data (Alroy 2008). The probability of direct impact from a helium merger GRBs in this period is in the range $\sim 7.2 - 22\%$). Thus it is quite possible that one of these events has been caused by a nearby helium GRB.

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TABLE 1
FATE OF HMXBs

No	Name	M_x/ M$_\odot$	M_{opt}/ M$_\odot$	P_{orb}	e	Fate
1	IC10 X-1	30 (BH)	25 (WR)	5.6h	0	close BH-BH (100%)
2	NGC300 X-1	20 (BH)	15 (WR)	6.7h	0	close BH-BH (100%)
3	Cyg X-1	15 (BH)	19 (O)	5.6d	0	close BH-NS ($\lesssim$ 1%)
4	GX 301-2	1.9 (NS)	43 (O)	41.5d	0.46	CE merger
5	Vela X-1	2.0 (NS)	24 (O)	8.96d	0.09	CE merger
6	XTE J1855-026	1.4 (NS)	25 (O)	6.07d	0.04	CE merger
7	4U 1907+09	1.4 (NS)	27 (O)	8.38d	0.28	CE merger
8	Cir X-1	??[a] (NS)	$3-5$ (A/B)	16.6d	0.45	CE merger
			10 (O)[b]			CE merger
9	LMC X-1	10.9 (BH)	31.8 (O)	3.91d	0.0	CE merger
10	LMC X-3	> 5.8 (BH)	4.7 (B)	1.7d	< 0.1	wide BH-WD
11	M33 X-1	15.65 (BH)	70 (O)	3.45d	0.019	CE merger

[a] It is established that compact object in this system is a NS, however its mass has not been measured. In our calculations, we have assumed a NS mass of 1.4 M$_\odot$.

[b] The mass and evolutionary status of the companion is not well established. We use the two different mass estimates, however the fate of the system seems insensitive to these uncertainties.
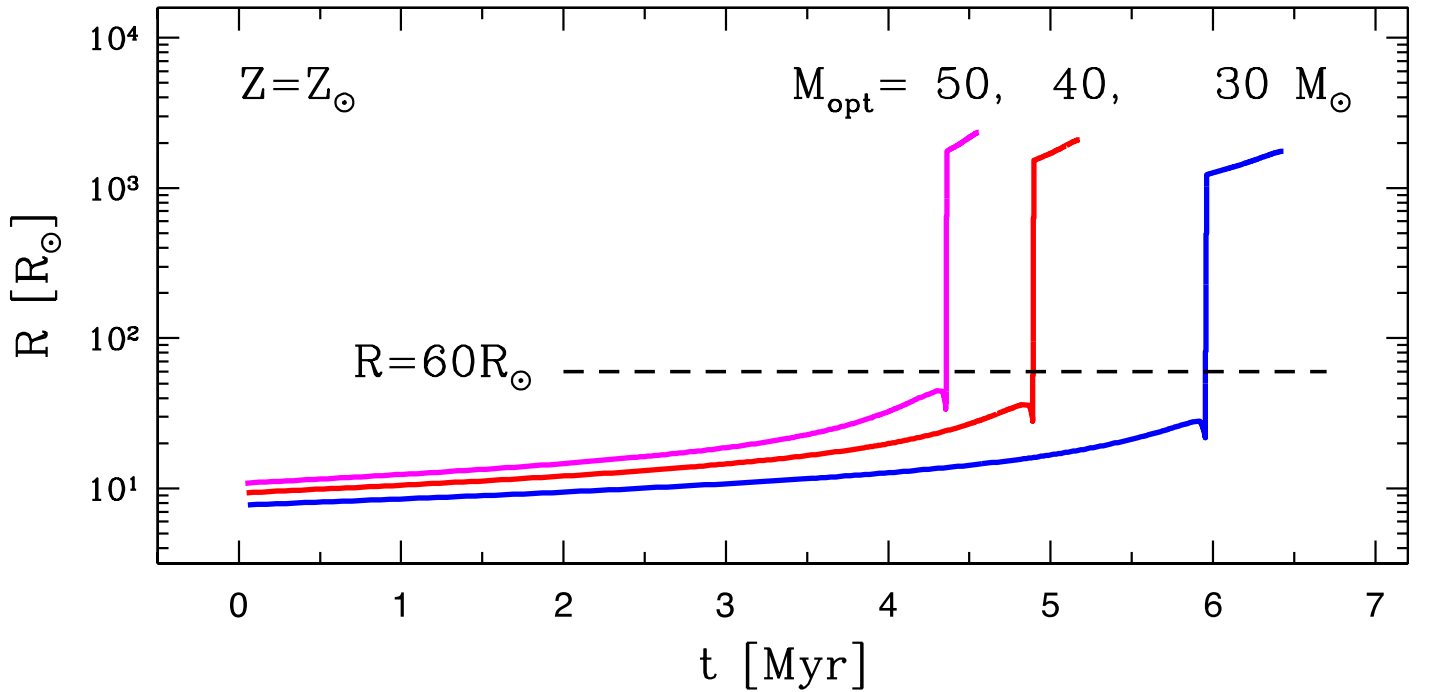
Fig. 1.— Radius evolution of star with mass $30, 40, 50$ M$_\odot$ at solar metallicity obtained with Hurley et al. (2000) stellar evolutionary formulae. At first, the star increases its radius by a factor of few over the long main sequence evolution. Then the expansion is extremely rapid and star increases its radius by factor of about hundred while crossing the Hertzsprung gap. Finally, after the ignition of helium in the core, the radial expansion slows down and eventually stops as star loses its entire H-rich envelope and becomes a compact naked helium star (not shown). The optical component in GX 301-2 has ~ 40 M$_\odot$ and at periastron its Roche lobe radius is ~ 60 R$_\odot$. The RLOF will start while the optical component is starting to cross Hertzsprung gap. This conclusion does not depend strongly on the optical component mass.
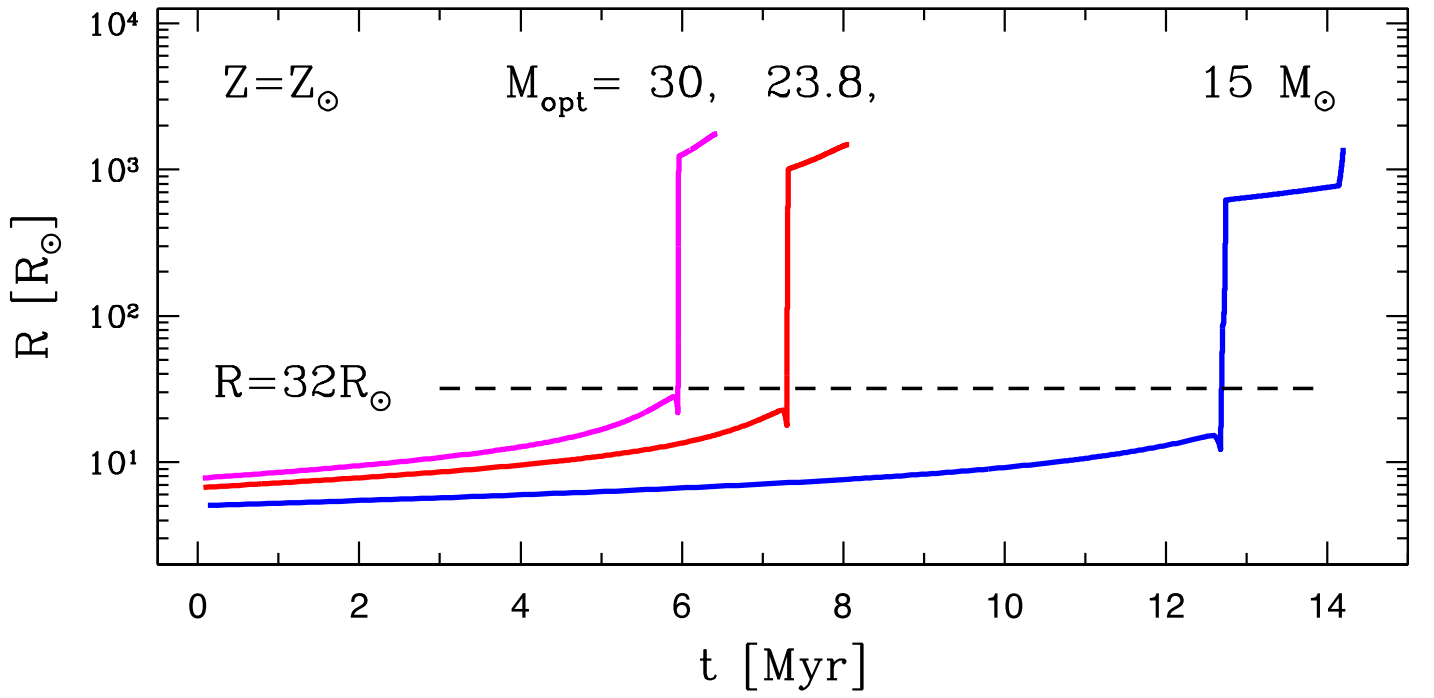
Fig. 2.— Radius evolution of stars with mass $15, 23.8, 30$ M$_\odot$. The optical component in Vela X-1 has mass 23.8 M$_\odot$ and its Roche lobe radius is ~ 32 R$_\odot$. The RLOF will start while the optical component is starting to cross Hertzsprung gap.
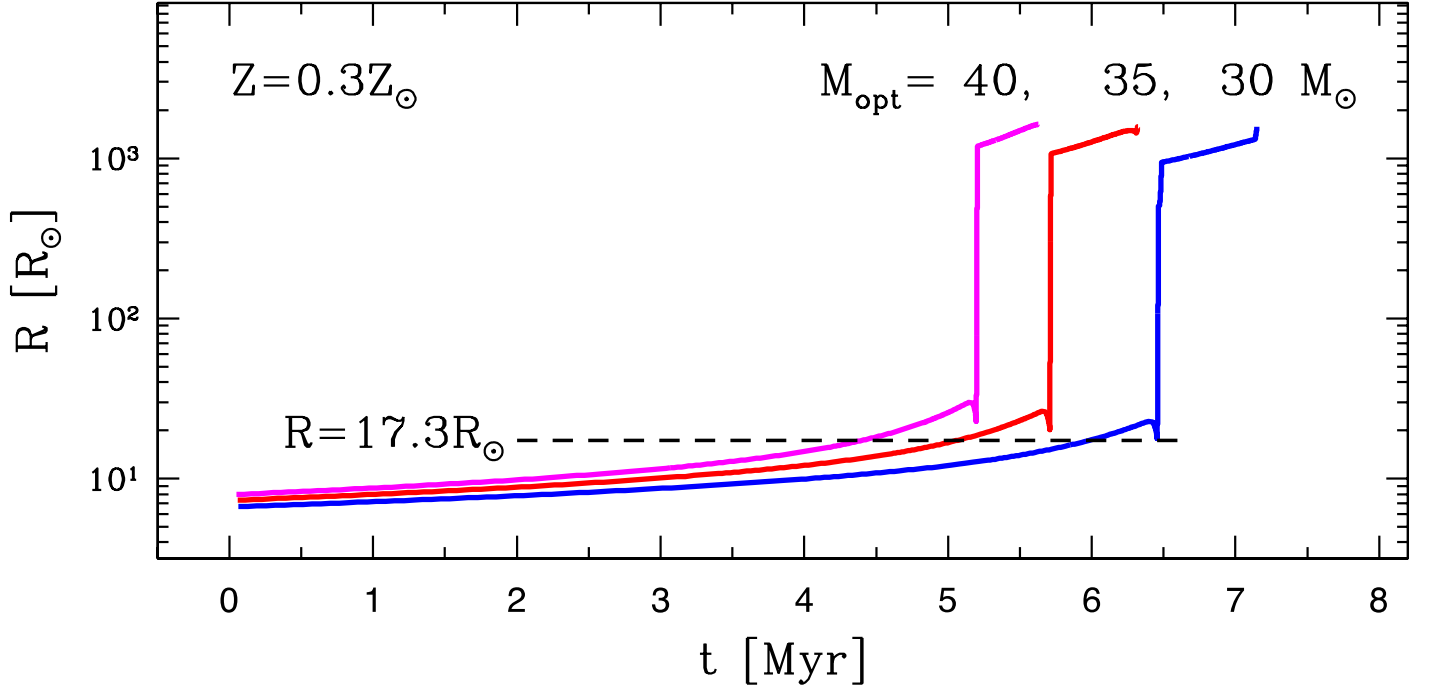
Fig. 3.— Radius evolution of stars with mass $30, 35, 40$ $M_\odot$ for a small metallicity typical of the LMC. Initial mass (ZAMS) of the LMC X-1 optical component was estimated at 35 $M_\odot$. The current mass and radius are 31.8 $M_\odot$ and 17.0 $R_\odot$, respectively. The estimated Roche lobe radius is ~ 17.3 $R_\odot$. The RLOF will start very soon ($\lesssim 10^5$ yr) while the optical component is still on Main Sequence.