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THE FATE OF CYG X-1: AN EMPIRICAL LIMIT ON BH-NS MERGER RATE

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ABSTRACT

The recent distance determination allowed precise estimation of the orbital parameters of Cyg X-1, which contains a massive 14.8 $M_{\odot}$ BH with a 19.2 $M_{\odot}$ O star companion. This system appears to be the clearest example of a potential progenitor of a BH-NS system. We follow the future evolution of Cyg X-1, and show that it will soon encounter a Roche lobe overflow episode, followed shortly by a Type Ib/c supernova and the formation of a NS. It is demonstrated that in majority of cases ($\gtrsim 70\%$) the supernova and associated natal kick disrupts the binary due to the fact that the orbit expanded significantly in the Roche lobe overflow episode. In the reminder of cases ($\lesssim 30\%$) the newly formed BH-NS system is too wide to coalesce in the Hubble time. Only sporadically ($\sim 1\%$) a Cyg X-1 like binary may form a coalescing BH-NS system given a favorable direction and magnitude of the natal kick. If Cyg X-1 like channel (X-ray active phase $\lesssim 10$ Myr) is the only or dominant way to form BH-NS binaries in the Galaxy we can estimate the empirical BH-NS merger rate in the Galaxy at the level of ~ 0.001 Myr^{-1}. This rate is so low that the detection of BH-NS systems in gravitational radiation is highly unlikely, generating Advanced LIGO/VIRGO detection rates at the level of only ~ 1 per century. If BH-NS inspirals are in fact detected, it will indicate that the formation of these systems proceeds via some alternative and yet unobserved channels.

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

1. INTRODUCTION

Estimates for the rates of gravitational radiation (GR) sources from coalescing degenerate binaries are typically performed with population synthesis methods (e.g., Lipunov, Postnov & Prokhorov 1997; Bethe & Brown 1998; De Donder & Vanbeveren 1998; Bloom, Sigurdsson & Pols 1999; Fryer, Woosley & Hartmann 1999; Nelemans, Yungelson & Portegies Zwart 2001, Voss & Tauris 2003 or more recently Belczynski et al. 2010). These studies attempt to explain the past evolution of the given observed binary or stellar population and put some constraints on the physics of stellar/binary evolution (e.g., Valsecchi et al. 2010). Nevertheless, there are often critical model parameters that are poorly constrained.

Recently, Bulik, Belczynski & Prestwich (2011) have taken a different approach, examining specific binary systems with well established parameters and investigating their future evolution. If a binary is chosen close to the end of its life (e.g., the formation of double compact object) such a method has potentially great predictive power as many unknowns relating to its prior binary and stellar evolution can be avoided. In particular, Bulik et al. (2011) considered two high mass X-ray binaries (HMXBs), IC10 X-1 and NGC300 X-1, and showed that these systems will soon form close black hole + black hole (BH-BH) systems that will merge within Hubble time and produce strong GR signature. This provided an empirical estimate of detection chances for the current GR instruments without direct reference to population synthesis methods.

In this study, we consider the future evolution of one of the most interesting binaries known in our Galaxy: Cyg X-1. Recently, the distance to this system was determined by radio parallax methods (Reid et al. 2011), allowing the basic parameters of this binary to be firmly established (Orosz et al. 2011). This HMXB hosts one of the most massive (15 $M_{\odot}$) Galactic BHs in a close orbit around a massive (20 $M_{\odot}$) O star. Since the companion is in the mass range for neutron star formation, we have selected this system to investigate yet another unobserved population of potential GR sources: black holes + neutron star (BH-NS) systems.

2. ESTIMATES

2.1. *The future evolution of Cyg X-1*

To evolve the system forward in time we use evolutionary prescriptions incorporated in the `StarTrack` population synthesis code (Belczynski et al. 2002). The evolution of the system is relatively simple and we do not need any population synthesis tools at this point. We start off with the best estimate of current binary parameters; the black hole with the mass $M_{\rm BH} = 14.8$ $M_{\odot}$, the optical star with the mass $M_{\rm opt} = 19.2$ $M_{\odot}$ and radius of $R_{\rm opt} = 16.2$ $R_{\odot}$ and the orbital period $P_{\rm orb} = 5.6$d (Orosz et al. 2011).

The optical companion is almost filling its Roche lobe and will start Roche lobe overflow (RLOF) in less than 0.2 Myr while still on Main Sequence (see Fig. 1). The mass ratio is close to unity so we do not expect the common envelope evolution, but rather a stable RLOF phase. However, the mass transfer rate may reach quite high values while the donor is moving through Hertzsprung gap (HG). The evolution of the system is presented in Figure 2. Mass transfer rate is calculated using physical properties of the donor and the system parameters (Belczynski et al. 2008a). The mass accretion onto BH is calculated using the thin disk advected accretion models (e.g., Abramowicz et al. 1988; Ohsuga et al. 2005; Ohsuga 2007) and thus can significantly exceed the classical Eddington limit (see Belczynski et al. 2008b for details). The BH increases its mass to $M_{\rm BH} = 17.8$ M$_\odot$, while the optical star loses most of its mass $M_{\rm opt} = 4.2$ M$_\odot$ to become a massive helium core with a bit of H-rich envelope. Note that the majority of the mass lost from the donor is lost from the system (highly non-conservative case). The period of the system increases to $P_{\rm orb} = 90$d. RLOF stops as the donor decreases in size due to the lost of its H-rich envelope. The massive helium or Wolf-Rayet (WR) star, (($R_{\rm WR} \lesssim 1$ R$_\odot$) is well within its Roche lobe $R_{\rm lobe} \approx 60$ R$_\odot$. After some wind mass loss (~ 0.5 M$_\odot$) and about 2 Myr after the RLOF termination, the WR star explodes in Type Ib/c supernova and forms a neutron star (NS).

There is about 2 M$_\odot$ mass loss in the supernova and that is not enough to disrupt the system. However, the pre-supernova binary is rather wide ($P_{\rm orb} = 104$d, and semi-major axis $a = 250$ R$_\odot$ due to additional orbit expansion caused by the mass loss from the WR star), and any significant natal kick tends to disrupt the binary. In Table 1 we list the disruption and survival probabilities for two assumptions about the distribution of kick velocities. The "full" kicks are adopted from the velocity distribution of the Galactic single pulsars that is best described by a Maxwellian with $\sigma = 265$ km s^{-1} (Hobbs et al. 2005). As there may be some observational and theoretical evidence that natal kicks are smaller in close binary systems (see the discussion in Belczynski et al. 2010) we also explore a "half" kick model with kicks drawn from the same distribution but with $\sigma = 132.5$ km s^{-1}. As expected for such a wide system, the binary disruption and formation of two single compact objects is most likely: 94% and 74% for full and half kicks, respectively. Less likely, but still quite probable is the formation of a wide BH-NS system: 6% and 26%. The least likely is the formation of the close BH-NS system with the coalescence time below Hubble time (13.47 Gyr): 0.2% and 0.8%.

Additionally, we have investigated an evolutionary scenario in which the RLOF starts early in the HG. Since at this point the optical star has a more massive core as compared with the above example, it will retain more mass through RLOF (only the H-rich envelope is transferred/lost). Since less mass is transferred/lost the orbital expansion is not as dramatic and the final orbital period of the binary at the supernova explosion is $P_{\rm orb} = 61.7$d ($a = 174$ R$_\odot$). This obviously leads to higher survival probabilities and higher chance of the close BH-NS formation: 0.4% and 1.4% for the full kick and half kick models, respectively.

2.2. *Rate Estimates*

Cyg X-1 has been detected because of its unusually strong X-ray luminosity. Let us consider the question of the formation rate of Cyg X-1 like binaries in our Galaxy. The upper limit on the X-ray active phase in Cyg X-1 is set by the evolutionary time of the secondary, which is 10 Myr for a 20 M$_\odot$ star. We employ this upper limit. Had we adopted more formal estimate of 5 Myr (it takes about 5 Myr for a massive star to form a BH that is already in the system and start an X-ray phase) the estimated detection rate of BH-NS systems would increase by factor of 2. Given that we see just one such object in the Galaxy we can infer the formation rate of Cyg X-1 like binaries as one per 10 Myr, i.e. $r \approx 10^{-7}$ yr^{-1}. Our simulations show that the chance of forming a merging BH-NS system is between 2×10^{-3} and 14×10^{-3} (see bottom row of Tab. 1) from a Cyg X-1 like progenitor. These means that the formation rate of BH-NS binaries from Cyg X-1 like progenitors will be only $2 - 14 \times 10^{-10}$ yr^{-1}. This means that only a handful $(2 - 14)$ close BH-NS systems might have been formed over a 10 Gyr history of the Milky Way. For comparison the Galactic empirical NS-NS merger rate is significantly higher: $3 - 190 \times 10^{-6}$ yr^{-1} (Kim, Kalogera & Lorimer 2010).

The implied Advanced LIGO/VIRGO detection rate follows once we determine the range of these detector for a BH-NS system. Given the mass of the BH ($M_{\rm BH} = 17.8$ M$_\odot$) and assuming the mass of a neutron star to be canonical $1.4M$ M$_\odot$, we obtain the chirp mass of the newly formed system to be 3.8 M$_\odot$. Since the range for the Advanced detectors for NS-NS system with a chirp mass of 1.2 M$_\odot$ is 300 Mpc, we obtain the range for such BH-NS systems of 786 Mpc (the detection distance scales like $\propto M_{\rm chirp}^{5/6}$). If we adopt the Milky Way like galaxies density in the local Universe to be 0.01 Mpc^{-3} (e.g., O'Shaughnessy et al. 2008), then within such distance there should be 2.0×10^7 galaxies. Combining it with the Galactic rate we obtain the detection rate in the range $0.4 - 2.8 \times 10^{-2}$ yr^{-1}, or a detection every 36 to 250 years in the Advanced LIGO/VIRGO.

3. DISCUSSION

HMXBs like Cyg X-1 are wind fed, and thus their non-degenerate stars do not fill their Roche lobes. It is therefore curious that those systems for which good system parameters are known tend to be close to RLOF. Cyg X-1 is an example: our analysis implies that the system will begin RLOF in 0.2 Myr, after a lifetime about 50 times longer than that. An even more extreme case is that of LMC X-1, in which an 11 M$_\odot$ black hole is found in a 3.9 day orbit with a 32 M$_\odot$ companion. The companion currently fills over 90% of its Roche lobe, implying that the system will undergo RLOF within ≈ 0.1 M$_\odot$ (Orosz et al. 2009). Note that the high mass of the companion implies that RLOF will result in unstable mass transfer and the likely formation of a common envelope system — this LMC X-1 is unlikely to produce any sort of double degenerate binary.

There are only a few HMXBs with precisely known system parameters, so this tendency to be alarmingly near RLOF may be a statistical anomaly. Alternatively, it may be a selection effect: a system in which the companion is far from RLOF will have a smaller fraction of its stellar wind accrete onto the compact object, and thus a lower X-ray luminosity. However, Cyg X-1 and LMC X-1 are among the brightest known X-ray sources, and it seems likely that galactic sources with 10% or even 1% of their X-ray luminosity would still be identified and studied in some detail.

Therefore it may be worth entertaining the idea that this effect is neither a statistical glitch nor an observational bias, but that there is some unknown physical process that halts the growth of the companion star near the Roche lobe boundary. We note that the gravitational potential becomes shallow near the L_1 point, and X-ray irradiation becomes a bigger effect for companion stars that present a relatively large cross section. Both of these effects may dramatically change the surface structure and stellar winds of the companion star as it approaches the Roche lobe, conceivably in a self-limiting way. If so, the evolutionary path of the binary system may prove to be quite different from what is commonly assumed, and what we have assumed above.

To evaluate the possible effect this might have on rates of GR sources, we consider how the future evolution of an HMXB like Cyg X-1 might proceed if it never reaches RLOF. As a limiting case, we constrain the orbital period to remain at its currently observed value of $P_{\rm orb} = 5.6$d. In fact, we expect the orbital period to increase somewhat (even without RLOF) as mass is lost from the system in stellar wind, but the short orbital period naturally produces the most intact binaries. In this case, the survival through the supernova and the formation of the close BH-NS system is expected in 8.4% of cases and corresponds to Advanced LIGO/VIRGO detection rate of ~ 1 per decade. So despite the fact that we have violated (in favor of producing close BH-NS systems) our current understanding of the stellar evolution we still do not get enough BH-NS mergers to expect detection in gravitational waves.

Thus we find that if indeed BH-NS mergers are observed as GR sources, their immediate precursors will not be systems like Cyg X-1 that are current observed.

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Table 1

BH-NS Formation Statistics[a]

Fate/$P_{\rm orb}$[b]	104d	61.7d	5.6d
SN disruption	0.944 (0.743)	0.914 (0.673)	0.680 (0.446)
Wide BH-NS	0.056 (0.257)	0.086 (0.327)	0.320 (0.554)
Close BH-NS	0.002 (0.008)	0.004 (0.014)	0.083 (0.054)

[a] Fraction of Cyg X-1 like systems that after the second supernova will be disrupted, will form a wide BH-NS or close BH-NS (merger time shorter than the Hubble time). The fractions are given for the full natal kicks with $\sigma = 265$ km s^{-1} (or half kicks with $\sigma = 132.5$ km s^{-1}).

[b] Numbers for $P_{\rm orb} = 104$ and 61.7d correspond to physical system modeling with RLOF starting while the optical star is on MS and HG, respectively. The last model is unphysical, no RLOF was assumed and the orbital period was kept constant at $P_{\rm orb} = 5.6$d through the evolution (see the Discussion).

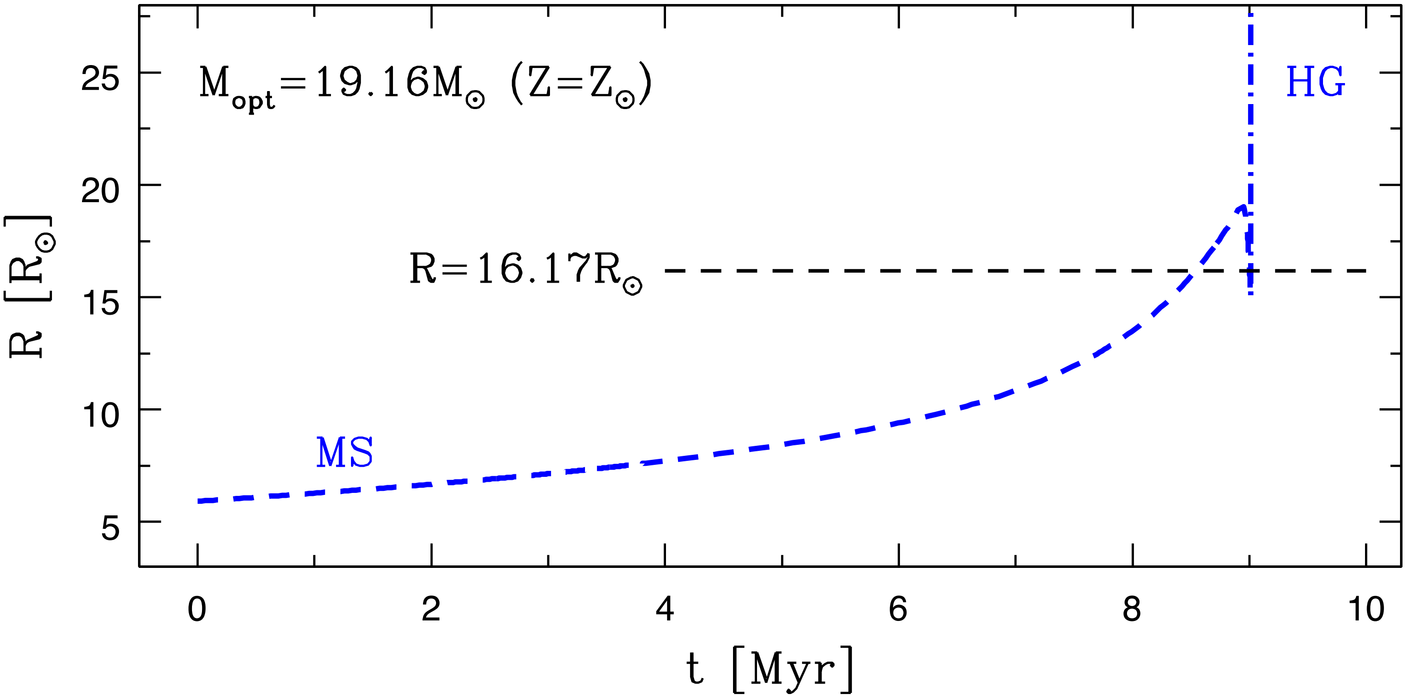

Fig. 1.— Radius evolution of optical star in Cyg X-1. Current radius is found at $R = 16.17 R_\odot$ and that places the star at the end of its Main Sequence (dashed line) or at the beginning of Hertzsprung gap (dot-dashed line). Since the star is very close to its Roche lobe ($R_{\rm lobe} = 17.24 R_\odot$ for the orbital period $P_{\rm orb} = 5.6$d) and since it has not yet started RLOF it means that the star is on Main Sequence at the first intersection of its evolutionary track and radius line of $R = 16.17 R_\odot$. Once the star increases its radius by about $1 R_\odot$ it will start RLOF while still on Main Sequence and the RLOF will last through Hertzsprung gap (see Fig. 2).

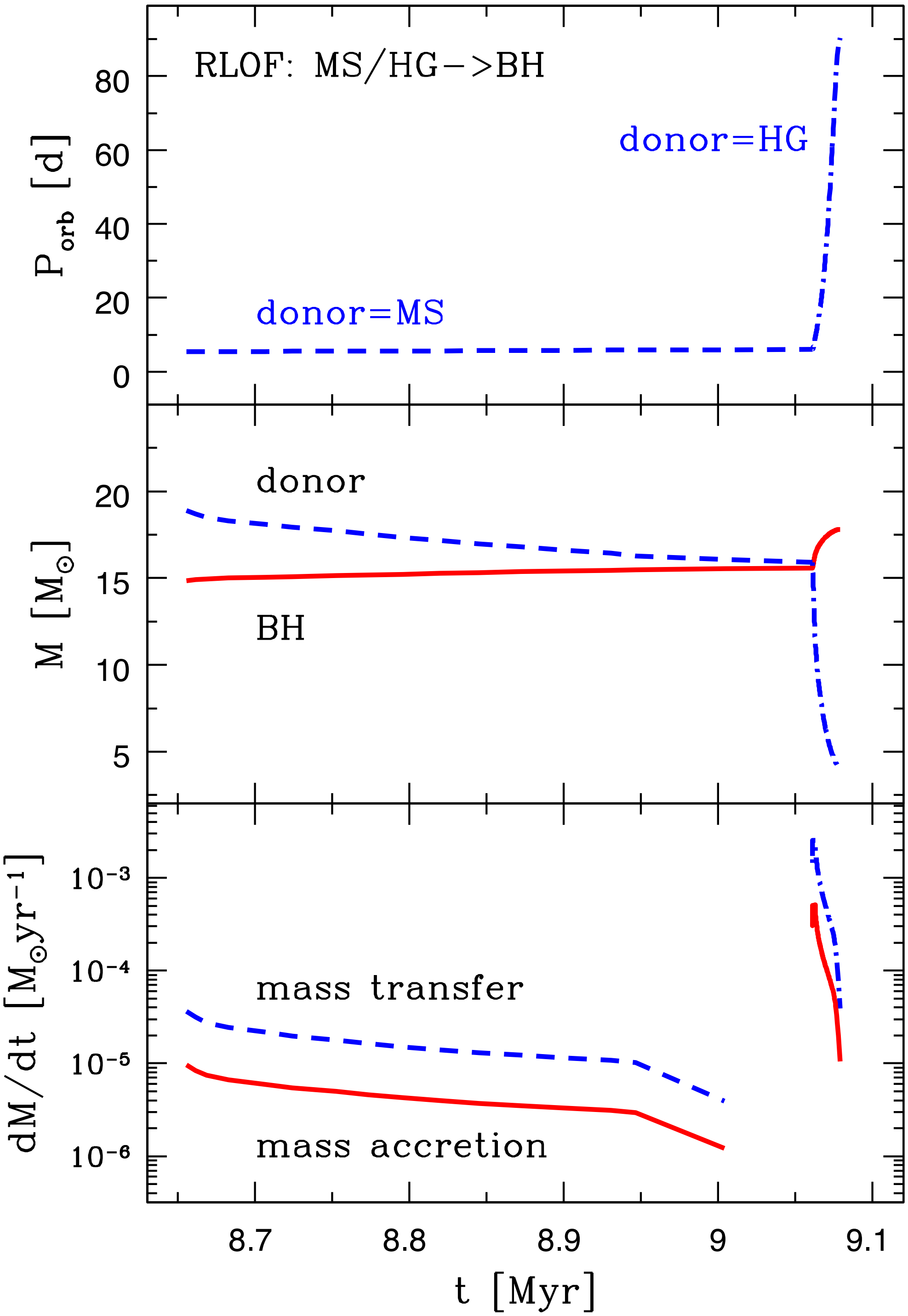

Fig. 2.— Evolution of Cyg X-1 through RLOF that will start in about 10^5 yr. *Bottom panel:* Mass transfer rate from the massive donor star is very high. However, it is much lower while the donor is on Main Sequence ($1-3\times10^{-5}$ $M_\odot$ yr^{-1}: dashed line) as compared to the transfer during Hertzsprung gap ($10^{-3}-10^{-4}$ $M_\odot$ yr^{-1}: dot-dashed line). Mass accretion onto BH is factor of $\sim 3-5$ lower than the transfer rate to account for the fact that BH cannot accept all the transferred material. Note that the accretion rate is significantly higher than typically employed Eddington rate (5×10^{-7} $M_\odot$ yr^{-1} for a 15 $M_\odot$ BH) as we account for more realistic super critical accretion (or ADAFs). *Middle panel:* The donor loses most of its mass to become a 4 $M_\odot$ helium core with a small H envelope. Most of the donor mass (~ 9 $M_\odot$) is lost from the system, while BH increases its mass from 14.8 to 17.8 $M_\odot$. *Top panel:* Period of the system changes from currently observed 5.6 days to 90 days. System becomes wide after the RLOF due to the non-conservative mass exchange and mass ratio reversal (most of the mass is accreted onto BH while the donor became the less massive component of the binary).