THE FATE OF Cyg X-1: AN EMPIRICAL LOWER LIMIT ON BLACK-HOLE–NEUTRON-STAR MERGER RATE

KRYSZTOF BELCZYNski1,2, TOMASZ BULIK1,3, AND CHARLES BAILYN4
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 UMR ARTEMIS, CNRS, University of Nice Sophia-Antipolis, Observatoire de la Cote d’Azur, BP 4299, 06304 Nice Cedex 4, France
4 Department of Astronomy, Yale University, PO, Box 208101, New Haven, CT 06520, USA
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ABSTRACT
The recent distance determination allowed precise estimation of the orbital parameters of Cyg X-1, which contains a massive $14.8M_{\odot}$ black hole (BH) with a $19.2M_{\odot}$ O star companion. This system appears to be the clearest example of a potential progenitor of a black hole + neutron star (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 neutron star (NS). It is demonstrated that in majority of cases ($\gtrsim 70\%$) the supernova and associated natal kick disrupt the binary due to the fact that the orbit expanded significantly in the Roche lobe overflow episode. In the remainder of cases ($\lesssim 30\%$) the newly formed BH–NS system is too wide to coalesce in the Hubble time. Only sporadically ($\sim 1\%$) may a Cyg X-1-like binary form a coalescing BH–NS system given a favorable direction and magnitude of the natal kick. If a Cyg X-1-like channel (comparable mass BH–O star bright X-ray binary) is the only or dominant way to form BH–NS binaries in the Galaxy, then we can estimate the empirical BH–NS merger rate in the Galaxy at the level of $\sim 0.001$ 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 $\sim 1$ 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.

Key words: binaries: close
Online-only material: color figures

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 et al. 1997; Bethe & Brown 1998; De Donder & Vanbeveren 1998; Bloom et al. 1999; Fryer et al. 1999; Nelemans et al. 2001; Voss & Tauris 2003; or more recently Belczynski et al. 2010a). 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 et al. (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 a 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 a Hubble time and produce strong GR signature. This provided an empirical lower limit 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 and other methods (Reid et al. 2011; Xiang 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 ($15M_{\odot}$) Galactic black holes (BHs) in a close orbit around a massive ($20M_{\odot}$) 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 hole + 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 BH with the mass $M_{\text{BH}} = 14.8M_{\odot}$, the optical star with the mass $M_{\text{opt}} = 19.2M_{\odot}$ and radius of $R_{\text{opt}} = 16.2R_{\odot}$ and the orbital period $P_{\text{orb}} = 5.6$ days (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 the main sequence (MS; see Figure 1). The mass ratio is close to unity so we do not expect the common envelope evolution, but rather a stable RLOF phase (Belczynski et al. 2008b; Wellstein et al. 2001). 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 the BH is calculated using the slim disk models (e.g., Abramowicz et al. 1988; Ohsuga et al. 2005; Ohsuga 2007) and since it has not yet started RLOF it means that the star is on the 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 the Hertzsprung gap (see Figure 2).

The radius evolution is taken from the single-star models of Hurley et al. (2000).

Figure 1. Radius evolution of an 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 the Hertzsprung gap (dot-dashed line). Since the star is very close to its Roche lobe (\( R_{\text{lobe}} = 17.24 \, R_\odot \) for the orbital period \( P_{\text{orb}} = 5.6 \) days) and since it has not yet started RLOF it means that the star is on the main sequence at the first intersection of its evolutionary track and radius line of \( R = 16.17 \, R_\odot \).

Table 1

| Fate/\( P_{\text{orb}} \) | 104 days | 61.7 days | 5.6 days |
|--------------------------|----------|----------|---------|
| SN disruption            | 0.944 (0.743) | 0.914 (0.673) | 0.680 (0.446) |
| Wide BH–NS               | 0.054 (0.249) | 0.082 (0.313) | 0.237 (0.500) |
| Close BH–NS              | 0.002 (0.008) | 0.004 (0.014) | 0.083 (0.054) |

Notes.

b Fraction of Cyg X-1-like systems that after the second supernova will be disrupted and 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 \( \sigma = 265 \, \text{km} \, \text{s}^{-1} \) (or half-kicks with \( \sigma = 132.5 \, \text{km} \, \text{s}^{-1} \)).

b Numbers for \( P_{\text{orb}} = 104 \) and 61.7 days correspond to physical system modeling with RLOF starting while the optical star is on MS and HG, respectively. The last model is unphysical, so RLOF was assumed and the orbital period was kept constant at \( P_{\text{orb}} = 5.6 \) days through the evolution (see the discussion).
Figure 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 the main sequence ($1 \times 10^{-5}$ to $3 \times 10^{-4} M_\odot$ yr$^{-1}$; dashed line) as compared to the transfer during the Hertzsprung gap ($10^{-3}$ to $10^{-2} M_\odot$ 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 the BH cannot accept all the transferred material. Note that the accretion rate is significantly higher than the typically employed Eddington rate ($5 \times 10^{-7} M_\odot$ yr$^{-1}$ for a $15 M_\odot$ non-spinning BH) as we account for more realistic supercritical accretion (slim disk advection dominated accretion flow) onto a rapidly spinning BH with $a = 0.9$ (Gou et al. 2011). 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 ($\sim 9 M_\odot$) is lost from the system, while the BH increases its mass from $14.8$ to $17.8 M_\odot$. Top panel: period of the system changes from the currently observed 5.6 days to 90 days. System becomes wide after 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). (A color version of this figure is available in the online journal.)

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 $2 \times 10^{-3}$ and $14 \times 10^{-3}$ (see bottom row of Table 1) from a Cyg X-1-like progenitor. This 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 formed over a 10 Gyr history of the Milky Way. For comparison the Galactic empirical neutron star + neutron star (NS–NS) merger rate is significantly higher: NS–NS $(3–190) \times 10^{-6}$ yr$^{-1}$ (Kim et al. 2010).

The implied Advanced LIGO/VIRGO detection rate follows once we determine the range of these detector for a BH–NS system. Given the final mass of the BH ($M_{BH} = 17.8 M_\odot$) and assuming the mass of an NS to be canonical, $1.4 M_\odot$, we obtain the chirp mass of the newly formed system to be $M_{\text{chirp}} \equiv (M_{BH} M_{\text{NS}})^{3/5}(M_{BH} + M_{\text{NS}})^{-1/5} = 3.8 M_\odot$. 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 $\propto M_{\text{chirp}}^{5/6}$). If we adopt the density of Milky-Way-like galaxies in the local universe to be $0.01$ Mpc$^{-3}$ (e.g., O’Shaughnessy et al. 2008), then within such a distance there should be $2 \times 10^7$ galaxies. Combining it with the Galactic rate we obtain the...
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The detection rate to be in the range \((0.4–2.8) \times 10^{-2} \text{ yr}^{-1}\), or a detection every 36–250 years in the Advanced LIGO/VIRGO.

The observational uncertainties on component masses \((\lesssim 2 M_\odot)\) do not play a significant role on our findings and qualitatively they do not change any of our results. The same applies to the stellar wind mass loss rate from the companion star as the 20 \(M_\odot\) star loses only about 1 \(M_\odot\) during its MS (e.g., Vink et al. 2001). The major uncertainties arise in the orbital evolution during RLOF in which \(\sim 15 M_\odot\) is lost/exchanged and supernova outcome (natal kicks).

3. DISCUSSION

So far we have discussed only one binary, Cyg X-1, as a potential progenitor of a BH–NS system. Tomsick & Mutearspski (2010) list several known Galactic HMXBs with an NS and a companion massive enough to potentially produce a BH: Vela X-1 (24 \(M_\odot\)), XTEJ1555-026 (25 \(M_\odot\)), 4U1907+09 (28 \(M_\odot\)), and GX301 (40 \(M_\odot\)). The expansion of massive companions will eventually lead to an RLOF. These systems due to extreme mass ratio will evolve into common envelope that will result in a merger of an NS with its companion, aborting the BH–NS formation. Such outcome follows from the fact that the mass of an NS is so small in respect to the mass of the envelope of a companion that there is not enough orbital energy to eject the companion envelope (e.g., Webbink 1984). An exagalaetic system LMC X-3 hosting a 10 \(M_\odot\) BH was believed to have a companion massive enough to form an NS. However, recent spectral analysis that takes into account irradiation of the companion indicates that it is a B5 dwarf setting its mass at about 5 \(M_\odot\) (Val-Baker et al. 2007) and makes it a WD progenitor.

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 some binaries 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 \(M_\odot\) BH 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 \(\sim 0.1\) Myr (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 have a lower X-ray luminosity.

Nevertheless, 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 hails 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. Such winds might be observable through the strength, shape, and variability of emission lines associated with the wind. If such an effect is present, 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 \(P_{\text{orb}} = 5.6\) days. In fact, we expect the orbital period to increase somewhat (even without RLOF) as mass is lost from the system in stellar wind. 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 an Advanced LIGO/VIRGO detection rate of \(\sim 1\) 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 currently observed.

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