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IC10 X-1/NGC300 X-1: THE VERY IMMEDIATE PROGENITORS OF BH–BH BINARIES

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ABSTRACT

We investigate the future evolution of two extragalactic X-ray binaries: IC10 X-1 and NGC300 X-1. Each consists of a high-mass black hole (BH; ∼20–30 $M_\odot$) accreting from a massive Wolf-Rayet (W-R) star companion ($\gtrsim$20 $M_\odot$), and both are located in low-metallicity galaxies. We analyze the current state of the systems and demonstrate that both systems will very quickly ($\lesssim$0.3 Myr) form close BH–BH binaries with short coalescence time (∼3 Gyr) and large chirp mass (∼15 $M_\odot$). The formation of a BH–BH system seems unavoidable, as (1) W-R companions are well within their Roche lobes and do not expand, so no Roche lobe overflow is expected; (2) even intense W-R wind mass loss does not remove sufficient mass to prohibit the formation of the second BH; and (3) even if the BH receives a large natal kick, the systems are very closely bound and are almost impossible to disrupt. As there are two such immediate BH–BH progenitor systems within 2 Mpc, and as the current gravitational-wave instruments LIGO/VIRGO (initial stage) can detect such massive BH–BH mergers out to ∼200 Mpc, the empirically estimated detection rate of such inspirals is $R = 3.36^{+8.29}_{-2.92}$ at the 99% confidence level. If there is no detection in the current LIGO/VIRGO data (unreleased year of *s*6 run), the existence of these two massive BH systems poses an interesting challenge. Either the gravitational radiation search is not sensitive to massive inspirals, or there is some fundamental misunderstanding of stellar evolution physics leading directly to the formation of BH–BH binaries.

Key words: binaries: close – black hole physics – gravitational waves – stars: evolution

Online-only material: color figure

1. INTRODUCTION

The interferometric gravitational-wave observatories LIGO and VIRGO have already reached their design sensitivities, and both are undergoing further improvements to reach the advanced sensitivity stage. The most promising sources of the gravitational waves for which these experiments are looking are coalescences of compact objects. Among these, most attention has been paid to double neutron star systems (NS–NS). There is observational evidence of their existence, and their merger rates seem to warrant detection with advanced interferometric experiments. The double black hole binaries (BH–BH) and black hole/neutron star binaries (BH–NS) have received less attention in rate prediction calculations. There are several reasons for this, including the fact that the direct detection of such systems in the electromagnetic domain is difficult. From the theoretical point of view, the formation of such systems is not easy, as they have to pass through an unstable mass transfer phase, which is not easy to survive for typical BH masses of around 10 $M_\odot$ (Belczynski et al. 2007). However, it was shown recently that in low-metallicity environments this obstacle can be overcome and that formation rates of binary BHs can be quite high (Belczynski et al. 2010a).

The recent advances in X-ray instrumentation allow the study of X-ray binaries in the Local Group galaxies. IC10 X-1 was discovered in the *ROSAT* data by Brandt et al.(1997). Bauer & Brandt (2004) found an X-ray variability of IC10 X-1 in a short *Chandra* observation. Clark & Crowther (2004) analyzed the possible optical counterparts of IC10 X-1 (Crowther et al. 2003) and argued that it is a 35 $M_\odot$ WNE star. Subsequent longer *Chandra* observations led to the discovery of X-ray periodicity (Prestwich et al. 2006). Prestwich et al. (2007) analyzed the X-ray and optical data of IC10 X-1 and found that it contains a BH of a mass at least 23 $M_\odot$ in a binary with a ≈35 $M_\odot$ companion. This result has recently been confirmed by Silverman & Filipenko (2008), who measured precisely the amplitude of the radial velocity of the companion. The binary NGC300 X-1 is a system similar to IC10 X-1 (Crowther et al. 2007). Crowther et al. (2010) measured precisely the radial velocity amplitude in NGC300 X-1 and showed that it contains a 20 $M_\odot$ BH accreting from a 26 $M_\odot$ Wolf-Rayet (W-R, or naked helium) star. The orbital periods in the two systems are similar.

Apparently, BHs of stellar origin can reach a much larger mass than previously thought. Such high-mass BHs are already fully explained by current evolutionary models (Belczynski et al. 2010b). Additionally, these more massive stellar BHs can be found in binaries with very massive companions. In this paper, we analyze the future binary evolution of IC10 X-1 and NGC300 X-1 using the `StarTrack` binary evolution code. We show that, regardless of evolutionary uncertainties, these systems should form close high-mass BH–BH binaries. Such BH–BH binaries formed at low metallicity were already predicted, on theoretical grounds, to be the first detectable sources for gravitational radiation instruments like LIGO and VIRGO (Belczynski et al. 2010a).

2. MODEL

2.1. Evolutionary Code

Our population synthesis code, `StarTrack`, was initially developed to study double compact object mergers in the context of gamma-ray burst progenitors (Belczynski et al. 2002b) and gravitational-wave inspiral sources (Belczynski et al. 2002a). In recent years, `StarTrack` has undergone major updates and revisions in the physical treatment of various binary evolution phases, especially the mass transfer phases. The new version has already been tested and calibrated against observations and detailed binary mass transfer calculations (Belczynski et al. 2008) and has been used in various applications (e.g., Belczynski & Taam 2004; Belczynski et al. 2004, 2005, 2006, 2007). The physics updates that are most important for compact object formation and evolution include a full numerical approach for the orbital evolution due to tidal interactions, calibrated using high-mass X-ray binaries and open cluster observations; a detailed treatment of mass transfer episodes fully calibrated against detailed calculations with a stellar evolution code, updated treatment of mass transfer, and common envelope phases; and the latest determination of natal kick velocity distribution for NSs (Hobbs et al. 2005). The kicks for BHs decrease proportionally to the amount of fall back during core-collapse/supernova explosion. For the most massive stars ($M_{\rm zams} \gtrsim 40\,M_\odot$) forming massive BHs without a supernova explosion (see Fryer & Kalogera 2001) we assume no natal kick.

The most recent update, employed in this study, concerns wind mass loss from massive stars. Of particular interest here are mass-loss rates from massive naked helium stars. For W-R stars, we adopt

$$(dM/dt) = 10^{-13} L^{1.5} \left(\frac{Z}{Z_\odot}\right)^m M_\odot\,{\rm yr}^{-1}, \qquad (1)$$

which is a combination of the Hamann & Koesterke (1998) wind rate estimate that takes into account W-R wind clumping (reduced winds) and the Vink & de Koter (2005) wind Z-dependence that estimates $m = 0.86$ for W-R stars. Using the above estimate, along with other updated mass-loss rates, we were able to recover the masses of most massive BHs in different galaxies (Belczynski et al. 2010b). The other helium star properties (e.g., radii, luminosities, and lifetimes) are adopted from Hurley et al. (2000), who employed detailed evolutionary calculations for W-R stars presented later by Pols & Dewi (2002). For a full description of the population synthesis code we refer the reader to Belczynski et al. (2008).

2.2. Host Galaxy Metallicity

IC10 is a barred irregular galaxy in the Local Group at a distance between 600 and 800 kpc (Saha et al. 1996, 1999). It is undergoing very rapid star formation and has a very high number of W-R stars. IC10 has low metallicity; Lequeux et al. (1979) estimate it to be $Z = 0.15\,Z_\odot$, but later studies by Massey et al. (2007) place it somewhere between the values for the LMC and the SMC. Thus, we conservatively adopt the value of $Z = 0.3\,Z_\odot$. IC10 is a galaxy with a high star formation rate (SFR) and it contains more than a hundred W-R stars (Massey & Holmes 2002).

The metallicity of the NGC300 galaxy has been measured by Urbaneja et al. (2005). The galaxy exhibits some metallicity gradients, and at the location of NGC300 X-1 it is log (O/H) + 12 ≈ 8.44, which corresponds to $Z = 0.6\,Z_\odot$ (Crowther et al. 2010).

3. RESULTS

3.1. The Future Evolution of IC10 X-1

At present, IC10 X-1 has an orbital period of 34.93 hr. BH mass is estimated to be 23–33 $M_\odot$, while its companion is a

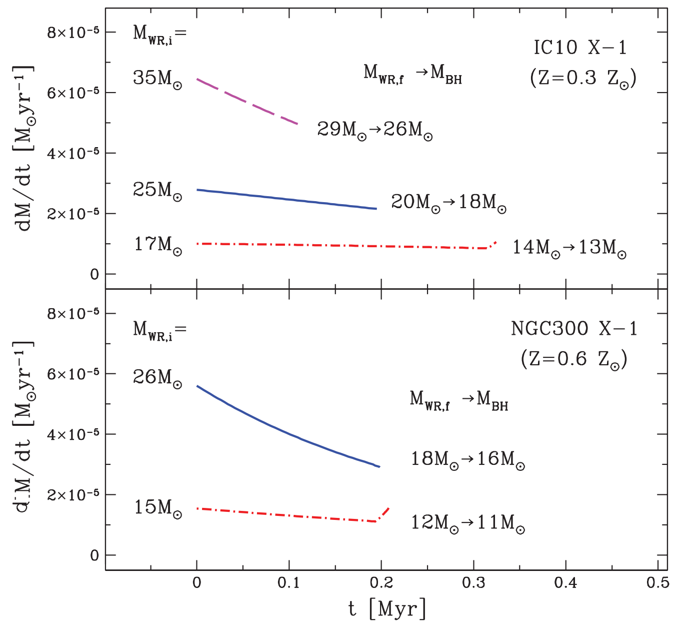

Figure 1. Mass-loss rates from W-R stars as a function of age in the two systems considered in the paper. The top panel corresponds to IC10 X-1 and the bottom panel shows the case of NGC300 X-1. Each line is labeled by the initial mass of the star on the left-hand side. On the right-hand side, we show the final mass of the star and the mass of the compact object (BH) formed as a result of the evolution.

(A color version of this figure is available in the online journal.)

helium star of a mass 17–35 $M_\odot$. The system is an eclipsing X-ray source with X-ray luminosity of 2×10^{38} erg s^{-1}; the lower limit on inclination was placed at 78° (Silverman & Filipenko 2008).

The fate of the W-R star is mainly set by wind mass loss. We consider three cases for the IC10 X-1, describing the current state of the systems: case (a), in which BH mass is 23 $M_\odot$ and W-R star mass is 17 $M_\odot$; case (b), in which BH mass is 28 $M_\odot$ while W-R star mass is 25 $M_\odot$; and case (c), in which BH mass is 33 $M_\odot$ while W-R star mass is 35 $M_\odot$. The evolution of the W-R stars with the metallicity $Z = 0.3\,Z_\odot$ (IC10) is followed (see the top panel of Figure 1). The wind mass loss rate strongly depends on the initial mass of the star and on its metallicity. In each case, we assume that the measured mass corresponds to the initial, unevolved state of the W-R star. In case (a) the 17 $M_\odot$ W-R star loses 3 $M_\odot$; in case (b) the 25 $M_\odot$ star loses 5 $M_\odot$; and in case (c) the 35 $M_\odot$ star loses 6 $M_\odot$ over its entire lifetime. Due to the mass loss from the W-R component, the orbit expands slightly (by ∼2 $R_\odot$) and the period increases to ∼40 hr. Throughout its evolution the massive W-R star, for any value of the adopted mass, is always well within its Roche lobe. For the intermediate mass of 25 $M_\odot$, the radius of the W-R component is $R_{\rm W\text{-}R} \sim 1$–$2\,R_\odot$ while the Roche lobe radius is $R_{\rm roche} \gtrsim 7\,R_\odot$. The Roche lobe volume filling factor is of the order of $f_{\rm fill} \equiv (R_{\rm W\text{-}R}/R_{\rm roche})^3 \sim 0.01$. The W-R component fills only 1% of its Roche lobe. There is no chance of Roche lobe overflow in this system; therefore, the only mass transfer proceeds via stellar wind as calculated in our model.

The W-R star eventually undergoes core collapse. In each case, it is so massive that the initial star mass must have been above $M_{\rm zams} = 40\,M_\odot$ (helium star mass is on average about 1/3 of the initial star mass, e.g., Hurley et al. 2000). While the details of stellar collapse are still far from being understood, the calculations of core collapse by Fryer & Kalogera (2001) indicate that such massive stars form BHs through direct collapse; in other words, the entire star ends up in the BH as the explosions are extremely weak for such high masses. However, we allow for 10% mass loss in neutrinos in our calculations. In each case a BH is formed (see Figure 1) and its mass varies from 14 $M_\odot$ for case (a) through 18 $M_\odot$ for case (b) to 26 $M_\odot$ in case (c). Since there is no (or almost no) mass loss in the core collapse, the BH most likely receives no (or only a small) natal kick.

In all cases, the binary survives the formation of a second BH, thus the IC10 X-1 evolution leads to the formation of a BH–BH binary. The mass loss in neutrinos induces a small eccentricity $e \approx 0.04$; however, the orbit remains mostly unchanged. The chirp mass of the newly formed binary varies from 15 $M_\odot$ for case (a) through 20 $M_\odot$ for case (b) and up to 26 $M_\odot$ in case (c). In each case, the binary mass and the size of the orbit cause it to merge in a relatively short time: 2.6 Gyr (a), 1.8 Gyr (b), and 1.2 Gyr (c).

3.2. The Future Evolution of NGC300 X-1

NGC300 X-1 has a period of 32.3 hr, which is very close to that of IC10 X-1. Crowther et al. (2010) report that the mass of the W-R companion is likely to be 26 $M_\odot$, which implies the mass of the BH to be 20 $M_\odot$. However, if other stars contribute to the measured optical flux, then the W-R star mass can be 15 $M_\odot$ and the implied BH mass is 14.5 $M_\odot$. We will refer to the latter estimate as case (a), while the former with its more massive BH will be denoted as case (b). The evolution of the W-R star at the metallicity appropriate for its location within NGC300 ($Z = 0.6\,Z_\odot$) is calculated. The results are shown in the bottom panel of Figure 1. In case (a), the 15 $M_\odot$ W-R star loses 3 $M_\odot$ and forms an 11 $M_\odot$ BH. In case (b), the W-R star loses 8 $M_\odot$ in the wind and forms a 16 $M_\odot$ BH. Note that mass loss in the case of NGC300 X-1 is relatively higher than that of IC10 X-1, as the former system's host galaxy has more metal-rich stars and therefore wind mass loss is more efficient. The system orbit expands slightly (by ∼2–4 $R_\odot$) and the period increases to ∼37–47 hr for case (a) and case (b), respectively. Throughout its evolution, the massive W-R star ($R_{\text{W-R}} \sim 1$–$2\,R_\odot$), for any value of the adopted mass, is always well within its Roche lobe ($R_{\text{roche}} \gtrsim 6\,R_\odot$). The Roche lobe volume filling factor is very small ($f_{\text{fill}} \sim 0.01$), and there is no chance for Roche lobe overflow.

At the time of core collapse, the W-R component is massive enough to form a BH through direct collapse. The mass of the second BH is 11 $M_\odot$ (a) or 16 $M_\odot$ (b). The system acquires small eccentricity ($e \approx 0.04$). The merger time of the binary BH system is 4.0 Gyr in case (a) and 3.8 Gyr in case (b). The chirp mass of the BH–BH binary is between 11 $M_\odot$ (a) and 15 $M_\odot$ (b). Thus, NGC300 X-1 is another example of a system that will evolve to form a merging BH–BH.

3.3. Estimate of the Coalescence Rate

The *Chandra* or *XMM-Newton* sensitivity to detect X-ray binaries like IC10 X-1 or NGC300 X-1 extends to distances beyond the Local Group. However, the sensitivity to fully analyze such binaries is limited by the possibility of obtaining spectroscopic orbits. This in turn is limited by the brightness and spectral properties of the W-R stars. The absolute brightness of a massive W-R star is about $M_v \approx -5$, and a spectroscopic orbit can be measured for stars with apparent magnitude down to $m_v \approx 21$. Thus, a detailed spectroscopic orbit of a W-R star can be obtained up to a distance of ≈2 Mpc. Let us assume that such binaries could be detected up to the distance of r_s, and only a fraction Ω_s of the sky has been searched for such systems; therefore, we can estimate the volume in which they are detectable as $V_s = \Omega_s r_s^3/3$.

The entire sky has not been surveyed for such binaries; however, we can assume that *almost* all the sky has been searched for such binaries, so $\Omega_s = 4\pi$. This is a conservative assumption, i.e., it underestimates the formation rate of binary BHs since we overestimate the volume surveyed for such binaries so far. The lifetime of the IC10 X-1 in the X-ray bright phase (accretion from intense wind of W-R companion) is not longer than $t_{\text{IC10}} \approx 0.3$ Myr, while for the NGC300 X-1 it is shorter than $t_{\text{NGC300}} \approx 0.2$ Myr (see Figure 1). The current formation rate density of merging compact object binaries from IC10 X-1- and NGC300X-1-like systems can be estimated as

$$\rho_{\text{IC10}} \approx V_s^{-1} t_{\text{IC10}}^{-1} \tag{2}$$

$$\rho_{\text{NGC300}} \approx V_s^{-1} t_{\text{NGC300}}^{-1} \tag{3}$$

$$\rho = \rho_{\text{IC10}} + \rho_{\text{NGC300}}. \tag{4}$$

Assuming that the SFR is constant, and noting that the merger times of the BH–BH binaries described above are significantly smaller than the Hubble time, this is also the estimate of the current BH–BH merger rate density. A detailed calculation, presented in the Appendix, leads to the estimate of the merger rate density: $\rho = 0.36^{+0.50}_{-0.26}$ Mpc^{-3} Myr^{-1} at the 90% confidence level.

In order to estimate the detection rate in current gravitational-wave detectors, we must take into account the different chirp masses of the two binaries. In order to be conservative, we will only consider the low-mass cases: (c) for IC10 X-1 with $M_{\text{chirp}}^{\text{IC10}} = 15\,M_\odot$ and (b) for NGC300 X-1 with $M_{\text{chirp}}^{\text{NGC300}} = 11\,M_\odot$.

We assume that current LIGO sensitivity allows it to detect an NS–NS binary with a chirp mass of 1.2 $M_\odot$ to a distance of $r_{\text{NSNS}} = 18$ Mpc. This is the sky-averaged horizon. The sensitivity range depends on the chirp mass M_{chirp} of a given binary and scales as $M_{\text{chirp}}^{5/6}$. The detection rate of BH–BH inspirals is a sum of the rates originating in IC10 X-1- and in NGC300 X-1-like binaries:

$$\mathcal{R}_{\text{IC10}} = \frac{4\pi}{3} {r_{\text{NSNS}}}^3 \rho_{\text{IC10}} \left(\frac{M_{\text{chirp}}^{\text{IC10}}}{1.2\,M_\odot} \right)^{5/2} \tag{5}$$

$$\mathcal{R}_{\text{NGC300}} = \frac{4\pi}{3} {r_{\text{NSNS}}}^3 \rho_{\text{NGC300}} \left(\frac{M_{\text{chirp}}^{\text{NGC300}}}{1.2\,M_\odot} \right)^{5/2} \tag{6}$$

$$\mathcal{R} = \mathcal{R}_{\text{IC10}} + \mathcal{R}_{\text{NGC300}}. \tag{7}$$

We present the probability density distribution of the total rate R as well as the contributions from each type of binary in Figure 2. We have calculated the confidence intervals for the total rate, and they are $R = 3.36^{+2.44}_{-1.62}$ at the 68% confidence level, $R = 3.36^{+4.55}_{-2.32}$ at the 90% confidence level, and $R = 3.36^{+8.29}_{-2.92}$ at the 99% confidence level.

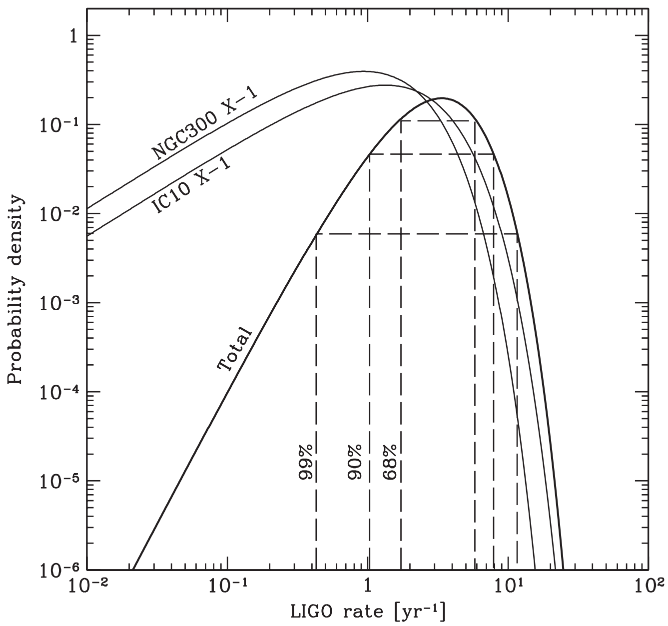

Figure 2. Probability distributions of the total detection rate in LIGO (thick solid line), along with the contributions from each of the binaries: IC10 X-1 and NGC300 X-1 (thin solid lines). The dashed lines denote the levels and intervals corresponding to the ranges containing 68%, 90%, and 99% of probability. The empirical estimate of the detection rate of BH–BH binaries for the initial LIGO is $R = 3.36^{+8.29}_{-2.92}$ at the 99% confidence level.

4. DISCUSSION

4.1. Potential Caveats

There are two crucial points that lead to determination of the mass of the BH in both systems: (1) the estimate of the mass of the companion W-R star, and (2) the estimate of its orbital velocity. In the case of (1), the W-R star mass, we have used the lowest estimate consistent with observations in both cases. Higher masses of the W-R star imply higher BH masses and only increase the estimate of the coalescence rate. Thus, the uncertainty from the W-R mass estimate is not crucial. The second point (2), the estimate of the orbital velocity, may however be overestimated by a systematic effect. It has been suggested by van Kerkwijk (1993) that the wind could be highly ionized except in the region shadowed by the star. This ionized wind model was originally developed in the context of Cyg X-3. In this model, large velocities of the lines in the spectrum in this model originate from the wind rather than from the orbital velocity of the W-R star. Such an effect would lead to overestimates of the orbital velocity and the mass of the BH. Such an ionized wind model predicts blueshifted spectra at the moment of the X-ray eclipse and can be distinguished by simultaneous X-ray and optical observations. Such observations are not yet available for the binaries considered here. Moreover, such a model would lead to a different shape of the radial velocity curve, so detailed time-resolved spectroscopy of the system might be helpful. Such an ionized model may be difficult to apply to IC10-X-1 and NGC300 X-1 because of their much longer orbital periods than that of Cyg X-3, which is 4.8 hr.

Our conclusion on the lack of ongoing or future Roche lobe overflow is based on the fact that stellar models indicate that massive W-R stars are very compact, $R_{\text{W-R}} \sim 1\text{–}2\,R_\odot$ (e.g., Pols & Dewi 2002), while both systems under consideration are relatively wide, with Roche lobe radii of W-R components of the order of $R_{\text{roche}} \gtrsim 6\text{–}7\,R_\odot$. However, it was claimed that some specific physical conditions (iron opacity peak) within W-R stars may lead to the radial inflation of the outer atmosphere (e.g., Ishii et al. 1999). This effect was recently examined in detail by Petrovic et al. (2006), and it was found that for sub-solar metallicities and realistic calculations (with wind mass loss) the W-R stars with mass $\sim$10–30 $M_\odot$ remain compact ($<2\,R_\odot$). Radii of massive W-R stars are very difficult to determine observationally even if bolometric luminosity and temperature are known (e.g., Hamann et al. 1995; Moffat & Marchenko 1996). Due to strong optically thick winds, W-R stars appear larger than they most likely are. For example, the radius of the W-R component in NGC300 X-1 was observationally determined to be $\sim$5–7 $R_\odot$ (Crowther et al. 2010), while stellar models indicate a much smaller value.

We have assumed that the currently observed W-R mass is its initial mass. If, in fact, the W-R star were initially more massive and by now has gone through part of its evolution (as it most likely has), then the mass loss from now on will be lower (less time left until core collapse) than we have estimated. Therefore, if anything, we underestimate the final mass of the W-R component and the BH mass it will form. Our mass-loss rates are on the high side and thus we may additionally be underestimating the mass of the second BH. For example, in the case of IC10 X-1, the mass loss is estimated at the level of $\sim 10^{-5}\,M_\odot\,\text{yr}^{-1}$ (Clark & Crowther 2004), while we employ the wind mass loss rates in the range $1\text{–}6 \times 10^{-5}\,M_\odot\,\text{yr}^{-1}$ depending on the adopted mass of the W-R component (see Figure 1). This is even more clear in the case of NGC300 X-1, for which the mass-loss rate is determined to be $\sim 5 \times 10^{-6}\,M_\odot\,\text{yr}^{-1}$ (Crowther et al. 2010), while we employ much higher rates $\sim 5 \times 10^{-5}\,M_\odot\,\text{yr}^{-1}$.

Based on high W-R star mass in both systems, we have followed Fryer & Kalogera (2001) to infer that the second BHs in IC10 X-1 and NGC300 X-1 will form through direct collapse of the entire star to a BH. While the core-collapse calculations and modeling are still uncertain, we must note that all models agree that stars with initial masses above 40 $M_\odot$ will form BHs. The initial masses of the progenitors of W-R stars in IC10 X-1 and NGC300 X-1 were above 40 $M_\odot$, so it is quite likely that BHs should be formed. The exact masses of the BHs may, however, vary between different models. Since there is no mass loss in direct formation of the BH, we have assumed zero natal kick in both cases. This holds true if the natal kicks are connected with asymmetry in mass ejection during supernova explosion. This has some observational support in the fact that most massive BHs in our Galaxy that are believed to have formed through direct collapse show no sign of natal kick (Mirabel & Rodrigues 2003; Dhawan et al. 2007; Martin et al. 2010). If, for some reason, these massive BHs received a kick as large as that observed for Galactic NSs ($\sim$200–300 km s^{-1}; e.g., Hobbs et al. 2005), both systems would survive and still form close (but rather eccentric) BH–BH binaries with coalescence time below the Hubble time. The relative orbital velocity in the pre-explosion binary for both IC10 X-1 and NGC300X-1 is $\approx$600 km s^{-1}. Since even a large natal kick is not likely to exceed the orbital velocity, the binaries are expected to survive (e.g., Kalogera 1996).

The estimate of the initial LIGO detection rate is very high and is actually quite conservative. Including the more accurate fraction of the sky that has been surveyed leads to a decrease of Ω_s and an increase of the expected rate. The estimated range r_s to obtain spectroscopic orbits of such binaries has been calculated neglecting the potential effects of extinction.

Decreasing this range increases the expected coalescence rate density. The expected rate depends on the inverse of the assumed lifetime in the X-ray phase, and we have chosen the maximum possible values for the W-R lifetime in Equation (4).

Both IC10 X-1 and NGC300 X-1 are very young systems with current ages shorter than $t_{\rm evol} \approx 10$ Myr (this is an evolutionary lifetime of an $M_{\rm ZAMS} = 20\,M_\odot$ star). Therefore, both systems were formed very recently in the universe with rather low star formation. The merger time for both systems was estimated at ∼2–4 Gyr. If the production of binaries like IC10 X-1 and NGC300 X-1 is in any way proportional to the SFR (as seems logical), it must have been more than 2–4 Gyr ago, as star formation increases with redshift all the way to redshifts of $z \approx 2$ (≈10 Gyr ago; e.g., Strolger et al. 2004). Since we have assumed that the SFR is constant as a function of redshift at a level that corresponds to the current low SFR (the very young age of both binaries), we have again underestimated the formation efficiency of similar binaries, and the predicted detection rates are lower limits with respect to the SFR. Moreover, the median metallicity of galaxies was lower a few billion years ago, when the currently merging systems formed (e.g., Pei et al. 1999; Young & Fryer 2007). This could also bring the current coalescence rate up, as it appears that the formation of binaries with massive BHs occurs in low-metallicity host galaxies.

On the other hand, it is obvious that our arguments are based on just two objects and therefore are subject to small number statistics. One should treat our results only as an indication of the possibility of existence of a large population of merging massive BH–BH binaries. In summary, the value of the rate presented here should be considered as a lower limit, while keeping in mind that our arguments and calculations are based only on two objects.

4.2. Conclusions

We have shown that the future evolution of the binaries IC10 X-1 and NGC300 X-1 will lead to the formation of BH–BH binaries with a merger time of 2–4 Gyr. Such systems are representative of a population that should be detectable by interferometric detectors like LIGO and VIRGO. Our estimate of the formation rate density of such systems is 0.36 $\rm Mpc^{-3}$ $\rm Myr^{-1}$, which implies the detection rate of their coalescences by current LIGO and VIRGO of 3.36 $\rm yr^{-1}$. This means that such a merger should be found in the LIGO data that have already been gathered. The absence of a massive BH–BH inspiral signal in the $s6$ LIGO and VIRGO data, at their current sensitivities, implies astrophysically interesting limits on the coalescence rates of massive BH–BH binaries.

This estimate is similar to the one in the recently published theoretical study of BH–BH formation in a low-metallicity environment (Belczynski et al. 2010a). In that paper, the authors find that a low-metallicity environment greatly enhances the formation rate of massive BH–BH binaries. This is due to the fact that low-metallicity binaries are much more likely to survive the common envelope stage and form close BH–BH systems. Survival of the common envelope stage was shown to be a key issue in BH–BH formation (Belczynski et al. 2007). Belczynski et al. (2010a) provided a population synthesis prediction of the BH–BH detection rate under the assumption that there is a significant population of low-metallicity galaxies (50%; Panter et al. 2008) in the local universe. They have provided a rate estimate for two models, one in which they do not allow for the suppression of BH–BH formation due to common envelope mergers (model A) and another in which such a suppression is physically motivated and allowed (model B). The BH–BH detection rates for the current LIGO were calculated at such a high level for model A (∼5 $\rm yr^{-1}$) that Belczynski et al. (2010a) excluded this model as unrealistic in anticipation of no detection in the just accomplished $s6$ LIGO run.[5] However, it seems that the existence of IC10 X-1 and NGC300 X-1 support such a high detection rate.

In conclusion, if in fact there is no gravitational radiation signal from inspiraling massive BH–BH binaries in the last $s6$ LIGO run, either the current search is insensitive to high chirp mass binaries or there is some fundamental misunderstanding of the last stages of evolution leading directly to the formation of BH–BH mergers from binaries like IC10 X-1 and NGC300 X-1.

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APPENDIX

Let us assume that the formation rate per unit time per unit volume of massive X-ray binaries similar to IC10 X-1 is ρ. Then the expected number of such binaries in a volume V, given that they are X-ray active for a time T, is $\lambda = \rho V T$. The probability of observing one object is then given by the Poisson distribution:

$$P(1|\lambda) = \lambda e^{-\lambda}. \tag{A1}$$

We are interested in measurement of ρ, thus we can use the Bayes theorem to obtain the probability of the rate given a single observation,

$$P(\lambda|1) = P(1|\lambda)P(\lambda)/P(1), \tag{A2}$$

where $P(\lambda)$ is the prior probability and $P(1)$ can be treated as the normalization of the resulting probability distribution. We assume a flat prior $P(\rho) = \text{const}$. Given the observed volume $V = \frac{4\pi}{3} R_s^3$, where $R_s \approx 2$ Mpc, and the time $T_{\rm IC10} = 0.2$ Myr, we obtain the probability distribution of $\rho_{\rm IC10}$, the formation rate of IC10-like systems:

$$\frac{dP}{d\rho_{\rm IC10}} = A^2 \rho e^{-A\rho}, \tag{A3}$$

where $A = VT_{\rm IC10}$. Analogously, for NGC300 X-1-like systems we have the probability distribution of the formation rate:

$$\frac{dP}{d\rho_{\rm NGC300}} = B^2 \rho e^{-B\rho}, \tag{A4}$$

where $B = VT_{\rm NGC300}$, and $T_{\rm NGC300} = 0.3$ Myr. We can now calculate the probability density of the total formation rate of binaries like IC10 X-1 and NGC300 X-1, $\rho = \rho_{\rm IC10} + \rho\rm NGC300$:

$$\frac{dP}{d\rho} = \iint d\rho_{\rm IC10}\, d\rho_{\rm NGC300}\, \delta(\rho - (\rho_{\rm IC10} + \rho\rm NGC300)) \times \frac{dP}{d\rho_{\rm IC10}} \frac{dP}{d\rho_{\rm NGC300}}. \tag{A5}$$

[5] For model B, the rates obtained by Belczynski et al. (2010a) are much lower (∼0.05 $\rm yr^{-1}$) and are consistent with no detection in the $s6$ LIGO run.

A simple calculation gives

$$\frac{dP}{d\rho} = \frac{A^2B^2}{(A-B)^3}\left[e^{-\rho B}(\rho(A-B)-2) - e^{-\rho A}\right. \\ \left. \times (\rho(B-A)-2)\right]. \quad \text{(A6)}$$

We identify the formation rate with the coalescence rate, which can be justified since the coalescence time of each binary is shorter than the Hubble time.

In order to find the probability distribution of the LIGO detection rate coming from each of the binaries, we note that the probability density of the detection rate is connected with the merger rate via $\mathcal{R}_{\rm IC10} = V^{\rm GW}_{\rm IC10}\rho_{\rm IC10}$, where

$$V^{\rm GW}_{\rm IC10} = \frac{4\pi}{3} r^3_{\rm NSNS}\left(\frac{\mathcal{M}_{\rm IC10}}{1.2\,M_\odot}\right)^{5/2} \quad \text{(A7)}$$

is the volume in which BH–BH from IC10 X-1-like binaries is detectable, $r_{\rm NSNS} = 18$ Mpc is the current sky-averaged sensitivity distance for detection by LIGO of binaries with the chirp mass of $1.2\,M_\odot$, and $\mathcal{M}_{\rm IC10}$ is the chirp mass of the BH–BH binary that will form from IC10 X-1. For the chirp mass, we conservatively assume the minimum value $\mathcal{M}_{\rm IC10} = 15\,M_\odot$. The probability density of the detection rate $\mathcal{R}_{\rm IC10}$ is

$$\frac{dP}{d\mathcal{R}_{\rm IC10}} = \frac{dP}{d\rho_{\rm IC10}}\frac{d\rho_{\rm IC10}}{d\mathcal{R}_{\rm IC10}}. \quad \text{(A8)}$$

Analogously, the LIGO probability density of the detection rate of BH–BH binaries originating in NGC300 X-1 like binaries is

$$\frac{dP}{d\mathcal{R}_{\rm NGC300}} = \frac{dP}{d\rho_{\rm NGC300}}\frac{d\rho_{\rm NGC300}}{d\mathcal{R}_{\rm NGC300}}; \quad \text{(A9)}$$

we use $\mathcal{M}_{\rm NGC300} = 11\,M_\odot$ for the calculation. A simple calculation shows that the probability distribution densities

$$\frac{dP}{d\mathcal{R}_{\rm IC10}} = a^2\rho e^{-b\rho} \quad \text{(A10)}$$

$$\frac{dP}{d\mathcal{R}\rho_{\rm NGC300}} = b^2\rho e^{-b\rho}, \quad \text{(A11)}$$

where $a = 0.749$ yr and $b = 1.07$ yr. The calculation of the probability density of the total rate $\mathcal{R} = \mathcal{R}_{\rm IC10} + \mathcal{R}\rho_{\rm NGC300}$ follows along the same lines as above:

$$\frac{dP}{d\mathcal{R}} = \int\!\!\int d\mathcal{R}_{\rm IC10} d\rho_{\rm NGC300}\delta(\mathcal{R} - (\mathcal{R}_{\rm IC10} + \mathcal{R}_{\rm NGC300})) \\ \times \frac{dP}{d\mathcal{R}_{\rm IC10}}\frac{dP}{d\mathcal{R}_{\rm NGC300}} \quad \text{(A12)}$$

leading to the result

$$\frac{dP}{d\mathcal{R}} = \frac{a^2b^2}{(a-b)^3}\left[e^{-\mathcal{R}b}(cal R(a-b)-2) - e^{-\mathcal{R}a}\right. \\ \left. \times(cal R(b-a)-2)\right]. \quad \text{(A13)}$$

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