Neutron star–black hole binaries in LIGO/Virgo O3b run were formed from Population I/II binaries

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ABSTRACT

Two neutron star (NS)–black hole (BH) binaries, GW200105 and GW200115 found in the LIGO/Virgo O3b run have smaller BH mass of 6–9 $M_\odot$ which is consistent with Population I and II origin. Our population synthesis simulations using 10$^6$ Population I and II binaries with appropriate initial parameters show consistent binary mass, event rate, and no detection of radio pulsar (PSR) and BH binaries in our Galaxy so far. Especially, we found possible progenitors of GW200105 and GW200115 which were formed at redshift $z = 0.15$ and $z = 1.6$ with binary mass of (34$M_\odot$, 9.2$M_\odot$) and (23.7$M_\odot$, 10.6$M_\odot$), respectively. The final masses of these binaries are (6.85$M_\odot$, 2.14$M_\odot$) and (6.04$M_\odot$, 1.31$M_\odot$) which look like (9.0$^{+1.7}_{-1.0}$ $M_\odot$, 1.91$^{+0.33}_{-0.22}$ $M_\odot$) of GW200105 and (5.9$^{+2.7}_{-1.9}$ $M_\odot$, 1.44$^{+0.85}_{-0.29}$ $M_\odot$) of GW200115, respectively. We also estimate that 4–20 PSR-BH binaries in our galaxy will be observed by SKA. The existence of NS-BH binaries in our galaxy can be confirmed in future SKA era.

Key words: stars: population I/II, binaries: general relativity, gravitational waves, black hole mergers

1 INTRODUCTION

Two gravitational wave (GW) events of neutron star–black hole (NS-BH) coalescences, GW200105_162426 (abbreviated as GW200105) and GW200115_042309 (abbreviated as GW200115) were observed by the LIGO–Virgo detector network (Abbott et al. 2021). Table 1 is the summary of the events. Here, we present only the chirp mass $M_{\text{chirp}} = (m_1 m_2)^{3/5}/M^{1/5}$ (where $M = m_1 + m_2$), primary mass $m_1$ and secondary mass $m_2$ although the other parameters (spin etc.) have been estimated (e.g., an effective spin parameter defined with nondimensional spin parameters $(\chi_{1,z}$ and $\chi_{2,z}$ parallel to the orbital angular momentum, $\chi_{\text{eff}} = (m_1/M)\chi_{1,z} + (m_2/M)\chi_{2,z}$) were estimated for GW200115, respectively.

The NS-BH merger rate density (combined with analyses based on the two events, and including less significant search triggers) was estimated as 12–242 yr$^{-1}$Gpc$^{-3}$. This estimation has been updated to 7.4–320 yr$^{-1}$Gpc$^{-3}$ in The LIGO Scientific Collaboration et al. (2021b) using the third Gravitational-wave Transient Catalog (GWTC-3) (The LIGO Scientific Collaboration et al. 2021b) (see also GWTC-2.1 The LIGO Scientific Collaboration et al. (2021a) and the fourth Open Gravitational-wave Catalog (4-OGC) (Nitz et al. 2021)).

After the announcement of Abbott et al. (2021), various works on the population of these binaries have appeared. Wang & Zhao (2022) explained these GW events in a scenario of primordial BH (PBH) binaries (not NS-BHs) that satisfies existing astrophysical/cosmological bounds (see also Chen et al. (2021)) for another study on a PBH scenario. Sasaki et al. (2021) showed that the NS-PBH merger rate is subdominant to the NS-BH rate. Shao & Li (2021) have studied merging BH binaries with compact star systematically based on binary evolution calculations which can reproduce the distributions of known Galactic binaries and obtained the NS-BH merger rate density of 10.2–71.7 yr$^{-1}$Gpc$^{-3}$. Landry & Read (2021) focused on the mass distribution of NSs in GW events. Mandel & Broekgaarden (2021) gave us a great summary on merger rates of compact object binaries, i.e., NS-NSs, BH-BHs and NS-BHs for GW observations and various formation channels. Using metallicity-specific star formation rate density prescriptions (Broekgaarden et al. 2021b) in an isolated binary evolution scenario, Broekgaarden & Berger (2021) concluded that the observed two NS-BHs can be explained from this formation channel, and gave some constraint on the common envelope efficiency and the natal kick velocities of supernovae by treating BH-BHs and NS-NSs simultaneously. Taking the spin direction of BH of GW200115 into account, Fragione et al. (2021) discussed this NS-BH in the evolution of isolated massive binary stars and effects

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1 To extract more detailed information from these binaries, we need multiband GW observations, i.e., ground-based and space-based detectors (see e.g., Liu & Shao (2021) as an extension of Isoyama et al. (2018); Nakano et al. (2021))

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of natal kick and common envelope ejection (see also Zhu (2021)). Li et al. (2021) treated the mass distributions of NSs and BHs in the NS-BHs and NS-NSs by GW observation by hierarchical population inferences. Gompertz et al. (2021) focused on the tilt angle of the BH spin, i.e., spin-orbit misalignment in the NS-BHs, and suggested stronger natal kicks and/or stable mass transfer as sources of the tilts. Using information from the NS-BH GW events and radio pulsar (PSR) surveys in which no PSR-BH has been observed, Pol et al. (2021) derived an upper limit (95% CL) of ~150 PSR-BHs in our galaxy with the beaming direction to the Earth. Combining population synthesis simulations with a galaxy evolution simulation, Mandhai et al. (2021) have predicted that 16–40% events of short-duration gamma-ray burst will be hostless. Antoniadis et al. (2021) focused on highly unequal mass components of BH-BHs and NS-BHs, and showed that the landscape of core-collapse supernovae would cause the unequalness. In quadruple-star systems, Vynatheya & Hamers (2021) discussed BH-BH, NS-BH and NS-NS merger rates, and especially found that this NS-BH merger rate is not sufficient for that estimated by LIGO/Virgo. Farah et al. (2021) found that the two NS-BH GW events may have a component in the lower mass gap between NSs and BHs. Focusing on dynamical interactions in low-mass young star clusters, Trani et al. (2021) have discussed hierarchical triple systems, and given 0.11 yr⁻¹ Gpc⁻³ for the NS-BH merger rate density. Wagg et al. (2021) gave a prediction on GW event rates of BH-BH, NS-BH and NS-NS observed by a space-based detector, LISA (Amaro-Seoane et al. 2017). Zhu et al. (2021) showed that the BH mass distribution of NS-BH binary candidates (including also GW190814 and GW200210) can be explained by a power-law with a (double) Gaussian peak model. It should be noted that the current various conclusions on the formation channels (for BH-BHs) is still premature (Belczynski et al. 2021). Also note that Broekgaarden et al. (2021a) have pointed out model uncertainties on population synthesis simulations for BH-BHs, NS-NSs and NS-BHs in the isolated binary evolution channel, and the NS-BH merger rate density can be affected by stellar evolution and the star formation history.

In Kinugawa et al. (2017) (hereafter Paper I), we discussed the merger rate of Population (Pop) I, II and Pop III NS-BH binaries by using population synthesis Monte Carlo simulations, including the kick of NSs (Lyne & Lorimer 1994; Hansen & Phinney 1997) (see also Hobbs et al. (2005); Verbunt et al. (2017)). From Table 3 of Paper I, we found that the merger rates of Pop I, II and Pop III are 6.38–19.7 yr⁻¹ Gpc⁻³, and 0.956–1.25 yr⁻¹ Gpc⁻³, respectively. Therefore, the merger rate of Pop I and II NS-BHs in Paper I is consistent with the LIGO-Virgo result of 7.4–320 yr⁻¹ Gpc⁻³ in The LIGO Scientific Collaboration et al. (2021c). This implies that there are many PSR-BHs made by Pop I and II binary systems. In this Letter, based on the analysis in Paper I, we also estimate the number of PSR-BHs detected by current and future observations.

### 2 ANALYSIS

Theoretically NS-BH binaries can be formed in a certain evolution of binary stars. BH is usually formed first and next is NS because BH is usually formed from more massive star with shorter evolution time than the progenitor of NS. This means that some of them can be observed as a binary radio PSR with BH. However, no such object has been observed so far. This situation of no observed radio counter object of NS-BH binary is allowed if the expected number of NS-BH radio PSRs observed by existing radio telescopes is smaller than or compatible with the order of unity.

In Paper I, we performed population synthesis Monte Carlo simulations of Pop I, II and III binary stars using 10⁶ binaries with primary masses more than 5M⊙ for each given metallicity of Z = Z⊙, 10⁻⁹ Z⊙, 10⁻¹ Z⊙, 10⁻¹⁵ Z⊙ and Z = 0 (i.e., Pop III stars) where Z⊙ is the metallicity of the Sun. We assume in the simulation that when NS is formed it gets kick velocity of Maxwellian shaped absolute value with random direction. We consider two values of velocity dispersion of the kick velocity σ_k of 265 km/s and 500 km/s. The former value of the kick velocity is that of the observed single PSRs (Hobbs et al. 2005) and the latter is that of young PSRs (Verbunt et al. 2017). We show two examples of our simulation: the first one shown in Figure 1 is a NS-BH binary formed at redshift z = 0.15 with m₁ = 6.85 M⊙ and m₂ = 2.14 M⊙ which looks like GW200105, while the second one shown in Figure 2 is that of a NS-BH binary formed at z = 1.6 with m₁ = 6.04 M⊙ and m₂ = 1.31 M⊙ which looks like GW200115. These examples are made from binaries with Z = 10⁻⁰.5 Z⊙ which were born within a range of z = 0.1–2.5. Note here that binaries with Z = 10⁻⁰.5 Z⊙ dominate the merger rate of NS-BHs at z = 0 as shown in Figures 2 and 3 of Paper I.

Table 2 of this Letter shows metallicity dependence on numbers of NS-BH formation in 10⁶ Monte Carlo simulations. The numbers in parenthesis are NS-BHs which merge within the Hubble time. We treat two velocity dispersion models of the kick velocity of σ_k = 265 km/s, and σ_k = 500 km/s. Two panels in Figure 3 show the NS-BH merger rate densities for each chirp mass. The peak of chirp mass distribution of detectable NS-BHs is around 2–3 M⊙, which is consistent with the observation of GW200105 and GW200115 since their chirp mass are 3.42 M⊙ and 2.43 M⊙, respectively.

Figures 1 and 2 suggest that PSR-BH binaries should be observed in a certain time of the universe for each NS-BH binary formed in our scenario. The typical maximum age of observable radio PSRs is ~ 5 × 10⁷ yrs from the PSR death line for the magnetic field strength of ~ 10¹² G which is typical for newborn PSRs and PSRs in high mass X-ray binaries (HMXBs) (Enoto et al. 2019). We first estimate the number of NS-BHs formed from 5 × 10⁴ yrs ago up to now in our galaxy. Using the first column of Table 2 for Z = Z⊙, we obtain that the fraction of NS-BH binary is (0.3–1.5) × 10⁻⁴.

The star formation rate of our Galaxy at present is

### Table 1. Abbreviated event name, chirp mass M_chirp, primary mass m₁ and secondary mass m₂ in unit of the solar mass, M⊙ are from GWTC-3 (The LIGO Scientific Collaboration et al. 2021b). Each value is shown with the 90% credible interval.

| Event name | M_chirp | m₁ (M⊙) | m₂ (M⊙) |
|------------|---------|---------|---------|
| GW200105   | 3.42±0.08 | 9.0±1.7 | 19.1±0.2 |
| GW200115   | 2.43±0.07 | 5.9±2.0 | 14.4±0.2 |
Table 2. Metallicity dependence on numbers of NS-BH formation in $10^6$ Monte Carlo simulations. The numbers in parenthesis are NS-BHs which merge within the Hubble time. We treat two velocity dispersion models of the kick velocity of $\sigma_k = 265 \text{ km/s}$, and $\sigma_k = 500 \text{ km/s}$.

|       | $Z$ | $Z_{\odot}$ | $10^{-0.5} Z_{\odot}$ | $10^{-1} Z_{\odot}$ | $10^{-1.5} Z_{\odot}$ | $10^{-2} Z_{\odot}$ |
|-------|-----|-------------|------------------------|---------------------|------------------------|---------------------|
| NS-BH | $\sigma_k = 265 \text{ km/s}$ | 147 (15) | 598 (191) | 1295 (524) | 1686 (755) | 1896 (862) |
| NS-BH | $\sigma_k = 500 \text{ km/s}$ | 32 (2) | 169 (67) | 416 (213) | 576 (377) | 617 (401) |

Figure 1. The formation of a NS-BH with $m_1 = 6.85 \text{ M}_\odot$ and $m_2 = 2.14 \text{ M}_\odot$ which looks like GW200105 shown in Table 1. The pulsar kick velocity is 376 km/s with kick angle (0.98, 0.21, 0.05) where the kick angle is defined in Figure A1 of Hurley et al. (2002). MS, CHeB SN, BH, HG, and NS means a main sequence phase, a core Helium burning phase, a supernova, a black hole, a Hertzsprung gap phase, and a neutron star, respectively.

Figure 2. The formation of a NS-BH with $m_1 = 6.04 \text{ M}_\odot$ and $m_2 = 1.31 \text{ M}_\odot$ which looks like GW200115 shown in Table 1. The pulsar kick velocity is 271 km/s with kick angle (0.6, 0.72, -0.35) where the kick angle is defined in Figure A1 of Hurley et al. (2002). RSG, RG, WR, and HeG mean a red super giant, a red giant, a Wolf-Rayet star, and a Helium giant, respectively.

Then, the constant $C$ is determined as

$$C = 1.9 \times 10^7 \text{ M}_{\odot}^{-3}.$$  \hspace{1cm} (3)

In the calculation of Paper I, we have considered only stars with mass larger than $5 \text{ M}_\odot$ because we are interested in NS-BHs. Then, the total number of stars with mass larger than $5 \text{ M}_\odot$ is given by

$$\int_{5 \text{ M}_\odot}^{\infty} \phi(m) dm = 2.0 \times 10^6.$$ \hspace{1cm} (4)

Assuming here that 50% of the stellar systems are binaries, the number of binaries is $6.7 \times 10^5$. Under this assumption,
Figure 3. Chirp mass distributions of detectable NS-BHs at $z = 0$. The left and right panels show the cases of $\sigma_k = 265 \text{ km/s}$ and $\sigma_k = 500 \text{ km/s}$, respectively. The blue solid lines show the sum of the merger rate of Pop I, II and the merger rate of Pop III for each case. The orange dashed lines and green dotted lines show the merger rates of Pop I, II and the merger rates of Pop III, respectively.

the number of the Pop I binary stars which evolve to NS-BHs become $(0.3–1.5) \times 10^{-4} \times 6.7 \times 10^5 = 20–100$.

Now PSRs are beaming so that only the fraction of $\sim 0.2$ can be observed (Pol et al. 2019) (see also Kim et al. (2015)). While at present all the PSRs in our Galaxy are not observed but only 10% (Lorimer 2008) or so (see also a recent review Combes (2021)) due to the sensitivity of radio telescopes at present, in the SKA era almost all the active radio PSRs in our Galaxy can be observed (Keane et al. 2015). Thus, the expected number of active NS-BHs in our Galaxy found in radio band at present is 0.40–2.0. This expected number for NS-BHs is marginal for detection which depends on the direction of magnetic field of the pulsar, the radio power, the distance to the pulsar and so on. Thus, the current no observation of NS-BH radio PSRs is more or less consistent.

In relation to this marginal situation, it would be interesting to point out the observation history of PSR J1740-3052 which was found in 2001 (Stairs et al. 2001). This binary PSR has a PSR period of 0.57 sec and the characteristic age of $3.5 \times 10^5$ yrs with the orbital period of 231 days and the mass function of $8.7 M_{\odot}$. Thus the companion mass exceeds $11 M_{\odot}$ so that it was not possible to rule out a BH companion in 2001 when this binary was found. At this time PSR J1740-3052 could be a NS-BH binary formed in our above scenario for example. After 11 years from the discovery of PSR J1740-3052, Madsen et al. (2012) found the main sequence star companion, and concluded that PSR J1740-3052 is not a NS-BH binary. However, because the expected number of observable NS-BH binaries in future SKA era is 4.0–20, the existence of NS-BH binaries in our galaxy can be confirmed in future.

Finally, Figure 4 shows BH mass distributions of detectable NS-BHs at $z = 0$ and galactic PSR-BHs. The left and right panels show the cases of $\sigma_k = 265 \text{ km/s}$ and $\sigma_k = 500 \text{ km/s}$, respectively. The blue solid lines associated with the left axis show the sum of the merger rate density of Pop I, II and the merger rate density of Pop III for each model. The orange dashed lines and green dotted lines associated with the left axis show the merger rate densities of Pop I, II and the merger rates of Pop III, respectively. The red solid lines associated with the right axis show the BH mass distributions of galactic PSR-BHs for each model. Since the galactic PSR-BHs are made by Pop I ($Z = Z_{\odot}$) stars, the BH masses of PSR-BHs are typically lower than those of NS-BHs which are detectable by the GWs.

3 DISCUSSION

Some of NS-BHs which have a radio emission can be observed as PSR-BHs. Our calculation shows that the SKA will detect 4–20 PSR-BHs in our galaxy. We can check the consistency of the field binary model not only with the merger rate of NS-BHs, but also with the PSR-BH observations by future SKA. Since the SKA will find only young NS-BHs because the PSR lifetime is only $5 \times 10^7$ yrs, the origin of such NS-BHs will be confirmed as Pop I stars. The maximum BH mass of Pop I PSR-BHs is $\lesssim 20 M_{\odot}$ (see Figure 4). On the other hand, NS-BHs which are detected by GW observations are possibly the summation of each metallicity of Pop I, Pop II and Pop III. The maximum BH mass of these NS-BHs is much more than $20 M_{\odot}$ (see Figure 4). Thus, the comparison of the BH mass distribution of NS-BH binaries detected by GW observations with the BH mass distribution of PSR-BHs detected by the SKA might show the dependence of BH mass on the metallicity.

In our calculation, we have ignored the life prolongation of the spin due to accretion from a companion star like millisecond PSRs. Here, $\sim 90\%$ of NS-BHs are formed as BH1st–NS2nd where BH1st–NS2nd means that the primary star which is initially more massive than the companion star evolves to the BH first, and the secondary star evolves to the NS next. In this case, accretion onto the NS does not occur. On the other hand, $\sim 10\%$ of NS-BHs are formed as NS1st–BH2nd which means that the primary star evolves to the NS first, and the secondary star evolves to the BH next. In this case, progenitors of NS1st–BH2nd evolve via HMXBs so that accretion onto the NS can occur. However the spin up due to accretion onto the NSs in HMXBs does not occur in general. The magnetic field strength of the NSs in HMXBs is typically so large ($\sim 10^{12} \text{ G}$) (Enoto et al. 2019) that the matter cannot accrete directly onto the NS surface in the disc plane, but rather forms a funnel flow onto the magnetic poles because it is constrained to follow the magnetic field lines (e.g. Pringle & Rees 1972). Thus, the PSR lifetime of NS1st–BH2nd has been treated similar to that of BH1st–NS2nd in this Letter.
Figure 4. BH mass distributions of detectable NS-BHs at $z=0$ and BH mass distributions of galactic PSR-BHs. The left and right panels show the cases of $\sigma_k=265$ km/s and $\sigma_k=500$ km/s, respectively. The blue solid lines associated with the left axis show the sum of the merger rate density of Pop I, II and the merger rate density of Pop III for each model. The orange dashed lines and green dotted lines associated with the left axis show the merger rate densities of Pop I, II and the merger rates of Pop III, respectively. The red solid lines associated with the right axis show the BH mass distributions of galactic PSR-BHs for each model.

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DATA AVAILABILITY

Results will be shared on reasonable request to corresponding author.

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