Black hole spins in coalescing binary black holes

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ABSTRACT

Possible formation mechanisms of massive close binary black holes (BHs) that can merge in the Hubble time to produce powerful gravitational wave bursts detected during advanced LIGO O1 and O2 science runs include the evolution from field low-metallicity massive binaries, the dynamical formation in dense stellar clusters and primordial BHs. Different formation channels produce different source distributions of total masses $M_{\text{tot}}$ and effective spins $\chi_{\text{eff}}$ of coalescing binary BHs. Using a modified BSE code, we carry out extensive population synthesis calculations of the expected effective spin and total mass distributions from the standard field massive binary formation channel for different metallicities of BH progenitors (from zero-metal Population III stars up to solar metal abundance), different initial rotations of the binary components and different common envelope efficiencies. Stellar rotation is treated in two-zone (core-envelope) approximation using the effective core-envelope coupling time and with account for tidal synchronization of stellar envelope rotation during the binary system evolution. We show that the total masses and effective spins distributions as inferred from the merging binary black holes reported by LIGO (GW150914, GW151226, GW170104 and possibly LVT151012) can be reproduced using zero-metal abundance (Population III) stellar evolution under minimal assumptions on black hole formation in the standard massive binary evolutionary scenario.

Key words: stars: black holes, binaries: close, gravitational waves

1 INTRODUCTION

The discovery of the first gravitational wave source GW150914 from coalescing binary black hole (BH) system (Abbott et al. 2016b) not only heralded the beginning of gravitational wave astronomy era, but also stimulated a wealth of works on fundamental physical and astrophysical aspects of the formation and evolution of binary BHs. The LIGO detection of GW150914, of the second robust binary BH merging event GW151226 (Abbott et al. 2016c) and the third BH merging binary GW170104 (Abbott et al. 2017) enables BH masses and spins before the merging, the luminosity distance to the sources and the binary BH merging rate in the Universe to be estimated (Abbott et al. 2016a). Astrophysical implications of these measurements were discussed, e.g., in Abbott et al. (2016c,d).

1.1 Historical remarks

This discovery of gravitational waves from coalescing binary BHs was long awaited and anticipated from the standard scenario of evolution of massive stars (Grishchuk et al. 2001). The historical development of binary BH studies can be briefly sketched as follows.

The evolution of massive binary systems was elaborated in the 1970s to explain a rich variety of newly discovered galactic X-ray binaries (van den Heuvel & Heise 1972; Tutukov et al. 1973). Formation of two relativistic compact remnants (neutron stars (NSs) or black holes) naturally followed from the binary evolution scenario (Tutukov & Yungelson 1973; Flannery & van den Heuvel 1975). The preponderance of massive black holes for broad-band gravitational wave interferometers was clear from the first considerations of astrophysical sources of gravitational waves (see, e.g., Thorne (1987)), due to the strong dependence of the characteristic GW amplitude $h_*$ from the coalescing binary system with masses $M_1$ and $M_2$ on the total mass $M_{\text{tot}} = M_1 + M_2$ of the binary, $h_* \sim M_{\text{tot}}^{5/2}$. However, the formation rate of such binaries was poorly known at that time.

At the dawn of the LIGO Project, Alexander Tutukov and Lev Yungelson (Tutukov & Yungelson 1993) calculated, using the standard assumptions of massive binary star evolution, the expected Galactic merging rate of binary NSs and BHs. They pointed out that although the Galactic merging rate of binary NSs is much larger than that of binary BHs, their detection rates by gravitational-wave interferometers from other galaxies can be comparable because of much larger detection horizon for binary BHs than for binary NSs. A few years later, independent population synthesis calculations by the Scenario Machine code were reported in a series of papers

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They showed that in a wide range of possible BH formation parameters (masses, possible kick velocities) and under standard assumptions of the massive star evolution, the detection rate of binary BH mergings should be much higher than that of binary NSs, and the first LIGO event should most likely to be a binary BH merging. Interestingly, the mean BH masses known at that time from dynamical measurements in galactic BH X-ray binaries were about 10 $M_\odot$, which forced (cautiously) the authors of (Lipunov et al. 1997b) to fix the parameter $k_{BH} = M_{BH}/M_\odot$, where $M_\odot$ is the mass of the star before the collapse, around $\sim 0.3$ (see Fig. 4 in that paper) in order to produce the total mass of coalescing binary BHs around 15$M_\odot$. Taking $k_{BH} = 1$ (i.e. assuming that all the mass of the collapsing star goes to a BH), one would immediately obtain the BH masses around 30-40 $M_\odot$, which seemed outrageously high at that time.

Starting from the end of the 1990s, various groups have used different population synthesis codes to calculate the merging rates of double compact objects with different degree of detailing of massive binary evolution (see especially numerous papers based on the StarTrack code (Belczynski et al. 2002; Dominik et al. 2012)), yielding a wide range of possible BH-BH merging rates (see e.g. Table 6 in Postnov & Yungelson (2014)). Clearly, the degeneracy of binary evolution and BH formation parameters has been so high (Abadie et al. 2010) that only real observations could narrow the wide parameter range.

1.2 Standard scenario of binary BH formation

The standard scenario of double BH formation from field stars is based on well understood evolution of single massive stars (Woosley et al. 2002). To produce a massive BH with $M > 10M_\odot$ in the end of evolution, the progenitor star should have a large mass and low mass-loss rate at evolutionary stages preceding core collapse. The mass-loss rate is strongly dependent on the metallicity, which plays the key role in determining the final mass of stellar remnant (see e.g. Spera et al. (2015)). The metallicity effects were included in the population synthesis calculations (Dominik et al. 2013), and the most massive BHs were found to be produced by the low-metallicity progenitors. Here early metal-free Population III stars provide an extreme example, see calculations by Kinugawa et al. (2014); Hartwig et al. (2016). After the discovery of GW150914, several independent population synthesis calculations were performed to explain the observed masses of binary BH in GW150914 and the inferred binary BH merging rate $\sim 9-240$ Gpc$^{-3}$yr$^{-1}$ (Abbott et al. 2016a) (see, among others, e.g. Belczynski et al. 2016; Eldridge & Stanway 2016; Lipunov et al. 2017).

In addition to the metallicity that affects the intrinsic evolution of the binary components, the most important uncertainty in the binary evolution is the efficiency of the common envelope (CE) stage which is required to form a compact double BH binary which can merge in the Hubble time. The common envelope stage remains a highly debatable issue. For example, in recent hydro simulations (Öhlmann et al. 2016) a low CE efficiency was found, while successful CE calculations were reported by other groups (see, e.g., Nandez & Ivanova (2016)). In a dedicated study (Kruckow et al. 2016), high CE efficiencies ($\alpha_{CE} < 1$) were found to be required for the possible formation of binary BH systems with parameters similar to GW150914 and GW151226 through the CE channel. Another recent study (Pavlovskii et al. 2017) argues that it is possible to reconcile the BH formation rate through the CE channel taking into account the stability of mass transfer in massive binaries in the Hertzsprung gap stage, which drastically reduces the otherwise predicted overproduction of binary BH merging rate in some population synthesis calculations. Also, the so-called stable ’isotropic re-emission’ mass transfer mode can be realized in high-mass X-ray binaries with massive BHs, thus helping to avoid the merging of the binary system components in the common envelope (van den Heuvel et al. 2017). This stable mass transfer mode can explain the surprising stability of kinetic characteristics observed in the galactic microquasar SS433 (Davydov et al. 2008).

Of course, much more empirical constraints on and hydro simulations of the common evolution formation and properties are required, but the formation channel with common envelope of binary BHs with properties similar to GW150914 and GW170104 remains quite plausible.

1.3 Other scenarios

To avoid the ill-understood common envelope stage, several alternative scenarios of binary BH formation from massive stars were proposed. For example, in short-period massive binary systems chemically homogeneous evolution due to rotational mixing can be realized. The stars remain compact until the core collapse, and only binary BH system is formed without common envelope stage (Mandel & de Mink 2016; de Mink & Mandel 2016; Marchant et al. 2016). In this scenario, a pair of nearly equal massive BHs can be formed with the merging rate comparable to the empirically inferred from the first LIGO observations. This scenario, however, can be challenged by recent observations of slow rotation of WR stars in LMC (Vink & Harries 2017).

Another possible way to form massive binary BH system is through dynamical interactions in a dense stellar systems (e.g., globular clusters). This scenario was earlier considered by Sigurdsson & Hernquist (1993). In the core of a dense globular clusters, stellar-mass BH form multiple systems, and BH binaries are dynamically ejected from the cluster. This mechanism can be efficient in producing 30+30 $M_\odot$ merging binary BHs (Rodriguez et al. 2016b), and binary BH formed in this way can provide a substantial fraction of all binary BH mergings in the local Universe (Rodriguez et al. 2016a).

Finally, there can be more exotic channels of binary BH formation. For example, primordial black holes (PBHs) formed in the early Universe can form pairs which could be efficient sources of gravitational waves (Nakamura et al. 1997). After the discovery of GW150914, the interest to binary PBHs has renewed (Bird et al. 2016). Stellar-mass PBHs can form a substantial part of dark matter in the Universe (Carr et al. 2016). The PBHs formed at the radiation-dominated stage can form pairs like GW150914 with the merging rate compatible with empirical LIGO results, being only some fraction of all dark matter (Eroshenko 2016; Sasaki et al. 2016). A different class of PBHs with universal log-normal mass spectrum produced in the frame of a modified Affleck-Dine supersymmetric baryogenesis mechanism (Dolgov & Silk 1993; Dolgov et al. 2009) were also shown to be able to match the observed properties of GW150914 Blinnikov et al. (2016) without violating the existing constraints on stellar-mass PBH as dark matter.

2 LOW EFFECTIVE SPINS OF BHS IN GW150914, GW170104 AND LVT151012 EVENTS

In General Relativity, a BH is fully characterized by its mass $M_{BH}$ and dimensionless angular momentum $a = J/M_{BH}^2$ (in geometri-
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3 SPIN EVOLUTION OF BINARY COMPONENTS

Our goal is to calculate the total mass and effective spin distributions of coalescing binary black holes in the astrophysical scenario of BH-BH formation from initially massive binary stars. To this aim, we use the population synthesis method based on the open BSE (Binary Stellar Evolution) code elaborated in Hurley et al. (2000, 2002) with the treatment of metallicity-dependent stellar wind mass loss from O-B stars according to Vink et al. (2001). Evolution of zero-metallicity (primordial Population III) stars was parametrized as in Kinugawa et al. (2014). The common envelope phase is α-parametrized. The initial parameters of binaries are taken to be as follows: the primary is distributed according to the Salpeter law, \( \frac{dN}{dq} \propto q^{-2.35} \), the binary mass ratio \( q = M_2/M_1 \leq 1 \) is assumed to follow a flat distribution, \( \frac{dN}{dq} = \text{const} \), the binary separation is distributed as \( \frac{dN}{dR} = \text{const} \), 10\( R_\odot \leq A \leq 10^5 R_\odot \). The mass of the BH remnant is assumed to be equal to the pre-collapse C-O core mass of a star with initial mass \( M \geq 35 R_\odot \). No kick velocity during BH formation is assumed.

As the effective spin \( \chi_{\text{eff}} \) of a coalescing BH-BH binary depends on the value and orientation of BH spins, we should specify how to calculate BH spins and their orientation relative to the binary orbital angular momentum. Here the following processes have been taken into account.

3.1 Core-envelope coupling

The value of a BH remnant spin \( \alpha \) depends on the rotational evolution of the stellar core, which is ill-understood and strongly model-dependent. For massive binaries, one possible approach is to match theoretical predictions of the core rotation with observed period distribution of young neutron stars observed as radio pulsars (Postnov et al. 2016). Initially, a star is assumed to rotate rigidly, but after the main sequence the stellar structure can be separated in two parts – the core and the envelope, with some effective coupling between these two parts. The coupling between the core and envelope rotation can be mediated by magnetic dynamo (Spruit 2002), internal gravity waves (Fuller et al. 2015), etc. In this approximation, the time evolution of the angular momentum of the stellar core reads

\[
\frac{dJ}{dt} = -\frac{I_2 J_2}{I_1 + I_2} \frac{\Omega_1 - \Omega_2}{\tau},
\]

where \( I_1 \) and \( I_2 \) is the core and envelope moment of inertia, respectively, and \( \Omega_1 \) and \( \Omega_2 \) are their angular velocity vectors, which can be misaligned in due course of evolution (see below). Long values of \( \tau \) correspond to the case of an almost independent rotational evolution of the core and envelope, while short \( \tau \) describes the opposite case of a very strong core-envelope coupling.

The validity of such an approach was checked by direct MESA
Figure 1. $M_{\text{tot}} - \chi_{\text{eff}}$ plane for different stellar metallicities and CE efficiencies. Initial components’ spins are randomly oriented relative to the orbital angular momentum. The effective core-envelope coupling time $\tau_c = 5 \times 10^5$ years. Open circles with error bars show the observed BH-BH systems GW150914, LVT151012, GW151226 (Abbott et al. 2016a), and GW170104 (Abbott et al. 2017), in order of decreasing total mass.

3.2 Initial rotational velocity of the components

The initial rotational velocity of the binary components was chosen according to the empirical relation between the mass of main-sequence stars $M_0$ and their equatorial velocities (as used, e.g., in the BSE code (Hurley et al. 2002))

$$v_0 = 330 \frac{M_0^{1.3}}{15 + M_0^{0.4}} \text{ km s}^{-1}$$ (2)

(here $M_0$ is in solar units). The main-sequence stars were assumed to be initially uniformly rotating. This assumption has some support from Kepler asteroseismology (Moravveji 2016).

To check the effect of the initial velocity (see below), we performed calculations for (a) initially non-rotating stars, $v_{\text{rot}} = 0$, (b) stars rotating according to Eq. (2), $v_{\text{rot}} = v_0$, and (c) stars rotating with $v_{\text{rot}} = \min(4v_0, v_{\text{crit}})$, where $v_{\text{crit}} = \sqrt{2/3GM_0/R_0}$ is the limiting equatorial (break-up) velocity for a rigidly rotating star with mass $M_0$ and polar radius $R_0$.

3.3 Components spin alignment/misalignment

Initial spins of the components of a binary system are likely to be coaligned with orbital angular momentum $\hat{\mathbf{L}}$. This assumption is supported by recent observations of coaligned spins of stars in old stellar clusters (Corsaro et al. 2017). However, due to violent turbulence in proto-stellar clouds and possible dynamical interactions, binary component spins (especially for sufficiently large orbital separations) can be initially misaligned. Therefore, as extreme case we also consider totally independent initial spin orientation of...
the binary components. In the course of binary evolution, the spin-orbit misalignment can be also produced by an additional kick velocity during BH formation (Postnov & Prokhorov 1999; Kalogera 2000; Grishchuk et al. 2001). The possibility of BH generic kicks is actively debated in the literature; see, e.g., the recent discussion of potential constraining BH natal kicks from GW observations in O’Shaughnessy et al. (2017); Zevin et al. (2017). In the present study, to keep minimal assumptions on BH formation, no generic BH kick was assumed.

3.4 Tidal synchronization of the envelope rotation and orbital circularization

During evolution of a binary system, we assumed that the rotation of the stellar envelope gets tidally synchronized with the orbital motion with the characteristic synchronization time $t_{\text{sync}}$, and the processes of tidal synchronization and orbital circularization were treated as in the BSE code (see Hurley et al. (2002), Eqs. (11), (25), (26), (35)). Due to possible misalignment of the spin vectors of the stars with the binary orbital angular momentum $\hat{L}$, as discussed above, we separately treated the change of the core and envelope spin components parallel and perpendicular to $\hat{L}$, $J_{\text{c,e}} = J_{\parallel} + J_{\perp}$. On evolutionary stages prior to the compact remnant formation, for each binary component we assumed that due to tidal interactions the stellar envelope spin components $J_{\text{e}}$ evolve with the characteristic time $t_{\text{sync}}$:

$$\frac{dJ_{\text{e}}}{dt}_{\parallel} = I_{\text{e}} \Omega_{\text{e}} - \Omega_{\text{orb}} t_{\text{sync}},$$

and

$$\frac{dJ_{\text{e}}}{dt}_{\perp} = \frac{J_{\text{e}}}{t_{\text{sync}}},$$

respectively. Here we have assumed that the tidal interactions tend to exponentially synchronize the envelope’s parallel rotation with the orbital motion (Eq. (4)), and to decrease the perpendicular component of the envelope’s rotation (Eq. (5)) on
Figure 3. Effective spins $\chi_{\text{eff}}$ vs total mass $M_{\text{tot}}$ of coalescing binary black holes for different CE efficiency parameter $\alpha_{\text{CE}}$ for zero-metallicity Population III stars and different effective core-envelope coupling time $\tau_c = 5 \times 10^4, 5 \times 10^5, 10^7$ years. For each coupling time, upper row: initially co-aligned spins of the components; bottom row: randomly misaligned initial spins.

4 RESULTS

With these additions to the BSE code, the population synthesis of typically 1,000,000 binaries per run has been carried out for different parameters of binary evolution (the common envelope stage efficiency $\alpha_{\text{CE}}$, stellar metallicities etc.). We found that the initial metallicity and rotational velocity of the components mostly affect the distribution of the effective spin and total mass of the coalescing binary black holes.

4.1 Effect of the initial stellar metallicity

The results of calculations of BH total mass and effective spin distributions for different stellar metallicites and for different CE efficiency parameter $\alpha_{\text{CE}}$ ranging from 0.05 to 4 are shown in Fig. 1. The initial spin components were assumed to be randomly oriented. Typical evolutionary tracks leading to coalescing binary BHs formation with different effective spins $\chi_{\text{eff}}$ are listed in Table 1. The effect of the core-envelope coupling time $\tau_c = 10^4 - 10^7$ yrs on
the resulting $M_{\text{tot}}-\chi_{\text{eff}}$ distribution for low-metal $Z = 10^{-4}$ stars is found to be insignificant (see Fig. 2).

Fig. 3 plots the distribution of coalescing binary BHs on the $M_{\text{tot}}-\chi_{\text{eff}}$ plane for zero-metal Population III stars. BH spin misalignments with orbital angular momentum in coalescing binary BHs for different stellar metallicities are presented in Fig. 4.

4.2 Effect of the initial rotational velocity of the binary components

Fig. 5 illustrates the effect for two extreme cases of initially non-rotating ($v_{\text{rot}} = v_0$, with $v_0$ determined by Eq. (2)) and rapidly rotating ($v_{\text{rot}} = \min(4v_0, v_{\text{cef}})$) binary components for zero-metal Population III stars. In these calculations, we have assumed the standard core-envelope coupling time $\tau_c = 5 \times 10^5$ years and varied the common envelope efficiency parameter $\alpha_{\text{ce}}$ as above.

Clearly, increase in the initial rotational velocity of the components enhances the dispersion of the effective spin of coalescing black holes $\chi_{\text{eff}}$, making it more homogeneously distributed in the range $\sim (0.3 - 1)$.

5 DISCUSSION AND CONCLUSIONS

Fig. 1 shows that coalescing BH+BH binaries with total mass $M_{\text{tot}} > 10M_\odot$ and effective spins $\chi_{\text{eff}}$ varying in a wide range from $\sim 0.2$ to $1$ can be obtained in the standard astrophysical binary evolution scenario, especially for low-metal stellar abundance (the bottom row of the Figure). It is seen that measured properties of LIGO binary BH sources can be reproduced from these calculations, especially for zero-metal Population III stars (the bottom row of Fig. 1). The variation in the effective core-envelope coupling time from very short ($\tau_c = 10^3$ years) to very long ($\tau_c = 10^5$ years) does not significantly affect the source distributions (see Fig. 2 for low-metallicity stars with $Z = 10^{-4}$).

The simulated distribution of coalescing binary BH formed from zero-metal Population III binaries on the $M_{\text{tot}}-\chi_{\text{eff}}$ plane is separately shown in Fig. 3. It is seen that generally the random initial spin misalignment smoothens the dispersion in $\chi_{\text{eff}}$ of the coalescing binary BHs, which is quite expected. It is also seen that in this case all four reported sources, GW150914, LVT151012, GW151226 and GW170104 can be reproduced on the $M_{\text{tot}}-\chi_{\text{eff}}$ plane simultaneously for different
Figure 5. The role of the initial rotation on the $\chi_{\text{eff}} - M_{\text{tot}}$ distribution of coalescing binary black holes from zero-metal Population III stars. The effective core-envelope coupling time is $\tau_c = 5 \times 10^5$ years. Initial component spins are randomly misaligned. Upper panel: initially non-rotating stars, $v_0 = 0$. Middle panel: initial equatorial velocity $v_{\text{rot}} = v_0$ (Eq. (2)). Bottom panel: initially rapidly rotating stars with $v_{\text{rot}} = \min(4v_0, v_{\text{crit}})$.

combination of the parameters. For short core-envelope coupling time $\tau_c = 10^5$ years the location of the four sources can be reproduced even for aligned initial spins of the binary components (the upper row in Fig. 3). In this case slightly negative values of $\chi_{\text{eff}}$ (as possibly observed in GW170104) can be obtained by adding a generic BH kick (which we intentionally excluded in our calculations). For weaker core-envelope coupling (longer $\tau_c$), however, the initially misaligned components spins are required.

Fig. 4 illustrates the change in the orbital misalignment of the BH spin (here shown is BH1 which is formed from the evolution of the initially more massive primary component), assuming random initial spin orientation of the binary components. Prior to the coalescence, the spin misalignment effect is less pronounced for less effective common envelopes because post-CE systems live longer before the merging, and the stellar rotation has time to become tidally aligned with orbital motion.

Increase in the initial rotation velocity of the components illustrated by Fig. 5 leads to higher dispersion of $\chi_{\text{eff}}$ of coalescing BH+BH binaries on the $M_{\text{tot}} - \chi_{\text{eff}}$ plane. It is seen that even initially non-rotating stars (the upper row) can produce rapidly rotating black holes due to tidal interaction during binary star evolution, especially for less effective common envelopes (large values of the $\alpha_{\text{CE}}$). Negative effective spins as reported in GW170104 can be produced in systems with the standard and high initial rotational velocity of the components (the middle and bottom rows in the Figure).

The results of our calculations suggest that the effective spin $\chi_{\text{eff}}$ of binary BH produced from massive binary star evolution (the standard formation scenario) can be distributed in a wide range, especially if the initial spins of the binary components are randomly misaligned (as we checked in the present calculations) or if a generic BH kick is assumed. Of course, the predictive power of multi-parametric population synthesis calculations should not be overestimated. In addition to the inferred parameters of the individual coalescing binary BHs, their occurrence rate can also be used to constrain their evolutionary formation channels. This, however, requires adding the evolution of star formation rate and stellar metallicity with time in the Universe, etc., as has been done in other more de-
Presently, there are different viable pathways of producing massive binary BHs that merge in the Hubble time. They can be formed from low-metallicity massive field stars, primordial Population III remnants, can be results of dynamical evolution in dense stellar clusters or even primordial black holes. It is not excluded that all channels contribute to the observed binary BH population. For example, the discovery of very massive ($M > 50 M_\odot$) Schwarzschild BHs would be difficult to reconcile with the standard massive binary evolution, but can be naturally explained in the PBH scenario (Blinnikov et al. 2016).

As of time of writing, another eight event candidates were reported by the LIGO collaboration from the analysis of several months of joint operation of two LIGO interferometers during O2 run (see http://ligo.org/news/index.php#02july2017update). With the current LIGO sensitivity, the detection horizon of binary BH with masses around 30 $M_\odot$ reaches ≈700 Mpc. So far the statistics of binary BH merging rate as a function of BH mass as inferred from three reported LIGO O1 events is consistent with a power-law dependence, $dR/dM \sim M^{-2.5}$ (Hotokezaka & Piran 2017), which does not contradict the general power-law behavior of the stellar mass function. Our calculations presented in this paper confirm that presently the formation of LIGO coalescing binary black holes can be explained in the frame of the standard astrophysical formation scenario, but the discovery of massive BH-BH binary with large negative effective spin may require additional formation channels to these extremal objects. Clearly, the increased statistics of BH masses and spins inferred from binary BH mergings will be helpful to distinguish between the possible binary BH populations which can exist in the Universe.

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