ON THE APPARENT DICHOTOMY BETWEEN THE MASSES OF BLACK HOLES INFERRED VIA X-RAYS AND VIA GRAVITATIONAL WAVES

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ABSTRACT

Prior to the detection of black holes (BHs) via the gravitational waves (GWs) they generate at merger, the presence of BHs was inferred in X-ray binaries, mostly via dynamical measurements, with measured masses in the range between \( \sim 5 - 20 M_\odot \). The LIGO discovery of the first BHs via GWs was surprising in that the two BHs that merged had masses of 35.6 and 28.6 \( M_\odot \), which are both above the range inferred from X-ray binaries. With 10 binary BH detections to date, it has become apparent that, while the two distributions are not disjoint, they are most certainly distinct.

In this Letter, we suggest that the reason for the apparent dichotomy is due to a predominance of different formation channels: isolated binary evolution for X-ray binaries, and dynamical exchanges in dense star clusters for the LIGO BHs. We show, via timescale arguments, that BHs in high-mass X-ray binaries are preferentially seen when they have lower mass accretors. We then perform high-resolution N-body simulations of a cluster of isolated BHs with a range of initial mass spectra, and show that BH binaries are preferentially formed by the most massive BHs, and additionally that these tend to be the tightest binaries (hence with shorter merger timescales). We also perform a simulation with neutron stars (NSs) in addition to BHs, more abundant by a factor of 5, and show that the formation of NS-BH binaries is \(<1\%\) that of BH-BH binaries, hence making the dynamical formation of NS-BH systems much less likely than that of binary BHs.

Keywords: gravitational waves — black hole physics — methods: numerical — binaries: general

1. INTRODUCTION

The existence of black holes (BHs) is one of the primary predictions of the Theory of General Relativity. Prior to their direct discovery via the gravitational waves they generated in a merger event (Abbott et al. 2016), their presence was inferred via dynamical mass measurements in X-ray binaries (see i.e. Wiktorowicz et al. 2014 for a summary). The values of the inferred masses vary between \( \sim 4 - 5 M_\odot \) to about 20 \( M_\odot \), marking a clear separation with the inferred neutron star masses, for which the largest measurement to date is 1.96 \( M_\odot \) (Demorest et al. 2010).

The discovery of the first binary black hole merger via the gravitational waves generated at the time of coalescence led to a mass measurement for the BH components of the merging binary: \( M_1 = 35.6^{+3.0}_{-3.4} \) and \( M_2 = 28.6^{+1.6}_{-1.5} \). The large BH masses, both well above the maximum value measured to date in X-ray binaries, came as a surprise. The discovery triggered an intense debate in the literature on the formation pathway of this BH binary.

Broadly speaking, most formation avenues can be classified within one of two channels: isolated binary evolution, in which two massive stars evolve till their death while remaining gravitationally bound (e.g. Podsiadlowski et al. 2003; Dominik et al. 2013; Belczynski et al. 2014, 2016; Marchant et al. 2016; Mandel & de Mink 2016), and dynamical formation by gravitational capture in dense environments, where binaries are being formed from isolated BHs as a result of frequent dynamical interactions (e.g. Portegies Zwart & McMil-
that it would require a cosmic conspiracy for the two rates to be just comparable so that both channels are sizeably represented in the relatively small sample of 10 BHs to date. Here, via high-resolution N-body simulations of a cluster of BHs with a range of mass spectra, we show that dynamically formed BH binaries have a strong bias towards forming high-mass binaries, even if higher mass BHs are smaller in number in the original isolated BH population.

2. MEASURED BH MASSES: X-RAYS VS GWS

Fig. 1 provides a visual summary of the BH masses measured to date. The X-ray data, partly based on dynamical measurements of black hole X-ray binaries, are taken from the stellar collapse website1 (based on data collected in Wiktorowicz et al. 2014). We have not included the BHs for which only upper limits are available. For the (four) cases in which two independent measurements are present, we have taken the mean value.

Heavier stellar remnants generally correlate with more massive progenitors, and more massive progenitors have shorter lifetimes. Hence, it is fair to assume that if the binary is not disrupted by the second supernova explosion and a compact object binary is formed, the measured BHs in the X-ray binaries would constitute the heavier remnants. Therefore, for a comparison with the BH masses measured in the O1/O2 runs by LIGO/Virgo (The LIGO Scientific Collaboration & the Virgo Collaboration 2018; Generozov et al. 2018; Antonini et al. 2018; Di Carlo et al. 2019). Both channels can in principle contribute to the observed population, something that can be tested since many more mergers are going to be detected in the future.

To date, after the first two observing runs of LIGO/Virgo, there have been 10 BBH mergers reported (The LIGO Scientific Collaboration & the Virgo Collaboration 2018). While the smallest masses (4 out of 20) fall within the upper range of the masses inferred for X-ray binaries, the other 16 are all bigger, with the largest being $50.6M_\odot$. Hence, while the distributions are clearly not disjoint, there is a marked preference in GW-detected BHs for larger masses than in those found via X-ray binaries. This apparent mass dichotomy may not be of an immediate interpretation. The BHs that we observe are either the direct remnants of the collapse of massive stars (first generation), or the product of BH mergers (second generation). The latter are expected to be on average larger than the former. Could this explain the observed dichotomy? Generally speaking, the more local (meaning closer to $z \approx 0$) a BH population is, the more likely it is to be comprised of a larger fraction of second generation BHs. The X-ray binary and the GW-detected BH populations are both reasonably local, but with the X-ray binary one being more local since it is mostly Galactic. On the other hand, the GW-detected BHs range in redshift between 0.07 and 0.48 (The LIGO Scientific Collaboration & the Virgo Collaboration 2018). Hence, based on this argument alone, larger masses should be expected in the X-ray binary population, if at all.

In this paper, we propose that the reason for the apparent mass dichotomy stems from the fact that the two populations are dominated by different production channels: isolated binary evolution for the X-ray population, and dynamical formation for the GW-detected BHs. For the former, we use timescale arguments to show that lower-mass BHs in high-mass X-ray binaries are preferentially selected from the observations. For the latter, as already noted, both formation channels have been proposed to explain the LIGO results; the theoretically-predicted rates are rather uncertain for both scenarios: the models explored by Belczynski et al. (2016) yield rates which vary between $\sim 6-1000$ Gpc$^{-3}$ yr$^{-1}$. More recent, state-of-the-art estimates of the rates of dynamical formation in Globular Clusters yield a range of 4–18 Gpc$^{-3}$ yr$^{-1}$ (Rodriguez & Loeb 2018). Both these rates are compatible with the current observationally-determined value by LIGO, of 9.7–101 Gpc$^{-3}$ yr$^{-1}$ (The LIGO Scientific Collaboration & the Virgo Collaboration 2018). While both channels are ultimately modulated by the local star formation rate, their subsequent evolutionary paths are different enough that it would require a cosmic conspiracy for the two rates to be just comparable so that both channels are sizeably represented in the relatively small sample of 10 BHs to date. Here, via high-resolution N-body simulations of a cluster of BHs with a range of mass spectra, we show that dynamically formed BH binaries have a strong bias towards forming high-mass binaries, even if higher mass BHs are smaller in number in the original isolated BH population.

1 https://stellarcollapse.org/sites/default/files/table.pdf
tion & the Virgo Collaboration 2018), we take the masses of the primary BHs (i.e. the most massive BHs of the binaries). The comparison between the two distributions is illustrated in Fig. 1. It clearly shows that, while the X-ray and GW-determined mass distributions are not disjoint and have some overlap, they appear to be drawn from different distributions. More quantitatively, a KS-test yields a null probability for the two distributions to be drawn from the same intrinsic BH population.

Taken at face value, the above results may be surprising. As discussed in §1, each of the BHs in both the X-ray binaries and in the GW binaries originally came from the collapse of a massive star\(^2\) (first or second generation of BHs). Hence, why a different range of masses is probed by different measurements is a very interesting question, to which we aim at providing an answer in this Letter.

3. MASS INFERENCES FROM X-RAY BINARIES

Stellar-mass black holes are discovered in X-ray emitting binary systems, where their mass can be determined from the dynamics of their companion stars. These are generally field binaries, since Globular Clusters and crowded dense environments do not allow reliable spectroscopy. For isolated binary evolution, the resulting BH mass spectrum is preferentially biased towards low masses (i.e. Belczynski et al. 2016; Di Carlo et al. 2019), but see also Marchant et al. (2016); Mandel & de Mink (2016). As discussed below, additional factors contribute to prevent the observation of the high-mass tail of the distribution.

The black holes in low and intermediate mass X-ray binaries (LMXBs and IMXBs) have stellar companions with masses typically well below 8 \(M_\odot\), while only high-mass X-ray binaries (HMXBs) host massive stars that can leave behind compact remnants. Moreover, the masses of the BHs in HMXBs mostly occupy the high mass tail of the X-ray binaries distribution in Fig. 1. The luminosity of HMXBs is powered either by accretion of the massive star companion’s stellar wind, or by Roche-lobe overflow. In the first case, the HMXB luminosity is persistent, and can in principle be sustained for a timescale as long as the nuclear burning timescale of the massive star. All 6 HMXBs for which a dynamical mass measurement is available are wind-fed, persistent systems.

The main sequence lifetime of a massive star scales as \(t \sim M^{\alpha}\), with \(\alpha \approx -2\) in the mass range 9-20 \(M_\odot\), \(\alpha \approx -1.3\) in the mass range 20-60 \(M_\odot\) and \(\alpha \approx -0.7\) for 60-120 \(M_\odot\) (see e.g. Maeder 2009). Therefore, the main sequence duration of stars varies by an order of magnitude between a star of 9 \(M_\odot\) and stars with \(M > 90M_\odot\) (for which the main sequence duration is about 2.5 Myr). Hence, HMXBs eventually leading to BH-BH binaries with relatively high mass ratios (as observed in the LIGO mergers) are more easily observed for low values of black hole mass due to a generally longer duration of the very accretion phase that makes them visible. This effect can further bias the BH masses inferred from X-rays to lower values.

4. MASS INFERENCES FROM BBH MERGERS

As discussed in §1, the various models proposed to explain the binary origin of the BHs whose mergers were observed by LIGO and Virgo fall under the umbrellas of two broad channels: isolated binary evolution, and dynamical capture in dense environments. Both of these channels could in principle contribute to the GW-detected events. However, as it would require a cosmic conspiracy for two different formation pathways to yield comparable rates (albeit both rates are ultimately modulated by the local star formation rate), it is plausible that there is a dominant mechanism. For the isolated binary evolution channel, several groups (i.e. Belczynski et al. 2016; Di Carlo et al. 2019) have shown that the mass distribution of merging binaries is a declining function of mass in the range of LIGO detectability. This renders it difficult for this channel to account for a large fraction of high-mass binaries without a sizable fraction of corresponding lower-mass counterparts.

The mass spectrum of BH binaries produced as a result of dynamical interactions in clusters has a long history in the literature, predating the era of gravitational waves. A preferential tendency for dynamically formed binaries to have heavier mass has been noted in a number of works (O’Leary et al. 2006; Miller & Lauburg 2009; Ryu et al. 2016; Rodriguez et al. 2018; Di Carlo et al. 2019). Here, motivated by the results from the O1/O2 LIGO runs, we perform high-resolution N-body simulations of a cluster of BHs, with the goal of exploring the dependence of the mass spectrum and the orbital parameters of the dynamically-formed binaries on the mass spectrum of the isolated BH population.

For these simulations we consider a cluster of 20 BHs (which can be imagined as the remnant of an OB star association), with an initial binary fraction equal to zero in order to purely explore the binary properties due to dynamical formation. Their positions in the cluster are initially distributed randomly in a sphere of radius 0.1 pc, with a mean speed of 5 km/s. This characteristic velocity is typical of the velocity dispersions observed in low-mass globular clusters (e.g. Harris 1996). We follow their evolution using our code SpaceHub (see Wang et al. 2019 for details), which employs the ARCHAIN algorithm (Mikkola & Merritt 2008) to accurately trace the motion of tight binaries with arbitrarily large mass ratios and eccentricities, and a chain structure to reduce the round-off errors from close encounters. The initial BH

\(^2\) Note that black holes have also been predicted as the result of gravitational instabilities in the early Universe (i.e. Carr et al. 2016.)
masses are drawn from a distribution with \( M_{\text{min}} = 5M_\odot \) and \( M_{\text{max}} = 50M_\odot \). We explore three spectra within these limits: a flat distribution, a power-law \( M^{-\alpha} \) with index \( \alpha = 0.5 \), and a power-law with index of 1. Note that the former is the closest to that found with stellar evolutionary calculations (Spera et al. 2015); however, we explore also cases with a larger fraction of smaller-mass BHs to investigate the robustness of our results to the initial mass spectrum. For each case, we ran at least \( 10^7 \) realizations, and followed each system for a million year.

The results of these simulations are displayed in Fig. 2 (\( \alpha = 0 \)), Fig. 3 (\( \alpha = 0.5 \)), and Fig. 4 (\( \alpha = 1 \)). In the left panels we show the mass ratio \( q \), while in the right panels the merger times calculated according to Peters’ formulae (Peters 1964), both versus the total mass of the binaries. The flat mass spectrum yields a peak of binaries with total mass exceeding \( 80M_\odot \). Interestingly, not only is there an exceedingly large number of very massive binaries formed, but they are also the ones which are more tightly bound, hence resulting in shorter merger times due to GW emission (note a similar result found by Ryu et al. (2016) in the context of the formation of the first X-ray binaries). For those massive binaries with merger times shorter than a Hubble time, the mass ratios are distributed roughly uniformly in the range \( q \sim 0.6–1 \). The distribution of binaries still remains mostly concentrated at large masses, with the bulk between \( 50–80M_\odot \), even...
for a mass spectrum $\propto M^{-0.5}$. The mass ratio $q$ has a wider spread of values, from $\sim 0.5 - 1$ for $m_b \sim 80 M_\odot$ to $\sim 0.2 - 1$ for $m_b \sim 60 M_\odot$. In the least favorable mass spectrum that we studied, $M^{-1}$, the mass distribution of the binaries is more spread out in mass, but the peak of the distribution is still at high masses, around $55 M_\odot$. This corresponds to the heaviest BHs in the distribution (of $\sim 50 M_\odot$) forming binaries with the lightest ones (of $\sim 5 M_\odot$).

Our numerical experiments show that the formation of preferentially massive binaries via dynamical interactions among isolated BHs is quite robust versus the initial mass spectrum of the BH population. Additionally, these massive binaries tend to be more tightly bound; the heaviest objects are in fact the ones with the largest cross-sections for encounters, hence they undergo the most scatterings and end up as the hardest binaries. As a consequence, their merger times by GW emission are shorter, thus enhancing the probability of their detection by LIGO/Virgo. This bias gets further enhanced by the higher sensitivity of LIGO and Virgo to detection of larger masses (see e.g. Fig. 1 in Fishbach et al. 2018). However, it seems unlikely that this GW detection bias, and the timescale argument discussed in Sec. 3 for the BHs in X-ray binaries, are alone sufficient to explain Fig. 1, and we suggest that they just reinforce an underlying trend caused by the predominance of two different channels for the GWs and X-ray BH populations, as discussed in this paper. This claim will have to be tested quantitatively with larger data sets in the years to come.

As a further numerical investigation, we add a population of NSs with masses $M = 1.4 M_\odot$ to the BHs, for the case with a flat BH mass spectrum, and study again binary formation. For each random realization, the number of NSs is taken to be 5 times larger than the total number of BHs. The results are shown in Fig. 5. We do not find any NS-BH binaries among our realizations (while we have $\gtrsim 1\%$ of binary BHs), hence setting the ratio of dynamically formed NS-BH systems to BH-BH ones to be below about 1%. Thus, if both the BH-BH and the NS-BH populations were dominated by dynamical formation, we would expect the NS-BH rates to be considerably lower than the BH-BH ones. We note that, to date, no NS-BH system has been detected by the LIGO/Virgo collaboration (The LIGO Scientific Collaboration & the Virgo Collaboration 2018), with an upper limit to the rates of 610 Gpc$^{-3}$ yr$^{-1}$.

5. SUMMARY AND DISCUSSION

The discovery of BHs via the GWs emitted when they merge in a binary has confirmed one of the milestone predictions of the Theory of General Relativity, while at the same time opening a new window into our exploration of the Universe. As often happens with new observations, this new window has also brought some puzzles. In the case of the 20 BHs discovered by the LIGO/Virgo collaboration via their mergers in binaries, their mass spectrum has been surprising, being shifted towards considerably larger masses with respect to the BHs whose masses had previously been measured dynamically in X-ray binaries.

In this Letter we have suggested a solution to this apparent mass dichotomy puzzle, if X-ray and GW-detected BHs are dominated by different formation channels: isolated binary evolution for the former, and dynamical formation for the latter. In the case of X-ray binaries, high-mass BHs in the range discovered by LIGO/Virgo are disfavored by the mass function of the remnant BHs in the isolated binary evolutionary channel, which predicts fewer high-mass BHs. Additionally, the duration of the accretion period in HMXBs is also shorter for higher mass companion stars, which leads to preferentially observe lower mass BHs. Both effects contribute to an observed distribution skewed towards low-mass BHs in X-ray binaries (Fig. 1).

On the other hand, we suggest that the massive GW-detected BH binaries are preferentially produced via dynamical interactions among isolated BHs. Via high-resolution N-body simulations of a mini-cluster of initially isolated BHs, we have shown a strong tendency for binary BH formation among the heaviest objects in the cluster. The heaviest BH binaries tend to also be the ones which are more tightly bound, hence resulting in shorter merger times, which enhances the probability of being detected via GWs. We find our results to be robust against variations in the mass spectrum of the interacting (isolated) BHs: even a mass spectrum $\propto M^{-1}$, with a larger number of less massive BHs, yields a binary population dominated by the heavier objects. However, while weighed towards larger masses, the precise shape of the mass distribution of the dynamically-formed binary BHs is different depending on the particular initial BH mass function. Hence, if the dynamical channel is indeed the dominant one, as much more data is gathered in the years to come, the mass distribution of BH binaries can be used to reconstruct the mass spectrum of the initial BHs, hence shedding a new light on massive stars and their evolution.

An important result of our simulations is that, if both BH-BH and NS-BH are preferentially formed via dynamical interactions, then the rate of NS-BH mergers should be considerably lower than that of BH-BH mergers. In one of our simulations in which we added NSs by a factor of 5 more abundant than BHs, we found that no NS-BH binaries were formed, making the ratio of NS-BH binaries smaller than that of BH-BH ones by a factor of at least 0.01. Hence the discovery by LIGO/Virgo of an NS-BH system will strongly point towards a channel of isolated binary evolution.
$f(M) \propto M^{-1}$

$M_{\text{min}} = 5 M_{\odot}$

$M_{\text{max}} = 50 M_{\odot}$

Figure 4. Same as in Fig. 2 but for a power-law mass spectrum of index -1 for the interacting isolated BHs.

Figure 5. Same as in Fig. 2, but with the addition of NSs, out-numbering the total number of BHs by a factor of 5.

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