On the Assembly Rate of Highly Eccentric Binary Black Hole Mergers

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Abstract

In this Letter we calculate the fraction of highly eccentric binary black hole (BBH) mergers resulting from binary-single interactions. Using an \textit{N}-body code that includes post-Newtonian correction terms, we show that $\gtrsim 1\%$ of all BBH mergers resulting from this channel will have an eccentricity $e > 0.1$ when coming into the LIGO frequency band. As the majority of BBH mergers forming in globular clusters are assembled through three-body encounters, we suggest that such interactions are likely to dominate the population of high-eccentricity BBH mergers detectable by LIGO. The relative frequency of highly eccentric events could eventually help to constrain the astrophysical origin of BBH mergers.

Key words: gravitational waves – stars: black holes – stars: kinematics and dynamics

1. Introduction

Recent studies indicate that there are many mechanisms for assembling binary black hole (BBH) binaries, with merger rates that are broadly consistent with those currently inferred from LIGO observations (Abbott et al. 2016). Such models include BBH mergers forming as a result of isolated binary evolution (e.g., Belczynski et al. 2016), dynamical interactions in globular clusters (GCs; e.g., Rodriguez et al. 2015, 2016a, 2016b), single–single captures in galactic nuclei (e.g., O’Leary et al. 2009), gas hardening of BBH binaries in active galactic nuclei disks (e.g., Bartos et al. 2017; McKernan et al. 2017; Stone et al. 2017), as well as primordial BBH mergers (e.g., Bird et al. 2016; Carr et al. 2016; Cholis et al. 2016). In addition, not only are the rates estimated to be of similar magnitude, but their associated BBH mass distributions can be similarly constructed as well. As a result, it might be difficult to discern useful astrophysical information from future gravitational wave (GW) data if only merger rates and BH masses are measured and recorded (e.g., Chen & Amaro-Seoane 2017).

Despite some similarities, the BBH eccentricity and BH spin orientations at the time of merger are likely to differ between models. For example, one expects spins to be mostly aligned and eccentricity to be near zero for BBH mergers forming from isolated binary channels (e.g., Kalogera 2000), where dynamical channels are more likely to lead to randomized spin orientations and non-zero eccentricities (e.g., Gültekin et al. 2006; O’Leary et al. 2009; Samsing et al. 2014; Cholis et al. 2016; Rodriguez et al. 2016c). Estimating the BBH eccentricities and spins expected from different assembly models could thus provide us with key discerning information. Hence, it is not surprising that major effort is currently being devoted to develop templates and fast techniques for measuring GW waveforms for varying spin and eccentricity (e.g., Harry et al. 2016; Huerta et al. 2017).

In this Letter we study the eccentricity distribution of BBH mergers resulting from dynamical binary–single interactions (Hut & Bahcall 1983; Samsing et al. 2014, 2016) in GCs (Heggie 1975). As shown in Samsing et al. (2014), when post-Newtonian (PN) corrections (e.g., Blanchet 2006) are implemented in the few-body equation-of-motion (EOM), BBH mergers can occur during the chaotic three-body interaction (e.g., Gültekin et al. 2006). We here refer to such BBH mergers as GW inspirals. Interestingly, GW inspirals often come into the LIGO frequency band with a very high eccentricity. Here we perform binary–single experiments with PN terms implemented in the EOM, from which we reconstruct the eccentricity distribution of BBH mergers found by Rodriguez et al. (2016a), and, for the first time, provide an estimate for the number of mergers taking place at high eccentricities. The above exercise leads us to conclude that $\gtrsim 1\%$ of all BBH mergers forming in GCs via the binary–single channel have eccentricities $e > 0.1$ when entering the LIGO band.

2. Black Hole Binary–Single Interactions

Interactions between a binary and a single interloper are among the most common few-body interactions taking place in a typical GC. Such encounters not only play a key dynamical role (Heggie 1975), but might be essential for assembling BBHs as well. As an example, recent work by Rodriguez et al. (2016a) estimates that about 80% of BBHs that are ejected from GCs and subsequently merge through GW emission originate from binary–single interactions.

Motivated by this, we derive here the eccentricity distribution of BBH mergers resulting from binary–single interactions when PN terms are included in the three-body EOM. We only consider binary–single interactions for which the total initial energy is negative, a limit that is usually referred to as the hard binary (HB) limit (e.g., Hut & Bahcall 1983).

2.1. Post-interaction BBH Mergers

The most likely outcome of a binary–single interaction is a binary with an unbound single (Heggie 1975). In this study we generally refer to the final binary from that outcome as the post-interaction binary. Such post-interaction binaries are generally formed with an eccentricity distribution that to leading order follows a thermal distribution, and binding energies that are slightly higher than that of the initial target binary (Heggie 1975). As a result, the GW merger time of post-interaction binaries can be significantly shorter than the GW merger time.
of the initial target binary (Peters 1964). For this reason, the binary–single channel is considered to be an effective pathway for transforming binaries with long GW inspiral times into binaries that could merge within a Hubble time.

The rate of BBH mergers forming in this way has recently been studied by Rodriguez et al. (2015, 2016a) using detailed dynamical simulations of GCs. The rate of BBH mergers forming in GCs is estimated by these authors to be somewhere between 2 and 50 Gpc$^{-3}$ yr$^{-1}$, with all of their resulting mergers having circularized long before entering the LIGO band. The population of post-interaction BBHs is thus not expected to contribute to the rate of highly eccentric BBH mergers.

2.2. Formation of Highly Eccentric BBH Mergers

High eccentricity GW inspirals have recently been shown to be produced during resonant binary–single interactions when PN terms are included in the three-body EOM (Güttik et al. 2006; Samsing et al. 2014, 2016). As described in Samsing et al. (2014, 2016), a resonant interaction can be envisioned as a series of intermediate states that are each composed of a binary with a bound single. Between each of these states, the three objects undergo a strong interaction that results in a semi-random redistribution of orbital energy and angular momentum. Each intermediate state binary therefore has a finite probability for being formed with a high eccentricity, even if the initial target binary is circular. If the eccentricity is high enough, the intermediate state binary will undergo a GW inspiral and merge while still being bound to the single object. On the other hand, if the eccentricity is too low, the corresponding GW inspiral time is too long, and the single will simply return to the intermediate state binary after which a new binary–single state will form. As a result, GW inspirals will generally form at high eccentricity.

Although such GW inspirals are generally assembled with an initial high eccentricity, they do not necessarily come into the LIGO frequency band with the same high eccentricity. In fact, as described in Samsing et al. (2014), a finite fraction of the GW inspirals will circularize before entering the LIGO band. This population originates from the fraction of interactions, where the bound single in the intermediate state is sent out on an orbit with close to zero orbital energy. For this reason, it is important to not only identify and count the number of GW inspirals, but also to evolve them until they reach the frequency band observable by LIGO. We thus now turn our attention to the eccentricity distribution of BBH mergers forming through the binary–single channel at the time that their GW frequency is 10 Hz. We refer to this frequency threshold as coming into the LIGO band. As inferred from our previous arguments, the eccentricity distribution is expected to have two peaks: one arising from the post-interaction binary GW mergers, and another one from the GW inspirals forming during the three-body interaction.

For this study, we perform $2.5 \times 10^5$ numerical binary-single scatterings with 2.5 PN corrections included in the EOM (for details on our N-body code, the reader is referred to Samsing et al. 2016). The scatterings are between \( [\text{BH}(20 M_\odot), \text{BH}(20 M_\odot)] \) binaries with an initial semimajor axis (SMA) distribution that is uniform in \( \log(a_0) \), where \( a_0 \) denotes the initial SMA between 0.1–0.2 au, and an incoming single BH(20M_\odot). The relative velocity at infinity is set to \( v_\infty = 10 \text{ km s}^{-1} \); however, our presented relative rate estimates do not depend on this value as long as we are in the HB limit (Samsing et al. 2014). These initial conditions (ICs) are inspired by the derived distributions of BBH mergers in our local universe from Rodriguez et al. (2016a). For each BBH that forms and eventually merges, we follow its SMA and eccentricity using the GW quadrupole equations given in Peters (1964), together with its GW peak frequency derived using the fitting formulae by Wen (2003). We only include BBHs that merge within a Hubble time; for the post-interaction binaries, we further require that the dynamical kick velocity in the three-body center of mass is $>50$ km s$^{-1}$. These two requirements are included for consistency, but do not significantly affect our results.

Our scattering results are shown in Figure 1. We first note that our derived post-interaction binary eccentricity distribution at 10 Hz is very similar to that obtained by Rodriguez et al. (2016a), using a more sophisticated GC modeling approach. While this is expected due to our choice of ICs, it gives credence to the validity of the formalism used here. We note that the main shape of the distribution depicted in Figure 1 originates from the thermal distribution of eccentricities (Heggie 1975), where both the BBH mass and initial SMA determine the location of the peak. The high-eccentricity
component of the distribution, originating from our inclusion of GW emission in the EOM through the 2.5 PN term, is clearly evident in Figure 1 and contains $\gtrsim 1\%$ of all BBH mergers. If 2.5 PN corrections are not included, this high-eccentricity component within the LIGO frequency band is absent from the distribution.

Having numerically derived the relative fraction of highly eccentric mergers, it is important to explore how this fraction changes when the initial SMA $a_0$ and BH mass $m_{BH}$ are altered. This is done in the following, assuming the equal-mass case. We start by noting that low-eccentricity mergers are dominated by post-interaction binaries that merge within a Hubble time, $t_H$, while high-eccentricity ones are dominated by GW inspirals. The relative rate of highly eccentric BBH mergers can thus be approximated by the ratio between the GW inspiral cross-section, $\sigma_{\text{I}}$, and the cross-section for post-interaction binaries to merge within time $t_H$, denoted here as $\sigma_{\text{am}}$. The cross-section $\sigma_{\text{I}}$ was shown in Samsing et al. (2014) to scale as $\sigma_{\text{I}} \propto a_0^{12/7}m_{BH}^{-12/7}$. For deriving $\sigma_{\text{am}}$, we first express it as the cross-section for a close binary–single interaction, which scales $\propto a_0m_{BH}$ (e.g., Samsing et al. 2014), times the probability for a post-interaction binary to merge within time $t_H$, $P(<t_H)$. In the limit $t_0 < t_H$, where $t_0$ is the average merger time of post-interaction binaries with $e \approx 0$, the cross-section scales as $e_0^2 \propto a_0m_{BH}$ since $P(<t_H) \approx 1$. In the limit $t_0 > t_H$, the post-interaction binary eccentricity must instead be above a certain value, $e_M$, for the corresponding merger time to be $< t_H$. Assuming a thermal distribution for the eccentricities (Heggie 1975), one finds $P(<t_H) \approx 1 - e_M^2$. From relating this probability to the binary merger time (Peters 1964), we find $\sigma_{\text{am}} \propto a_0^{13/7}m_{BH}^{-5/7}$. As a result, the fraction of BBHs that merge with notable eccentricity, $f_{e > 0}$, can then be written as

$$f_{e > 0} \propto a_0^{-5/7}m_{BH}^{-5/7}, \quad t_0 < t_H$$

$$f_{e > 0} \propto a_0^{3/7}m_{BH}^{-1/7}, \quad t_0 > t_H$$

We note here that $t_0$ in the equal-mass case is approximately given by the merger time of the initial target binary. If we keep $m_{BH}$ fixed, we then see that $f_{e > 0}$ will always increase with $a_0$, provided that $t_0 \approx t_H$. As $t_0 \approx t_H$ for our ICs, we can safely conclude that an increase in $a_0$ will actually lead to a larger $f_{e > 0}$ than the one reported in this Letter. The scaling solutions further illustrate that $f_{e > 0}$ is not expected to change much within the variations reported by Rodriguez et al. (2016a). The fraction of high-eccentricity BBH mergers derived here is likely to be an accurate estimate of the fraction for a broad range of GC properties.

3. Discussion

Recent studies show that the BBH spin vectors are likely to differ between different merger channels (e.g., Kushnir et al. 2016; Rodriguez et al. 2016c; Zaldarriaga et al. 2017); however, not much work has been done on deriving corresponding differences in BBH eccentricity despite its importance (e.g., Amaro-Seoane & Chen 2016; Chen & Amaro-Seoane 2017). In this Letter we have shown that $\gtrsim 1\%$ of all BBH mergers forming in GCs via binary–single interactions will have eccentricities $e > 0.1$ when coming into the LIGO band. Together with spin, eccentricity is probably the other most promising parameter to help observationally distinguish between different astrophysical BBH merger channels.

In Antonini et al. (2016) it was argued that the rate of high eccentricity ($e > 0.1$) BBH mergers observable with Advanced LIGO is likely to be dominated by BBHs that are driven to merge via Lidov–Kozai (LK) oscillations (Kozai 1962; Lidov 1962) in hierarchical triples formed in GCs. By using a MC method for simulating the evolution of GCs (Morscher et al. 2015) together with the ARCHAIN code (Mikkola & Merritt 2008), Antonini et al. (2016) concluded that $\approx 1\%$ of all BBH mergers formed in GCs will merge with high eccentricity via the LK mechanism.

Antonini et al. (2016) compared their derived LK merger rates to a broad range of other dynamical channels, from which they concluded that the LK channel is likely to dominate the population of eccentric BBH mergers. However, they overlooked the possibility of forming a sizable number of high-eccentricity BBH GW mergers through the binary–single channel. Antonini et al. (2016) did note that about 1% of all BBH mergers assembled through the binary–single channel are likely to merge at high eccentricity (as argued by Samsing et al. 2014), but they mistakenly estimated the corresponding rate by using their in-cluster mergers population (see Table 1 in Antonini et al. 2016). A more accurate estimate can be made when considering their ejected binaries population, as this group primarily represents the hard (unbound) binaries formed via binary–single interactions (Rodriguez et al. 2016a). Using the population of ejected binaries in Antonini et al. (2016), one finds that similar rates of highly eccentric GW mergers can be derived from binary–single interactions than from their proposed KL channel.

In this study we have not only demonstrated that a significant number of GW inspiral mergers do form in three-body interactions, but also that they keep their high eccentricity until they come into the LIGO frequency band. While deriving an absolute merger rate is difficult, our results robustly indicate that the binary–single channel is a competitive alternative for producing high-eccentricity GW mergers. In fact, the rate of LK mergers estimated by Antonini et al. (2016) is highly uncertain, as their sample of hierarchical triples was not self-consistently evolved in their simulations. The rate derived here for GW inspirals is also not exact, as we have only considered equal-mass isolated binary–single interactions. Having said this, we do find that GW inspiral mergers happen relatively promptly, are easy to identify, and their outcomes are only mildly dependent on black hole mass and initial SMA distribution. This indicates that a relative rate of highly eccentric GW mergers can be robustly estimated from this dynamical channel.

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