BLACK HOLES BINARIES FROM GLOBULAR CLUSTERS AS SOURCES OF GRAVITATIONAL WAVES

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We analyse about a thousand globular cluster (GC) models simulated using the MOCCA Monte Carlo code for star cluster evolution to study black hole - black hole interactions in these dense stellar systems that can lead to gravitational wave emission. We extracted information for all coalescing binary black holes (BBHs) that merge via gravitational radiation from these GC models and for those BHs that collide or merge due to 2-body, 3-body and 4-body dynamical interactions. By obtaining results from a substantial number of realistic star clusters, that cover different initial parameters (masses, metalicities, densities etc) we have an extremely large statistical sample of two black holes which merge or collide within a Hubble time. We discuss the importance of BBH originating from GC for gravitational waves observations.

1 Introduction

The direct detections of gravitational waves (GWs) from the merger of binary black holes (BBHs) by the Advanced LIGO (aLIGO) detectors has ushered astrophysics into a new era of observing violent events that were previously invisible. Following the detection of GW150914 [3], two more confirmed BBH mergers, GW151226 [4] and GW170104 [5] were observed by aLIGO. The detections confirm the existence of heavy stellar mass black holes (BHs) in binary systems and prove that such systems merge via GW emission within a Hubble time. Masses inferred from the GW signal of coalescing BBHs detected by aLIGO show that these BHs are typically more massive than accreting stellar mass BHs in X-ray binaries. Existence of BHs with masses higher than $20M_{\odot}$ may indicate that they were formed in low metalicity environments like GCs but the formation scenario for massive BBHs and the origin of the detected coalescing binaries remains debatable. Such systems may form also in the field via binary stellar evolution or galactic nuclei [7,6]. It is also possible that the detected events maybe coalescing primordial BHs [24]. In this contribution we study the astrophysical properties of BHs which merge via GW emission in a binary system or collide in GCs due to dynamical interactions. The coalescence will lead to the chirp signal while collisions to a short, burst signal.

2 Method

We analyze about 1000 GC models generated by the MOCCA (MOnte Carlo Cluster simulAtor) code [17,8] as part of the MOCCA-Survey Database I. The initial conditions for these models models cover a wide range of the parameter space (different initial masses, densities, primordial binary fraction, metallicity). The code follows most of the important physical processes that occur during the dynamical evolution of star clusters. MOCCA includes:

1. Synthetic binary stellar evolution using the prescriptions provided by Hurley, Pols & Tout (2000) and Hurley, Tout & Pols (2000) (BSE code),
2. Direct integration procedures for small N sub-systems using the FEWBODY code provided by Fregau *et al.* (2004),
3. Realistic treatment of escape processes in tidally limited clusters based on Fukushige & Heggie (2000).

MOCCA has been extensively tested by Giersz *et al.* (2013), Heggie (2014), Wang *et al.* (2016), Madrid (2017) and Mapelli (2016) against the results of N-body simulations of star cluster models comprising of thirty thousand to one million stars. The agreement between these two types of simulations was excellent. In the MOCCA-SURVEY Database I cluster models are more or less representative of the GC population in our Galaxy [8]. The code has been recently used to determine properties of coalescing binary black holes originating from GC [8]. The mass of each BH in a binary system was limited to $M < 100M_{\odot}$. In this contribution we consider all BH masses and take into account all BH-BH interactions which lead to GW emission. For BBHs that were ejected from GC, we calculated the merger times using the formulae derived by Peters (1964) and the time when the BBH escaped the GC. For coalescing BBHs retained in GC models, results from BSE code incorporated within MOCCA were used to obtain correct merger times. For BH collisions and mergers during binary-single and binary-binary interactions, the results from the FEWBODY code used in MOCCA for strong interactions were analyzed. Direct collisions between all single objects from MOCCA results were also analyzed to look for direct collisions betwen BHs. For BH collisions we consider 2-body, 3-body and 4-body interactions. This also included interactions with an Intermediate Mass Black Hole (IMBH, which is defined as a BH with mass above 100 $M_{\odot}$) that are dynamically formed in 30% GC models. [15].

3 Merging BBHs and Colliding BHs From Globular Clusters

Globular cluster are spherical and dense group of 10^5 to 10^6 stars orbiting a host galaxy. In GCs star density is so high that interactions between them are becoming widespread. Such interactions can affect the parameters of binary systems and radically change their evolution. This is particularly important for compact objects binaries: change of orbital parameters due to gravitational interactions with nearby objects; exchange of an object in a binary system as a result of close interaction; formation of new binary systems as a result of several-body interactions; the merger or the collision of two objects as a result of dynamical interactions. The whole analysis involves BHs that merged in a binary system or collided with each other within Hubble time $T = T_{\rm H} = 13 \times 10^9$ yrs. In addition, only binaries with enabled mass fallback were taken into account. The above limitations have reduced the sample of the simulated models from 1948 to 985.

3.1 Characteristics of the BH-BH interactions

Analysing the output of the MOCCA code we can distinguish five different interactions, which can lead to the emission of *chirp* GW signal due to the coalescence of two black holes in a binary system or to the *burst* GW signal due to the collision of two BHs. The number of mergers inside or outside cluster models or collisions due to 2-body, 3-body and 4-body dynamical interactions as a function of time are provided in Fig. 1.

1. Interactions leading to the *chirp* GW signal:

- EBE - Ejected Binary Evolution - a binary systems which, due to interactions in a cluster, gained sufficient velocity to escape the gravitational potential of GC. Such ejected BBH systems evolve in isolation outside GC. The coalescence time is determined by the orbital parameters set at the time of the escape which are taking into account while integrating Peters (1964) equations. Over 50 % of the OBE merge during the first two billion years of the cluster model evolution. This is the interaction that produces the largest number of GW *chirp* signal. By the T_{H}, 15 236 BBH merged, and only 102 of them had the mass of one of the two BHs greater than 100 $\mathrm{M}_{\odot}$.
- RBE - Reteined Binary Evolution - the BBH merger due to binary evolution or due to gravitational interaction inside the cluster. Most of these binaries, about 90% merge at early time of the cluster evolution (up to 5×10^8 years), when the most massive stars evolve rapidly, there is ongoing mass segregation process and the dynamical interactions are very common. There were 3 628 binary mergers found in this interaction, more than 80% of them are binaries, in which none of the BHs exceed 100 $\mathrm{M}_{\odot}$. As in the case of EBE interactions, the presence of IMBH results in a greater number of coalescence (over 2/3 of found binaries).

2. Dynamical interactions leading to the *burst* GW signal:

   - 2-BI - 2-Body Interactions - a collision of two BHs, which is based on a physical collision (the minimum distance is less than the sum of the Schwartzschild radius of both BHs). Collisions occur only in the clusters where the IMBH was formed, and the collision percentage in which it took part is 99.9%. Such objects have a significant influence on the evolution of the entire cluster. In our analysis we found 32,122 these interactions, and only 35 of them were with BHs that had less than 100 M $_{\odot}$. More than 50% of 2-body collisions occur during the first billion years of globular cluster model evolution.
   - 3-BI - 3-Body Interactions - interactions involving three objects - a binary system and a star. In this interaction, as in the case of 2-BI, a dynamical physical collision occurs. To designate the relevant objects involved in a collision all possible permutations must be taken into account. These collisions are very rare (1,064 found events) and, as in the case of IBE interactions, the majority of the collisions occur during the first billion years of the GC model evolution. Over 97% of them are collisions in clusters with IMBH.
   - 4-BI - 4-Body Interactions - interactions involving two binary systems, in which two BHs are colliding. These interactions have properties very similar to 3-BI, but with even less statistics (783 found events), although more collisions were reported, both quantitatively and in percent, in clusters without IMBH. Just like other interactions, 4-BIs accumulate at the beginning of the cluster model evolution.

4 Local and Cosmological Merger and Collision Rate Density

In order to determine the merger and the collision rate density we used the same formalism as Bulik *et al.* (2004). We used GC star formation rate model (GCSFR) from Katz & Ricotti (2013). We found a local merger rate density for EBE and RBE in GCs of at least $5.6\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ up to $30\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$. It is comparable to the rate calculated by Rordriguez *et al.* (2016) and consistent with the lower bound on the observed LIGO BBHs merger rate density of $12 - 213\mathrm{Gpc}^{-3}$ [5]. In Figure 2 one can see that rate of merging BBHs depends on cluster metallicity. The obtained masses of BH are consistent with aLIGO observations. The uncertainty in the metallicity composition of GCs in early galaxies and the uncertainties connected with stellar

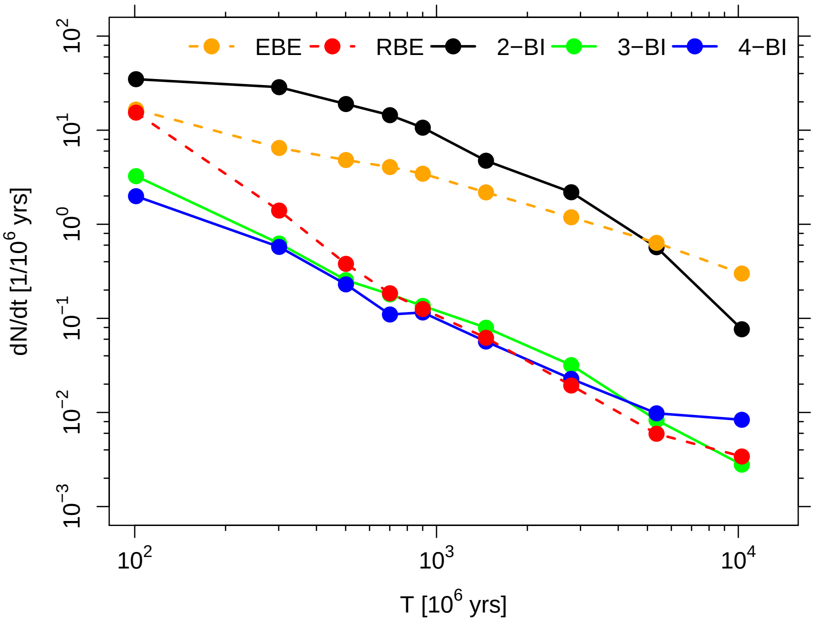

Figure 1 – Number of merging BBHs per unit time (1 Myr) as a function of merger time limited to Hubble time $T_{\rm H}$. Orange and red dashed point-lines correspond to binary mergers with *chirp* GW signal (outer and inner binary evolution respectively). Black, green and blue solid point-lines correspond to *burst* GW signal interactions, which are 2-, 3- and 4-body interactions respectively.

initial mass function and the maximum stellar mass may introduce an additional increase in the merger rate. This shows that BBHs from GC could contribute to the observed events by aLIGO and other ground based detectors. The efficiency of BBHs mergers is higher in GC than in the field but the total mass of GC could be lower than 1

We also determined the merger and collision rate density as a function of redshift z. In Figure 3 different types of interactions are marked with different colours. Dashed lines correspond to the interactions leading to the *chirp* GW signal, while solid lines correspond to interactions which lead to *burst* GW signal. In the local universe, the dominant interactions are those of EBE, the binaries that escaped the cluster and evolve due to GW emission outside GC. For higher value of $z > 0.6$ 2-BI collisions dominate the rate. Aside from 2-BI, a large coalescence ratio on high values of z has also OBE and IBE interactions. Collisions due to 3-body and 4-body interactions are less significant than others in full range of z.

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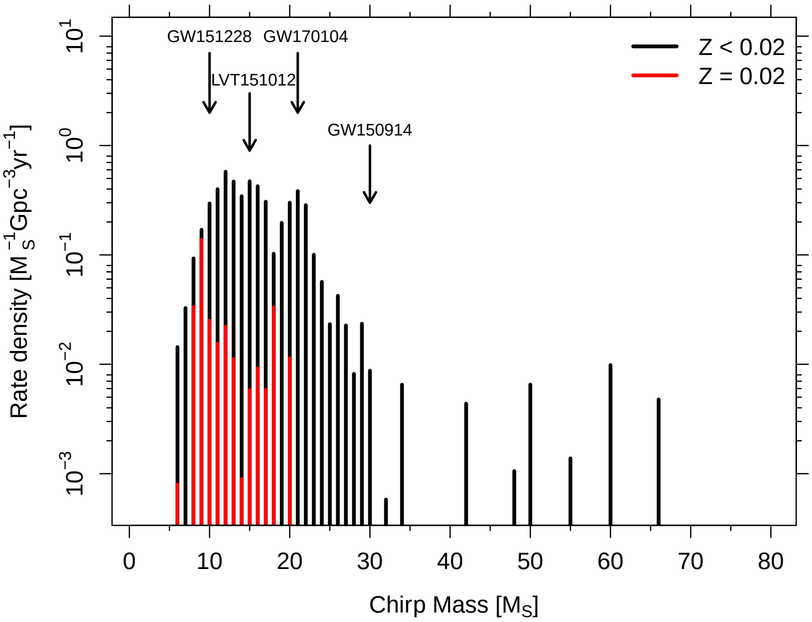

Figure 2 – Local merger rate density in function of *chirp* mass $\mathcal{M}$. Data includes only OBE interactions, which are divided by the initial metallicity of the cluster model: solar $Z = 0.02$ (red) and sub-solar $Z < 0.02$ (black). Arrows indicate all signals detected by the aLIGO detector of merging BBHs.

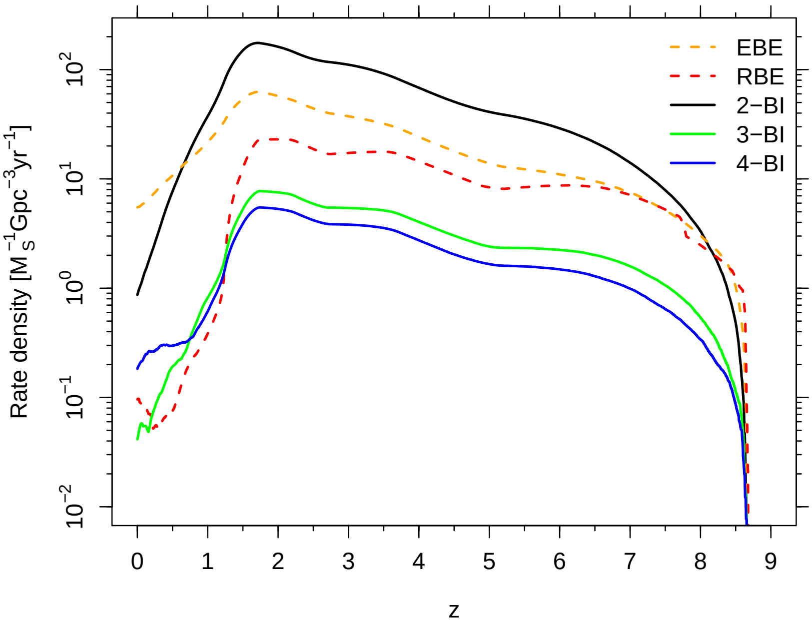

Figure 3 – Merger and collision rate density in function of redshift for fixed GCSFR [20] for all types of interactions. Orange and red dashed lines correspond to binary mergers (outer and inner binary evolution respectively) which produce *chirp* GW signal. Black, green and blue solid lines correspond to interactions, which are sources of *burst* GW signal (2-, 3- and 4-body interactions).

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