Simulation of Formation of Binary Compact Objects in Globular Cluster

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Abstract. Binary compact objects are the special binary systems, which were composed of compact objects (i.e., white dwarf, neutron star and black hole). They contribute a lot to the sources of gravitational waves. The study of binary compact objects in star clusters and galaxies can provide a theoretical guidance for gravitational wave detection and improve the probability of detection effectively. We simulate the formation and fraction of binary compact objects in a small globular cluster, via NBODY6++GPU, an efficient N-body simulation code. We obtain the fractions of white dwarf binaries and neutron star binaries at different ages. The results show that the dynamic interactions among stars can also result in some binary compact objects besides binary evolution.

Keywords: Binary compact object, N-body simulation, globular cluster.

1. Introduction

Gravitational wave (GW) is not only an important way to verify general relativity, but also a new approach for astronomical researches. It opened up a new direction for exploring the universe. It is well known that binary compact objects (BCOs), such as neutron star binaries (NSBs), black hole binaries (BHBs) and neutron star-black holes (NSBHs), are the major sources of GWs. The studies of BCOs are helpful for understanding the formation and evolution of GWs. Many studies showed that most of the GWs came from BCOs, including BHB, NSB and NSBH merging (Abbott et al. 2019, Abbott et al. 2020\textsuperscript{[1],[2]}. However, the GWs of white dwarf binaries (WDBs) are not detected. There are still some limitations in current GW detection techniques, and the theoretical researches of GWs are not comprehensive. The study of BCOs components in star clusters and galaxies can provide a theoretical basis for the detection of GW. In this way, the detected range and efficiency can be improved significantly.

There are two major formation modes of BCOs, evolution of massive binaries (Sigurdsson & Hernquist 1993\textsuperscript{[3]} and dynamic processes (Di Carlo et al. 2019\textsuperscript{[4]}) among stars. So, the probability of BCOs being produced in a dense stellar environment is very high. Globular clusters are the collections of numerous stars. They have large numbers of stars and high densities. Hence, globular clusters are the ideal sites of BCOs formation. On the one hand, BCOs in globular cluster can be formed through a series of complex stellar evolution processes. On the other hand, BCOs can be produced under the dynamic processes among member stars.
This paper aims to simulate the formation and fraction of all kinds of BCOs in a globular cluster by N-body simulation. Section 2 briefly introduces the method. Section 3 presents the input parameters. The result is shown in section 4 and we make a conclusion in section 5.

2. Method
We apply a powerful numerical simulation code to investigate the globular cluster, which includes a large number of particles with masses. An updated version of NBODY6++GPU (Wang et al, 2015)[5] is used to calculate BCO fractions in this work. It is widely-used because of its powerful computing capability by using GPU parallelization. Besides the dynamic processes among stars, this code also calculates the evolution of stars in the globular cluster. NBODY6++GPU uses a stellar evolution code, BSE (Hurley et al. 2002)[6], which takes both single and binary stars into account. The code can calculate stellar evolution quickly and accurately.

3. Input Parameters
In order to shorten the computing time, we build a small globular cluster model with a star number of 10000. It is similar to some observed globular clusters. The simulation finished at the age of 5.0 Gyr. We set the metallicity to a typical value, i.e., solar metallicity ($Z=0.02$). The masses of stars are generated by taking the initial mass function (IMF) of Kroupa (2001)[7]. According to the stellar physics, the stellar masses cover a range of $0.08\sim100M_\odot$, and the average mass is $0.55M_\odot$. At zero age, stars distribute randomly with a Plummer sphere (Plummer 1911)[8] in space.

Binary stars are common objects in the universe. In Milky Way, more than 50% stars are binaries. The binary fractions in young star clusters are extremely high, they can be as large as 80% ~ 100% (Milone et al. 2012)[9], so we define the primordial binary fraction as 50%. For the primordial binaries, the upper and lower limits of masses are set to $58.33M_\odot$ and $0.08M_\odot$. The eccentricities of binaries follow a thermal distribution (the square of eccentricities follows a uniform distribution). In addition, the orbital periods are given randomly in the range from 0 to 100000 yr. According to the theory of stellar evolution, the binaries whose orbital periods are larger than 100 yr have no binary material interaction. The fundamental parameters of the simulation are listed in Table 1. Note that, the masses of secondary stars (stars with lower masses) in binaries are lower than $6M_\odot$, thus it is hard to form NSBs and BHBs in binary evolution. It implies that the resulting NSBs and BHBs in the simulation are probably produced by dynamic processes.

| Parameter | Value |
|-----------|-------|
| $N$       | 10000 |
| $f_b$     | 50%   |
| $Z$       | 0.02  |
| Age       | 5.0 Gyr |
| $M_{max}$ | 100 $M_\odot$ |
| $M_{min}$ | 0.08 $M_\odot$ |

4. Results
In this work, the cluster is simulated to the age of 5.0 Gyr. The computation spent 16 days. The initial number of stars is 10000, and it then decreases with time, because of the merging and escaping of stars. We focus on the formation of BCOs in the simulation. According to the output files, we can obtain the numbers of BCOs. The fractions of BCOs can be calculated by comparing the numbers of BCOs and all stars in the star cluster. The results are shown in Table 2. We find that WDBs form in a very short time with the evolution of star cluster. As we see, the fraction of WDBs reaches 0.031% in the first 0.5 Gyr, and increases until 5.0 Gyr. The fraction of NSBs changes slightly within this time in the range of 0.0 ~
5.0 Gyr. The fraction of NSBs is 0.012%, the corresponding binary number is only 1. Figure 1 shows the evolution of BCO fractions in this work. We can see that the fractions of WDBs are always much larger than that of NSBs.

**Table 2.** BCO fractions in N-body simulation.

| Age (Gyr) | 0.0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| WDBs      | 0.000 | 0.031 | 0.052 | 0.066 | 0.111 | 0.135 | 0.179 | 0.195 | 0.220 | 0.222 | 0.235 |
| NSBs      | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.012 | 0.012 |

The formation processes of the two kinds of BCOs are also studied. There are two WDBs come from primordial binaries within three in total WDBs when WDBs form within the first 0.5 Gyr. We find that dynamic processes usually separate the WDBs evolved from isolated binaries. As a result, all WDBs are formed by dynamic interactions among stars.

The other kind of BCOs, NSB, is also well studied in this simulation. The only one NSB is produced in the process of dynamics. Because NSBs are one of the main sources of GWs, we analyze the formation of the NSB in this simulation in detail. Figure 2 summarizes the entire process of the NSB formation. The evolution processes of two components (Nos. 135 and 10024) that finally form the NSB are shown. Star No. 135 goes through a very complicated formation process. In detail, at the beginning of the evolution, the star is included in a binary system. With the evolution of the binaries, the original binary system was destroyed. Then star No. 135 becomes a single red-giant. Next, it evolves to a single neutron star. After that, the single neutron star encounters a single main sequence star, a new binary system is formed. Meanwhile, the massive star No. 10024 evolves to a single neutron star. Finally, Star No. 10024 collides the new binary system, a NSB and a single star are formed.

![Figure 1](image-url)  
**Figure 1.** Evolution of fractions of BCO in N-body simulation. The blue solid line is the result of WDBs, the orange thick line is for NSBs.
5. Conclusion
In this work, we simulate the formations and fractions of BCOs in a small globular cluster. This paper first introduces the importance of binary stars in the future development, then describes the method used in this paper and the specific simulation process, and finally carries on the further analysis and summary of the simulation results. We use an advanced N-body simulation code, which has comprehensive consideration to simulate a globular cluster. The fraction of WDBs increases significantly in the age range of 0.0 ~ 5.0 Gyr, but the result of NSBs increases very slowly. Therefore, the formation of NSBs is much slower than that of WDBs. This is normally according to the IMF. Both WDBs and NSBs are formed mainly from dynamic interaction among stars.
We do not observe NSBHs and BHBs in our simulation. The reasons are that there are few super massive binary stars according to the IMF, and the small number of stars in the mimic globular cluster. In future works, it is necessary to enlarge the number of stars in the cluster and extend the simulated age.

Acknowledgments
This work is supported by Yunnan Academician Workstation of Wang Jingxiu (No. 202005AF150025), National Natural Science Foundation of China (No. 11863002), and Sino-German Cooperation Project (No. GZ 1284).

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