Formation of binary black holes in star clusters as gravitational wave sources

Jun Kumamoto¹, Michiko S. Fujii¹ and Ataru Tanikawa²,³

¹ Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
² Department of Earth Science and Astronomy, College of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan
³ RIKEN Center for Computational Science, 7-1-26 Minatojima-minami-machi, Chuo-ku, Kobe, Hyogo 650-0047, Japan
E-mail: kumamoto@astron.s.u-tokyo.ac.jp

Abstract. Direct detections of gravitational wave suggest that ∼ 30 solar mass binary black holes (BBHs) commonly exist in the Universe. One possible formation scenario of such BBHs is dynamical three-body encounters in a dense core of globular clusters, which consist of millions of stars. Compared to globular clusters, open clusters are less dense and less massive but more populous. Because of their shallow potential, they have not been considered to be a formation site of merging BBHs. However, we found a new channel for the formation of BBHs, which is dominant in open clusters. We performed direct N-body simulations of open clusters with a mass of 2500 solar mass for metallicity of $Z/Z_\odot = 0.1$. The core-collapse time of open clusters is much shorter than that of globular clusters. Therefore, massive main-sequence stars can form binaries before they evolve to BHs. These main-sequence binaries experience mass transfer evolution, and some of them evolve to BBHs merging within the Hubble time. From our simulations, we estimated the merger rates of BBHs originated from open clusters.

1. Introduction

LIGO and Virgo have observed binary black holes (BBHs) mergers. These observations suggest that about $30 M_\odot$ BBHs commonly exist in the Universe. There are two possible scenarios for the formation process of these merging BBHs. One is considered that BBHs with the small semi-major axis are formed as a result of mass transfer [1], [2]. Another scenario is the dynamical interaction of stars in the dense core of the star cluster [3].

About the formation process of BBHs in a cluster, the globular cluster may be dominant because there are many black holes in the clusters and that black holes tend to stay in the cluster due to the strong gravitational potential. On the other hand, in the open cluster, the number of black holes is limited, and the gravitational potential is shallower. Therefore, the formation of merging BBHs may be difficult in a open cluster.

However, the number of open clusters is higher than that of globular clusters in the Universe [4]. Therefore, open clusters can be a dominant formation region of BBHs. Then, we investigated the formation of BBHs in the open cluster using the $N$-body simulation.
2. Simulations
We used the gravity N-body simulation code NBODY6++GPU [5] and investigated the formation of BBHs in open clusters. The summary of our calculation is as follows. See also [6] for more information.

The initial parameters of our cluster models used in this study are shown in Table 1. We simulated the evolution of star clusters with \(2.5 \times 10^5 M_\odot\). As an initial condition, the stars in the cluster are main-sequence stars with Kroupa’s initial mass function [7]. In our model, the expected average stellar mass is 0.586 \(M_\odot\).

Table 1. The initial parameters of our simulation models.

| Our Model | \(M_\text{cl}^1 [M_\odot]\) | \(N_\text{ini}^2\) | \(N_\text{RUN}^3\) | \(\rho_\text{hm}^4 [M_\odot]\) | \(r_p^5 [\text{pc}]\) | \(t_\text{cc}^6 [\text{Myr}]\) |
|-----------|-----------------|-------------|-------------|-----------------|-----------|-----------|
| 2500      | 4266            | 360         | 10^4        | 0.24            | 0.7       |

Notes:
1. Cluster mass.
2. Number of initial particles.
3. Number of simulation runs.
4. Half mass density.
5. Scale radius.
6. Core collapse time.

We adopt Plummer profile as the initial density profile:

\[
\rho(r) = \frac{3M}{4\pi a^3} \left(1 + \frac{r^2}{a^2}\right)^{-5/2},
\]

where \(r\) and \(r_p\) are the radius from the cluster center and the scale radius. The scale radius is determined so that half mass density become \(10^4 M_\odot \text{pc}^{-3}\). The core collapse time of our initial condition are 0.7. In this timescale, clusters form dense cores. We expected that the binary formation by the three-body encounter occurs in this dense core.

NBODY6 contains a stellar evolution model [8]. The evolution of stellar radius, mass and luminosity of each star can be calculated from the initial stellar mass and metallicity. We set the stellar metallicity to be 0.1Z_\odot. In our simulation, we can see binary formation and evolution by the three-body encounter. Binaries have much smaller time step than evolution timescale of the cluster. Therefore, binaries are treated using KS regularization. Also, some binary occurs common envelope. Stellar evolution model calculates the evolution of binaries parameter via common envelope. And we can see many ejections of single and binary stars from the cluster.

3. Properties of binary black holes
As a result of such simulations, 323 BBHs were formed in our model. These results mean that about one BBH was found from one cluster. We investigate properties of these BBHs.

Figure 1 shows the cumulative distribution of binary parameters of BBHs formed in our simulation. Solid lines and dashed lines show the distribution of BBHs without and with common envelope evolution. BBHs experienced common envelope tend to have smaller eccentricity and shorter semi-major axis.
Figure 1. The cumulative distribution for some binary parameters of BBHs formed in our simulation. Solid lines and dashed lines show the distribution of BBHs without and with common envelope evolution.

And also, we calculated merger time with the following equation [9].

\[
    t_{GW} = \frac{5}{256} \frac{e^5}{G^3 M_1^3} \frac{a^4}{q(1 + q)} g(e)
\]

\[
    \sim \left( \frac{M_1}{30 \, M_\odot} \right)^{-3} \left( \frac{a}{0.1 \, \text{AU}} \right)^4 \frac{g(e)}{q(1 + q)} \, \text{Gyr},
\]

where

\[
    g(e) = \frac{(1 - e^2)^{3.5}}{1 + (73/24)e^2 + (37/96)e^4}.
\]

Figure 2 shows the cumulative distribution of merger time and its fitting equation. From fitting equation we can found the merger rates per cluster:

\[
    \Gamma(t) \sim 3.4 \times 10^{-11} \left[ 0.79 \left( \frac{t}{\text{Gyr}} \right) + 1 \right]^{-1} \text{yr}^{-1}.
\]

If all clusters are 10 Gyr old, the merger rate density in the local universe is described as \( \Gamma(t = 10 \, \text{Gyr}) \times n_{cl} \). Here, \( n_{cl} \) is the number density of star clusters, and we adopt \( n_{cl} = \sim 77 \, \text{Mpc}^{-3} \) (see [6] for detail of this estimation). Therefore, merger rate densities are \( 0.29 \, \text{yr}^{-1} \text{Gpc}^{-3} \).
4. Formation of BBHs in open clusters

The majority of similar previous studies have focused on globular clusters (e.g. [3], [10], [11]). Our results show that some merging BBHs are formed in open cluster, contrary to the previous assumption. We discovered that the formation process of merging BBHs in open clusters is the difference to the globular cluster.

A star with 100 $M_\odot$ evolves to a black hole for about 3 Myr. Open clusters have a shorter core-collapse time than 3 Myr. Therefore, in the case of open clusters, core-collapse time is less than the life-time of massive main-sequence stars. Thus, binaries are formed before black holes formation, and these binaries evolve into BBHs with common envelope. Even in the open cluster, many merging BBHs may be formed by this process.

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