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Unexpectedly high formation rate of merging binary black holes in open clusters

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Abstract. Gravitational wave direct detections suggest that 30 $M_{\odot}$ binary black holes (BBHs) commonly exist in the universe. One possible formation scenario of such BBHs is dynamical three-body encounters in dense star clusters. We performed a series of direct N-body simulations with a mass of 2500 and 10000 $M_{\odot}$ and found a new channel for the formation of BBHs which is dominant in open clusters. In open clusters, the core-collapse time is shorter than in globular clusters, and therefore massive main-sequence (MS) binaries can form before they evolve to BHs. These MS binaries experience common envelope evolution and evolve to hard BBHs, which can merge within the Hubble time. The number of BBH mergers per unit mass obtained from our simulations reached 20–50 % of that for globular clusters, assuming an initial cluster mass function. Thus, open clusters can be a dominant formation site of hard BBHs.

Keywords. gravitational waves, methods: numerical, open clusters and associations: general

1. Introduction

In 2016, the first direct detection of gravitational waves by LIGO was presented (Abbott *et al.* 2016). The detected gravitational wave was estimated to be emitted by a merger between two black holes, and the masses of the merging black holes were estimated to be about 36 and 29 $M_{\odot}$, respectively. The detection of the gravitational wave continued afterwards, and more than ten gravitational waves which seemed to be caused by mergers of binary black holes (BBHs) were detected. These observations suggest that about 30 $M_{\odot}$ BBHs commonly exist in the universe.

Two possible scenarios have been proposed for the formation process of merging BBHs. One scenario considers that BBHs with small semi-major axes are formed as a result of mass transfer when the binaries consisting of two massive main-sequence stars evolve (Kinugawa *et al.* 2014; Belczynski *et al.* 2016). Another scenario is the dynamical interaction of multiple stars in the dense core of star clusters (Portegies Zwart & McMillan 2000).

For the second scenario, it has been considered that globular clusters (10^5–10^6 $M_{\odot}$) are the primary region for the formation of BBHs with small semi-major axes. The reasons are that there are many massive stars which become black holes and that black holes tend to stay in the cluster because of the strong gravitational potential. On the other hand, in open clusters (10^3–10^4 $M_{\odot}$), the number of black holes is limited, and the gravitational potential is shallower. Therefore, it has been considered that the formation of merging BBHs is difficult in open clusters.

However, more open clusters are formed than globular clusters in the Universe (Portegies Zwart *et al.* 2010). Therefore, even if there are few BBHs formed in individual

Table 1. The initial parameters of our simulation models.

Models	$M^1_{\rm cl}[M_\odot]$	$N^2_{\rm ini}$	$N^3_{\rm run}$	$\rho^4_{\rm hm}[M_\odot]$	$r^5_{\rm p}$ [pc]	$t^6_{\rm cc}$ [Myr]
Model A	2500	4266	360	10^4	0.24	0.7
Model B	10000	17064	90	10^4	0.38	2

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.

open clusters, it can be a dominant formation region of BBHs. Then, we focused on the formation of BBHs in open clusters as the origin of the gravitational wave sources and investigated the features of BBHs formed in open clusters using N-body simulations.

2. Simulation

In our simulation, the clusters were treated as gravitational N-body systems, and the calculation was carried out using the gravity N-body simulation code NBODY6++GPU (Wang *et al.* 2015). The main points of our calculation are as follows. See also Kumamoto *et al.* (2019) for more information.

Table 1 summarizes the main parameters of the initial conditions of our cluster model used in this study. We investigate the evolution of star clusters of two models (model A and B) with 2.5×10^3 and 1.0×10^4 $M_\odot$. As an initial condition, the stars in the cluster are main-sequence stars (0.1 $Z_\odot$) with 150 to 0.08 $M_\odot$. The mass distribution is given by the Kroupa initial mass function (Kroupa 2001). For this mass function, the expected average stellar mass is 0.586 $M_\odot$.

As the density distribution $\rho(r)$ of the star cluster, we adopt the Plummer model;

$$\rho(r) = \frac{3M}{4\pi a^3}\left(1 + \frac{r^2}{r_p^2}\right)^{-5/2}, \tag{2.1}$$

where r and r_p are the radius from the cluster center and the scale radius. The scale radius was determined so that the half mass radius is equal to $10^4 M_\odot$ pc^{-3}. The core-collapse time $t_{\rm cc}$ is also summarized in Table 1. When the dense core is formed, the binaries are formed in the core via the three-body interaction.

NBODY6++GPU includes a library of stellar evolution and a package of calculating binary star evolution, and it is often used in previous studies on star clusters. By using the stellar evolution model (Hurley *et al.* 2000), mass loss and stellar evolution according to initial stellar mass and metallicity can be calculated.

The majority of similar previous studies have focused on globular clusters (e.g. Tanikawa 2013; Portegies Zwart & McMillan 2000; Fujii *et al.* 2017). Some previous studies have focused on open clusters, binary stars have been added from the beginning and the subsequent binary evolution has been investigated (e.g. Ziosi *et al.* 2014; Di Carlo *et al.* 2019). The feature of our simulation is that we focused on the open cluster and investigated the binary formation process.

3. Merging BBHs

As a result of the simulation, we discovered that the BBHs were formed even in open clusters. We investigated whether such BBHs emit gravitational waves as found by observations. The following equation gives the merging time of binary (Peters & Mathews 1963).

$$t_{\rm GW} = \frac{5}{256}\frac{c^5}{G^3}\frac{a^4}{M_1^3 q(1+q)}g(e) \tag{3.1}$$

$$\sim 1.2 \times 10^4 \left(\frac{M_1}{30 M_\odot}\right)^{-3}\left(\frac{a}{1\ \rm AU}\right)^4 \frac{g(e)}{q(1+q)}\ \rm Gyr, \tag{3.2}$$

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Table 2. The number of BBHs in our simulation and Rodriguez *et al.* (2016).

	Model A	**Model B**	**Rodriguez *et al.* (2016)**
Mass $[M_\odot]$	2.5×10^3	1.0×10^4	6×10^5
$N_{\rm BBH,esc}$ per $9 \times 10^5 M_\odot$	323	335	182–210
$N_{\rm BBH,esc}(t_{\rm GW} < 10$ Gyr) per $9 \times 10^5 M_\odot$	36	15	65–81
Mergers per solar mass $[M_\odot^{-1}]$	4.0×10^{-5}	1.7×10^{-5}	7.2–9.2×10^{-5}

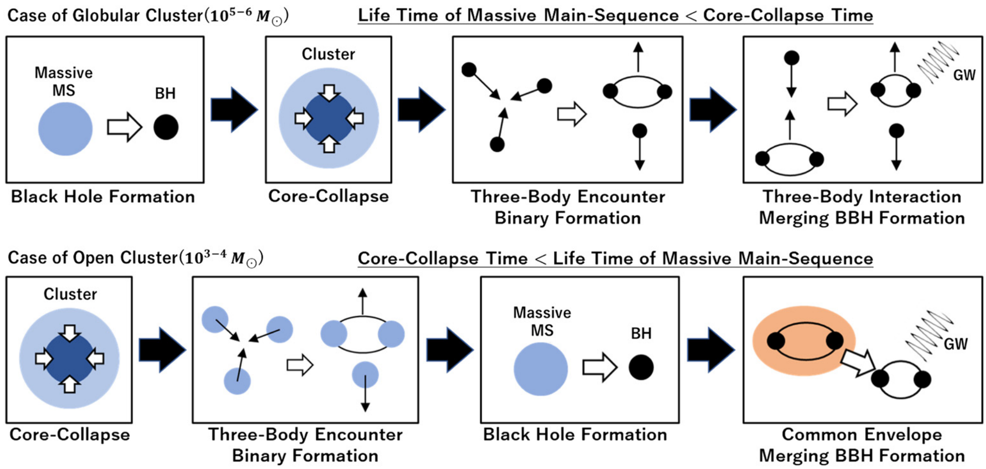

Figure 1. The schematic illustration of the differences in the major formation processes of merging BBHs between globular clusters (top panels) and open clusters (bottom panels).

where

$$g(e) = \frac{(1-e^2)^{3.5}}{1 + (73/24)e^2 + (37/96)e^4}. \tag{3.3}$$

Here, a and e are the semi-major axis and eccentricity of the binary, respectively. M_1 is the mass of the heavier star of the binary, and q is the mass ratio of the lighter star to M_1. If the merging time obtained from the above equation is not shorter than Hubble time, we can not detect gravitational wave in the present observation.

Table 2 shows the number of BBHs in our results and a previous study (Rodriguez *et al.* 2016) calculated for more massive clusters. In our simulation, more than 300 BBHs were formed in both models A and B. 36 BBHs in model A and 15 BBHs in model B have shorter merging time than 10 Gyr. Our results show that merging BBHs are also formed in open clusters with 10^3 to 10^4 $M_\odot$. The number of merging BBHs per unit mass obtained from our simulation reached 20–50 % of that for globular clusters (Rodriguez *et al.* 2016). Therefore, the open cluster may be a dominant formation region of merging BBHs.

4. Formation of BBHs in open clusters

Our results show that in open clusters, more merging BBHs are formed than the conventional assumption. We discovered that the formation process of merging BBHs in open clusters is unlike the globular cluster.

Figure 1 shows the difference of formation process of merging BBHs between globular clusters and open clusters. Whereas a star with 100 $M_\odot$ evolves to a black hole in about 3 Myr, the cluster used in our simulation has a shorter core-collapse time than 3 Myr (see Table 1). The core-collapse time tends to be longer as the cluster mass increases, and in

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the globular clusters, the core-collapse time becomes longer than the lifetime of massive main-sequence stars. As a result, the core-collapse of a globular cluster (see top panels in Figure 1) occurs after the formation of massive black holes. Then, the formation and evolution of binary occurs by the three-body interaction in the dense core.

On the other hand, in the case of open clusters (see bottom panels in Figure 1), the core-collapse time is less than the lifetime of massive main-sequence stars. Therefore, binaries are formed before massive stars evolve into black holes, and these massive star binaries evolve into BBHs with shorter semi-major axis via common-envelope. Even in the open cluster, merging BBHs are formed more than the conventional assumption by this process.

References

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R. Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., *et al.* 2016, *Physical Review Letters*, 116, 061102

Belczynski, K., Holz, D. E., Bulik, T., & O'Shaughnessy, R. 2016, *Nature*, 534, 512

Di Carlo, U. N., Giacobbo, N, Mapelli, M., Pasquato, M., Spera M., Wang, L., & Haardt, F. 2019, *MNRAS*, 487, 2947

Fujii, M. S., Tanikawa, A., & Makino, J. 2017, *PASJ*, 69, 94

Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, *MNRAS*, 315, 543

Kinugawa, T., Inayoshi, K., Hotokezaka, K., Nakauchi, D., & Nakamura, T. 2014, *MNRAS*, 442, 2963

Kroupa, P. 2001, *MNRAS*, 322, 231

Kumamoto, J., Fujii, M. S., & Tanikawa, A. 2019, *MNRAS*, 486, 3942

Peters, P. C. & Mathews, J. 1963, *Physical Review*, 131, 435

Portegies Zwart, S. F. & McMillan, S. L. W. 2000, *ApJL*, 528, L17

Portegies Zwart, S. F., McMillan, S. L. W., & Gieles, M. 2010, *ARAA*, 48, 431

Rodriguez, C. L., Morscher, M., Wang, L., Chatterjee, S., Rasio, F. A., & Spurzem, R. 2016, *MNRAS*, 463, 2109

Tanikawa, A. 2013, *MNRAS*, 435, 1358

Wang, L., Spurzem, R., Aarseth, S., Nitadori, K., Berczik, P., Kouwenhoven, M. B. N., & Naab, T. 2015, *MNRAS*, 450, 4070

Ziosi, B. M., Mapelli, M., Branchesi, M., & Tormen, G. 2014, *MNRAS*, 441, 3703