Evolution of massive black hole binaries in the core of galaxies

Junichiro Makino *

Abstract

We investigated the evolution of the black hole binary formed by the merging of two galaxies each containing a central massive black hole. Our main goal here is to determine if the black hole binary can merge through the hardening by dynamical friction and the gravitational wave radiation. Using N-body simulation, we found that the evolution timescale is independent of the number of particles in the galaxy N until the semi-major axis reaches a critical value. After the semi-major axis became smaller than this critical value, the evolution timescale is longer for larger number of particles. Qualitatively, this behavior is understood naturally as the result the "loss-cone" effect. However, the dependence of the timescale on N is noticeably weaker than the theoretical prediction.

1. Introduction

Recent high-resolution observation by HST (*e.g.*, [7]) has changed our view of the structure of the "cores" of large elliptical galaxies rather drastically. Many large ellipticals were believed to have large, flat core, of which the radius is typically a few percents of the effective radius (*e.g.*, [6]). High-resolution ground-based observations suggested that the structure of these cores are non-isothermal [5]. However, HST observations have revealed that they are not flat cores at all.

Lauer et al. [7] found that the "cores" observed by HST are actually very shallow central density cusps ($\rho \sim r^{-1}$). Such a shallow cusp poses a serious problem to almost any scenario of the formation of the ellipticals. If these ellipticals do not have central black holes (MBHs), we are faced with very strange structure with the velocity dispersion decreasing inward. Neither dissipationless/dissipational collapse nor merging have been able to make such a density distribution.

Ebisuzaki et al. [3] proposed the merging of galaxies with central MBHs as the mechanism to form "flat cores". Their main interest was to reproduce the correlation between the "core radius" and the effective radius in [6]. Simulations of merging of galaxies without MBH produces the core size much smaller [14]. Ebisuzaki et al. [3] pointed out that the energy generation from MBH binary (MBHB) can heat up and expand the core.

Makino and Ebisuzaki [10] performed N-body simulations of merging of two galaxies with central MBHs with 32k particles using GRAPE-4 [12]. They found (a) that MBHs increase the apparent core radius through energy production and (b) that the "core" is actually a rather shallow cusp which resembles to the cusp observed by HST.

*Department of Graphics and Computer Science, College of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153, Japan.

The result of Makino and Ebisuzaki [10], however, has one limitation: they assumed that the lifetime of MBHB is fairly short. This assumption is necessary to explain the existence of very large core with very massive black hole. If the lifetime of MBHB is very long, large ellipticals might have small clusters of MBHs. Such small cluster would evaporate by ejecting its members in dynamical timescale.

There have been a number of studies (see [18] and references therein) on the lifetime of MBHB. Unfortunately, no definite conclusion was obtained yet. The main reason is that most of the results relies on theoretical estimates with many simplifying assumptions (see, *e.g.*, [2]). There are several studies with N-body method, either using self-consistent direct simulation or more approximate restricted three-body approach [13]. However, in these runs the number of particles was too small ($< 16,000$) and small-N effects might have changed the result.

In the present paper, we give the result of self-consistent direct N-body simulations of merging of two galaxies with central MBHs, with the number of particles much larger than previously used. In section 2, we describe the simulation method, and in section 3 we describe the result. Section 4 gives summary and discussion. Details of the result will presented in [8].

2. Numerical method and initial condition

The calculation code we used is NBODY1 [1] modified to be used with GRAPE-4 special purpose computer for gravitational N-body simulation [12]. We used softened potential for the force between field particles, and pure $1/r$ potential for forces to and from BH particles.

Calculations were performed on one cluster of GRAPE-4 system with the theoretical peak speed of 270 Gflops. A 256k-particle run took about five CPU days.

We used the King model with the nondimensional central potential $W_c = 7$ as the initial galaxy model. The number of particles is 2048 to 262144. The initial galaxy is created so that the total mass M_g is one and the total energy E_g is $-1/4$ in the system of units where gravitational constant G is one (the standard unit, [4]). The mass of a field particle is $m_{field} = 1/N$. For all calculations, $M_{BH} = 1/32$. The softening for the field particles is 1/1024.

The initial orbit of two galaxies is parabolic with the periastron distance equal to 1. The initial separation of two galaxies is 10. We integrated the system to time $t = 60$.

3. Results

Figure 1a shows the time evolution of the energy of the BH binary, E_b, for all runs. The energy E_b is defined as

$$E_b = \frac{1}{2}\mu v_b^2 - \frac{M_{BH}^2}{r_b} = -\frac{M_{BH}^2}{2a}, \tag{1}$$

where $\mu = M_{BH}/2$ is the reduced mass of the BH binary, r_b and v_b are the relative distance and velocity of the two BHs, and a is the semi-major axis of the BH binary.

From figure 1a we can see that the hardening rate of binaries, $-dE_b/dt$, is smaller for larger N. Moreover, it seems the difference in the hardening rate becomes larger as the binary evolves. Until E_b reaches around -0.05, the growth rate is similar for all runs except for $N = 2048$. In the 2048-body run, one of the BH particles had formed a bound pair with a field particle before it became bound with another BH. When two BHs became bound, this field particle was still

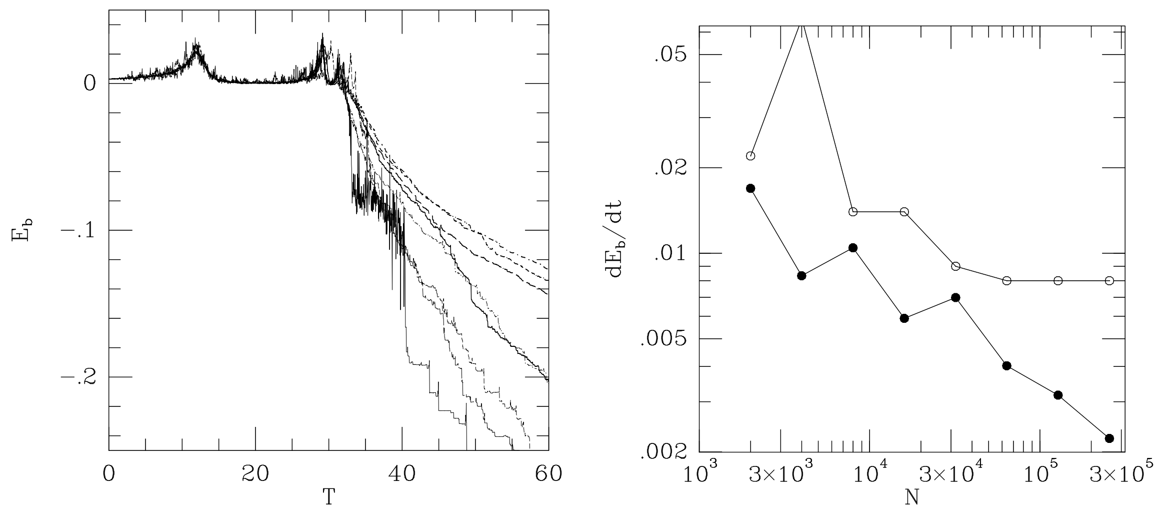

Figure 1. (a) The time evolution of the energy of the BH binary for runs with $N = 2$k (bottom) to 256k (top). Thin curves represent 2k (solid), 4k (short dashed), 8k (long dashed) and 16k (dot dashed) runs. Thick curves represent 32k (solid), 64k (short dashed), 128k (long dashed) and 256k (dot dashed) runs. (b) The growth rate of the binary binding energy $-dE_b/dt$ plotted versus the total number of particles N. Open and filled circles the average rate for $-1/160 > E_b > -1/80$ and $-1/10 > E_b > -1/5$, respectively.

bound to a BH particle. This particle was bound to the BH binary until $t = 40$. This is the reason why the curve for the 2048-body run is very noisy.

Figure 1b shows $-dE_b/dt$ as a function of N. Here, $-dE_b/dt$ is calculated for two intervals of E_b, $(-1/160, -1/80)$ and $(-1/10, -1/5)$. Note that for some runs E_b at the end of the run shown in figure 1 did not reach $-1/5$. For these runs, we extended simulation so that $|E_b| > 0.2$ at the end of the run.

Here we can clearly see that the hardening rate at the early phase the evolution seems to converge to $-dE_b/dt \sim 0.008$ for large N, while that for later phase shows the power-law like behavior expressed roughly as $dE_b/dt \propto N^{-1/3}$ for the entire range of N.

4. Summary and Discussion

We performed the simulation of the evolution of massive BH binaries formed through mergings of ellipticals by means of direct N-body simulations. Our main conclusion is that the timescale of the evolution of the binary depends on the total number of particles, in other words, the mass ratio between BHs and field particles. However, the dependence is very weak for the early phase of evolution. For later phase, we observed $t_b \propto N^{1/3}$, which is much weaker than the prediction of the theoretical model [2].

In order to really determine the dependence of the lifetime on N, we need to employ more particles. Simulations with number of particles a few times 10^6 would be necessary.

Simulations with number of particles larger than used here might be possible by means of more approximate schemes such as the treecode with individual timesteps [11] or an extension of the SCF method [17] to the case of central BH binary.

If our result can be extrapolated to real ellipticals, it implies that the lifetime of MBHB is very long, much larger than the Hubble time. Thus, many merger remnants might have central BH binaries. Begelman et al. [2] (see also [16]) argued that such a BH binary is likely to be kicked out from the core or the galaxy itself through the gravitational slingshot when the parent galaxy merges with yet another galaxy.

However, the slingshot mechanism might not as effective as assumed in [2] or [16], since gravitational wave radiation would lead two of the three MBHs merge during triple interaction [9]. Thus, it is quite possible that a large fraction of ellipticals have central BH binaries.

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