Effects of Minor Mergers on Coalescence of a Supermassive Black Hole Binary

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Abstract

We study the possibility that minor mergers resolve the loss cone depletion problem, which is the difficulty occured in the coalescence process of the supermassive black hole (SMBH) binary, by performing numerical simulations with a highly accurate *N*-body code. We show that the minor merger of a dwarf galaxy disturbs stellar orbits in the galactic central region of the host galaxy where the loss cone depletion is already caused by the SMBH binary. The disturbed stars are supplied into the loss cone. Stars of the dwarf galaxy are also supplied into the loss cone. The gravitational interactions between the SMBH binary and these stars become very effective. The gravitational interaction decreases the binding energy of the SMBH binary effectively. As a result, the shrink of the separation of the SMBH binary is accelerated. Our numerical results strongly suggest that the minor mergers are one of the important processes to reduce the coalescence time of the SMBH binary much less than the Hubble time.

Key words: black hole physics — gravitational waves — methods: n-body simulations — galaxies: nuclei

1. Introduction

It is well known that the merging of galaxies with central supermassive black holes (SMBHs) is an important process for growth of the SMBH mass. Recent studies, however, have shown the possibility that the SMBHs cannot coalesce within the Hubble time in the merger remnant (Begelman et al. 1980; Makino and Funato 2004).

Begelman et al. (1980) have examined the merging process of galaxies with central SMBHs with masses of $10^8 M_{\odot}$. They estimate the timescale of coalescence of SMBHs in the merger remnant and show that the timescale is more than the Hubble time. They describe the reason for this as follows: SMBHs sink into the center in the merger remnant because of the dynamical friction from field stars. During this process, the field stars near the center are scattered by SMBHs and the number of the field stars decreases. The loss cone depletion occurs because of the scattering. In this case, dynamical friction force on the SMBHs becomes very weak. Then, it is difficult for the SMBH binary to shrink to a small distance enough to emit significant gravitational waves in the final coalescence stage of SMBHs.

Makino and Funato (2004) have studied the dynamical evolution of a SMBH binary, that each mass of the SMBH is $10^8 M_{\odot}$, in the stellar system by performing high-resolution N-body simulations. Their results have shown that the hardening timescale of the binary strongly depends on the relaxation time of the host galaxy as predicted by Begelman et al. (1980). These results have confirmed the prediction that the SMBH binary cannot coalesce within the Hubble time by only gravitational interactions between SMBHs and field stars of the host galaxy since the relaxation time in a galactic stellar system is larger than the Hubble time. This difficulty in the coalescence process of SMBHs is called the "loss cone depletion problem".

To resolve the loss cone depletion problem, several ideas to accelerate the orbital decay of the binary are proposed. Gaseous torque in a massive gas disk is proposed in the wet merger cases (Escala et al. 2004; Escala et al. 2005; Dotti et al. 2006; Dotti et al. 2007; Hayasaki 2008). In the dry merger cases which are observed in neaby galaxies (Whitaker & Van Dokkum 2008), the effect of a galactic triaxial potential (Berczik et al. 2006), large mass ratio between a SMBH and Intermediate-Mass BH (Matsubayashi et al. 2007), and a triple SMBH system (Iwasawa et al. 2006) have been proposed. In the triple SMBH system, two SMBHs coalesce through the three body instability and the Kozai mechanism and the coalescence possibility is roughly 50 % (Iwasawa et al. 2006). Perets et al. (2007) and Perets & Alexander (2008) have proposed the role of massive perturbers. In their analytical studies, it has been shown the possibility that the massive perturbers of giant molecular clouds or molecular gas clumps accelerate the relaxation of stars in the galactic central region and, as a result, trigger the rapid coalescence of the SMBH binary. They pointed out the importance of three body interactions between the SMBH binary and stars. These ideas have possibility to lead to the coalescence of two SMBHs within the Hubble time, if some suitable conditions are realized.

In this paper, in order to resolve the loss cone depletion problem, we propose a new scenario that a minor merger triggers the rapid shrink of the SMBH binary. Similar idea was studied by Perets et al. (2007) and Perets & Alexander (2008) Our scenario is as follows: If a dwarf galaxy is compact enough, it can come close to the galactic center, and then, stellar orbits of the host galaxy are highly disturbed by the dwarf galaxy. In this case, many stars will be supplied into the loss cone. Moreover, if the dwarf galaxy is not destroyed before it closes enough to the central region, stars of the dwarf galaxy will be also supplied into the loss cone. In this way, gravitational interactions of the SMBH binary with these stars become effective and the hardening rate of the SMBH binary will become high. As a result, the binary can close to the unstable separation at which significant gravitational wave is emitted.

To demonstrate our scenario, we perform highly accurate Nbody simulations. We show that a merging of a dwarf galaxy is an effective process to decrease the binding energy of a SMBH binary and trigger the rapid shrink of the binary, if the core of the dwarf galaxy is not destroyed by the tidal force and comes very close to the galactic central region. We present our simulation model and method in §2, numerical results in §3, and discussions in §4.

2. SIMULATIONS

2.1. Simulation Model

The simulation process is described in the following. Firstly, we make a simulation of a host galaxy with a SMBH binary without a minor merger. Then, we add a dwarf galaxy to the host galaxy after the loss cone depletion is established, that is, evolution of the semi-major axis of the binary becomes very slow.

We describe the model of a host galaxy with a SMBH binary before a minor merger. For the stellar distribution of the host galaxy, we assume the King model with $W_0 = 7$, where W_0 is the nondimensional central potential of the King models. The total mass is $M_{\text{gal}} = 1$ and the total binding energy is $E_{\text{gal}} = -1/4$. Here, we use the standard N-body unit in which the gravitational constant is G = 1. The physical unit is described in §2.2. Its velocity dispersion is $\sigma_v = (0.5)^{1/2}$. Two equal mass SMBHs are set in the stellar system. Each mass is $M_{\text{SMBH}} = 0.01$. Initial positions and velocities of the SMBHs are $(x, y, z) = (\pm 0.5, 0, 0)$ and $(v_x, v_y, v_z) = (0, \pm 0.1, 0)$, respectively. This is the same model to Makino and Funato (2004).

For the stellar distribution of the dwarf galaxy, we also assume the King model. In our all models, the dwarf galaxies are assumed to be compact enough to be able to come close to the galactic central region without the destruction by the tidal force of the host galaxy. Its mass is $M_{dwarf} = 0.1$. Its velocity dispersion is $\sigma_v = (0.05)^{1/2}$. The ratio of the velocity dispersion of the host galaxy and the dwarf galaxy is about 3:1 which is expected by the cosmological simulation (Kase et al. 2007). In order to investigate effects of the compactness and the orbit of the dwarf galaxy on the dynamical evolution of the SMBH binary, we assume various W_0 and various initial orbits for the dwarf galaxy.

The initial positions, the initial velocities, and W_0 of the dwarf galaxy are shown in table 1. For the motion of the dwarf galaxy, two cases are considered. One is the zero impact parameter case and another is the nonzero impact parameter case. In the nonzero impact parameter cases, the dwarf galaxy has the initial orbital angular momentum. The specific angular momentum, J_d , are assumed to be 0.36 and 0.6 which are in the range expected from cosmological simulations as discussed in

§4.1. In models from Run 1 to Run 3 and in Run 9, the dwarf galaxy passes through the SMBH binary directly with the zero impact parameter. In Run 1 and Run 2, dwarf galaxies move in the same plane of the SMBH binary. In Run 3, it moves on the z-axis. From Run 4 to Run 8 and in Run 10, the dwarf galaxies have nonzero impact parameters initially. In these Runs, except for Run 6, dwarf galaxies move in the prograde sense. In Run 6, it moves in a orbit tilted from the plane of the SMBH binary. For the nondimensional central potential of the King model W_0 , $W_0 = 9$ and $W_0 = 11$ are assumed. Such compact dwarf galaxies have been observed in the nearby galaxies (Kormendy & Djorgovski 1989). Their cores can be close within r = 0.2 from the center of the host galaxy, which is the core radius of the host galaxy.

2.2. Physical Unit

We assume that the mass of the central region and the velocity dispersion of the host galaxy are $10^{10} M_{\odot}$ and 300 km s⁻¹, respectively. Then, the physical unit is interpreted as follows; the unit of mass is $10^{10} M_{\odot}$, the unit of length is about 239 pc, and the unit of time is about 5.51×10^5 yr.

2.3. Simulation Method

We perform N-body simulations of two SMBHs, field stars in the host galaxy, and stars in the dwarf galaxy. From Run 1to Run 8, the number of N-body particles is 100000 for the stellar component in the host galaxy and 10000 for that in the dwarf galaxy, respectively. In order to investigate effects of the number of particles, we also perform the simulation in Run 12and Run 13 by using 200000 and 20000 particles for the host galaxy and for the dwarf galaxy, respectively.

The equations of motion for SMBHs and field stars are

$$\frac{d^2 \boldsymbol{r}_{BH,i}}{dt^2} = \boldsymbol{a}_{Bf,i} + \boldsymbol{a}_{BB,i} \tag{1}$$

and

$$\frac{d^2 \boldsymbol{r}_{f,i}}{dt^2} = \boldsymbol{a}_{ff,i} + \boldsymbol{a}_{fB,i},\tag{2}$$

respectively, where $a_{Bf,i}$ is the acceleration on the SMBH from field stars, $a_{BB,i}$ is the acceleration on the SMBH from another SMBH, $a_{ff,i}$ is the acceleration on the field star from other field stars, and $a_{fB,i}$ is the acceleration on the field star from SMBHs. The softening lengths between field stars, SMBHs and field stars, and SMBHs are $\epsilon_{\rm ff} = 10^{-4}$, $\epsilon_{\rm fB} = 10^{-6}$, and $\epsilon_{\rm BB} = 10^{-6}$, respectively, in order to resolve much less than a sub-pc scale. The effect of gravitational wave is not considered.

The fourth-order Hermite scheme (Makino and Aarseth 1992) is used for time integration. The predictors are

$$\boldsymbol{x}_{p}(t_{0}+\Delta t) = \boldsymbol{x}_{0}(t_{0}) + \boldsymbol{v}_{0}(t_{0})\Delta t + \frac{1}{2}\boldsymbol{a}_{0}(t_{0})\Delta t^{2} + \frac{1}{6}\dot{\boldsymbol{a}}_{0}(t_{0})\Delta t^{3}(3)$$

and

$$\boldsymbol{v}_{p}(t_{0} + \Delta t) = \boldsymbol{v}_{0}(t_{0}) + \boldsymbol{a}_{0}(t_{0})\Delta t + \frac{1}{2}\dot{\boldsymbol{a}}_{0}(t_{0})\Delta t^{2}.$$
 (4)

The correctors are

$$\boldsymbol{x}_{c}(t_{0} + \Delta t) = \boldsymbol{x}_{p} + \frac{1}{24}\boldsymbol{a}^{(2)}\Delta t^{4} + \frac{1}{120}\boldsymbol{a}^{(3)}\Delta t^{5}$$
(5)

No.]

and

$$\boldsymbol{v}_{c}(t_{0} + \Delta t) = \boldsymbol{v}_{p} + \frac{1}{6}\boldsymbol{a}^{(2)}\Delta t^{3} + \frac{1}{24}\boldsymbol{a}^{(3)}\Delta t^{4}, \qquad (6)$$

 $oldsymbol{a}^{(2)}$ and $oldsymbol{a}^{(3)}$ are

$$a^{(2)} = \frac{-6(a_0 - a_1) - \Delta t(4\dot{a}_0 + 2\dot{a}_1)}{\Delta t^2}$$
(7)

$$a^{(3)} = \frac{12(a_0 - a_1) + 6\Delta t(\dot{a}_0 + \dot{a}_1)}{\Delta t^3},\tag{8}$$

where a_1 and \dot{a}_1 is the acceleration and its time derivative at $t = (t_0 + \Delta t)$. The individual timesteps are combined to this scheme (Makino 1991). The timestep formula is given by

$$\Delta t_{i} = \sqrt{\eta \frac{|\boldsymbol{a}_{i}||\boldsymbol{a}^{(2)}_{i}| + |\dot{\boldsymbol{a}}_{i}|^{2}}{|\dot{\boldsymbol{a}}_{i}||\boldsymbol{a}^{(3)}_{i}|^{2} + |\boldsymbol{a}^{(2)}_{i}|^{2}}},$$
(9)

where η is the parameter which controls the integration accuracy. In our simulations, we adopt $\eta = 0.005$ for SMBHs and $\eta = 0.02$ for field stars, respectively. The acceleration and the time derivative of the acceleration by field stars are calculated by GRAPE-6 (Makino et al. 2003) which is a special purpose hardware to make those calculations very fast. Those by SMBHs are calculated by a host computer in order to make energy error small. In our all simulations, the error of the total energy is less than 0.1 % of the initial total energy.

3. RESULTS

3.1. Loss Cone Depletion

Figure 1 shows the time evolution of the binding energy and the semi-major axis of the SMBH binary without a minor merger. The SMBH binary loses its binding energy because of the dynamical friction from field stars. As a result, the semimajor axis shrinks rapidly. After T = 20, the hardening rate, which is defined by $\beta \equiv |\Delta E_b/\Delta t|$, becomes very low and is almost constant. They are about $\beta = 0.0008$ and $\beta = 0.0006$ in the simulations with $N_{\text{host}} = 100000$ and $N_{\text{host}} = 200000$, respectively. Then, the semi-major axis hardly shrinks.

The reason that the hardening rate becomes low is the loss cone depletion. As evidence of the loss cone depletion, in Fig. 2 we show the distribution of star particles at T = 0 and T = 30 in (J, E) plane where J is a specific angular momentum about the center of mass of the galaxy and E is a specific binding energy of each star particle. The number of the star particles with low J and E, which are supplied into the loss cone, decreases significantly from the initial state at T = 0 to T = 30 at which the hardening rate is already low. This is clear evidence of the loss cone depletion.

The hardening rate and time evolution of the semi-major axis of the binary strongly depend on the particle number of the host galaxy. The hardening rate is smaller in higher resolution simulations with a larger number of N-body particles. This is because the timescale of the two body relaxation by which star particles are supplied into the loss cone is longer in the simulation with a larger number of particles. This property is reported by Makino and Funato (2004).

3.2. Effects of a Minor Merger

We add the dwarf galaxy to the host galaxy at T = 30 when the loss cone depletion is already realized.

3.2.1. *Minor mergers of zero impact parameter*

In Fig. 3, we show the time evolution of the binding energy and the semi-major axis of the SMBH binary from Run 1 to Run 3 in which the dwarf galaxy moves with zero impact parameter. After the dwarf galaxy passes through the center of the host galaxy at T = 31, the hardening rate becomes high. The average hardening rate from T = 31 to T = 60is $\beta = 0.0015 - 0.0016$ in all these models, which is about 2.0 times higher than that of the case without a minor merger $\beta = 0.0008$. Although the core of the dwarf galaxy is destroyed by the tidal force of the SMBHs after the first encounter with the binary in these simulations, the high hardening rate continues. In these cases, the minor merger reduces the binding energy of the binary effectively. As a result, the rapid orbital decay of the binary occurs and the semi-major axis shrinks rapidly. The rate of the shrink becomes similar to the case without a minor merger after about T = 45.

The high hardening rate and the rapid shrink of the semimajor axis are caused by following process: The core of the dwarf galaxy passes through the central region of the host galaxy without the destruction by the tidal force, since the density of the core is higher than that of the host galaxy. When the core is close to the center of the host galaxy, it perturbs the gravitational potential of the host galaxy. Due to the perturbed potential, orbits of star particles change and then a large number of star particle orbits are able to pass through the loss cone.

In Fig. 4, we show the distribution of the star particles of the host galaxy (left panel) and the dwarf galaxy (right panel) in the (J, E) plane in $Run \ 2$ at T = 31, here the center is set at the center of gravity of the binary. In the left panel, the star particles with low J and low E increase in comparison with the right panel of Fig. 2 in which the loss cone depletion is established. These star particles of the host galaxy are supplied into the loss cone. In the right panel of Fig. 4, there are star particles with low J. Such star particles of the dwarf galaxy are also supplied into the loss cone. These star particles are able to interact gravitationally with SMBHs.

In the case of the zero impact parameter, the hardening rate of the SMBH binary becomes high and the semi-major axis shrinks rapidly in all dwarf galaxy models with $W_0 = 9$ and $W_0 = 11$. Those evolution does not depend on the compactness of the dwarf galaxy, W_0 . The numerical results show that the minor merger during which the dwarf galaxy passes through the binary is an effective mechanism to decrease the binding energy of the binary.

3.2.2. Minor mergers of nonzero impact parameter

We show the results of the dwarf galaxy model with the nonzero impact parameter. The time evolution of the binding energy and the semi-major axis are shown in Fig. 5.

In Run 4, Run 5, and Run 6 in which initial specific angular momentum of the dwarf galaxy is $J_d = 0.36$, the time evolution of the binding energy is resemble to the results of the dwarf galaxy models with the zero impact parameter. The hardening rate becomes high at $T \sim 31$ when the dwarf galaxy comes close to the galactic central region. The hardening rate is about $\beta = 0.0013 - 0.0014$. It continues to the end time of our simulations. The rate is much higher than the case without a minor merger and little lower than that of the dwarf galaxy models with the zero impact parameter.

The distribution of the star particles in the (J, E) plane at T = 40 in Run 5 is shown in Fig. 6. In the left panel which shows the distribution of the star particles of the host galaxy, the number of star particles with low J and low E increase in comparison with the right panel of Fig. 2. The number of such star particles is almost similar to the cases of the dwarf galaxy models with the zero impact parameter. These star particles are supplied into the loss cone. However, there are a few star particles of the dwarf galaxy with low J and low E in the right panel which shows the distribution of the star particles of the dwarf galaxy. This result indicates that star particles of the dwarf galaxy are hard to be supplied into the loss cone, contrary to the cases of the zero impact parameter. In these cases, the SMBH binary loses the binding energy mainly by disturbed stars of the host galaxy. Since there are a few star particles of the dwarf galaxy which interact with the binary, the hardening rate is slightly lower than the dwarf galaxy models with the zero impact parameter.

Since the SMBH binary loses the binding energy effectively, the semi-major axis shrinks rapidly. The rapid shrink occurs as soon as the dwarf galaxy comes close to the galactic central region. It continues until about T = 45. After about T = 45, the decrease rate of the semi-major axis becomes same as the case without a minor merger.

For $J_d = 0.36$, time evolution of the binding energy and of the semi-major axis does not depend on the compactness of the dwarf galaxies, W_0 , although the destruction timescale of the core of the dwarf galaxy for each model is different, for examples, the core is destroyed at about T = 35 in $Run \ 4$ and at about T = 45 in $Run \ 5$.

In Run 7 and Run 8, in which initial specific angular momentum of the dwarf galaxy is $J_d = 0.6$, increase of the hardening rate of the binary is delayed till the dwarf galaxy comes close to the galactic central region. After the core is close to the galactic central region within about r = 0.2 without their destruction by the tidal force, the hardening rate and time evolution of the semi-major axis become high similarly to those in Run 4-6.

These results show that the dwarf galaxy with nonzero impact parameter also increases the hardening rate of the SMBH binary, since it can disturb orbits of star particle by its gravitational potential and such star particles are supplied into the loss cone.

3.2.3. Effects of the particle number

We perform simulations with $N_{\text{host}} = 200000$ and $N_{\text{dwarf}} = 20000$ in order to investigate effects of the particle number. The dwarf galaxy is added to the host galaxy at T = 35 when the semi-major axis of the SMBH binary is similar scale to that at T = 30 in the simulation with $N_{\text{host}} = 100000$. The dwarf galaxy models correspond to Run2 and Run5. The time evolution of the binding energy and the semi-major axis of the binary is shown in Fig. 7.

Time evolution of the binding energy and semi-major axis of the binary is similar to the results of $N_{\rm host} = 100000$. The hardening rate becomes high after the dwarf galaxy comes close to the galactic central region. The average hardening rates from T = 35 to T = 60 are $\beta = 0.0014 - 0.0015$ in Run 9 and $\beta = 0.0012 - 0.0013$ in Run 10, which is much larger than the case without a minor merger. As a result, the semi-major axis shrinks rapidly. This result confirms that a minor merger triggers rapid shrink of a SMBH binary in higher resolution simulations.

The effect of a minor merger on time evolution of the hardening rate and the semi-major axis becomes clear in the simulation of $N_{\rm host} = 200000$ than the results of $N_{\rm host} = 100000$. This is because the timescale of the two body relaxation of $N_{\rm bost}$ body particles is longer in the simulation of $N_{\rm host} = 200000$ and the number of supplied star particles by the two body relaxation is less than the simulation of $N_{\rm host} = 100000$. Therefore, effects of the two body relaxation become fewer and effects of a minor merger become clear. This result indicates that the effects of minor mergers appear clearly in higher resolution simulations.

4. DISCUSSION

4.1. Minor Mergers of the Compact Dwarf Galaxies

We demonstrate that separation of a SMBH binary shrinks rapidly after a compact dwarf galaxy comes close to the central region of a host galaxy. It is important for our scenario that the dwarf galaxies are compact and are able to come close to the galactic central region without their destruction by the tidal force of the host galaxy. In this section, we discuss the possibility that such minor mergers occur.

Dwarf galaxies formed in the early universe are compact, since the mean density of dark matter halos is higher in the earlier universe, $\rho_{\rm DM}(z) \propto (1+z)^{-3}$. Therefore, many compact dwarf galaxies are expected to form in the early universe and merge to their host galaxy. This is confirmed by the cosmological numerical simulations of the galaxy formation (e.g., Saitoh et al. (2006)).

To trigger the rapid shrink of a SMBH binary, such compact dwarf galaxies need to come close to the central region of a host galaxy. To investigate the possibility, we calculate the motions of the dwarf galaxies with various initial orbital parameters which are in the range expected from the cosmological numerical simulations. Here, the fourth order Runge-Kutta method is used for the time integration. We assume that the dark halo and stellar potentials of the host galaxy are fixed. For the dynamical friction force, we use the formula given by Fukushige et al. (1992). The initial position of the dwarf galaxy is set at 50 kpc from the center of the host galaxy which is vicinity of the virial radius of the dark halo. The initial parameter of the nondimensional orbital angular momentum of the dwarf galaxy is from $\lambda = 0.01$ to 0.04 which is the range of the spin parameter distribution of sub halos in a host dark halo (Sharma & Steinmetz 2005).

The time which is needed for the dwarf galaxies to move to the galactic central region (within 100 pc) is shown in the left panel of Fig. 8. The dwarf galaxy with $10^9 M_{\odot}$ can move to the galactic center for the spin parameter $\lambda = 0.01$ -0.04 within 2×10^9 yr. Such dwarf galaxies can come close to the galactic center within much less than 10^{10} yr. For the dwarf galaxies with $10^8 M_{\odot}$, they can come close to the center within 10^{10} yr in the case of the spin parameter of $\lambda = 0.01$ and $\lambda = 0.02$.

The right panel of Fig. 8 shows the specific angular momentum of the dwarf galaxy when it passes through r = 1 from the galactic center of the host galaxy. In the case of $\lambda = 0.01$, the specific angular momentum is about 0.37. For larger λ , it ranges from 0.5 to 0.6. The models from Run 4 to Run 6 and Run 10 correspond to the case of $\lambda = 0.01$. The models of Run 7 and Run 8 correspond to the case of $\lambda = 0.02 - 0.04$. Then, it is needed for our scenario that dwarf galaxies have mass more than $10^8 M_{\odot}$ and smaller λ than $\lambda = 0.03$.

4.2. Conclusions

We have performed *N*-body simulations and have shown that a minor merger is an effective process to resolve the loss cone depletion problem. If the core of the dwarf galaxy is not destroyed by the tidal force and comes close to the galactic central region, disturbed stars of the host galaxy are supplied into the loss cone. If the dwarf galaxy passes through the SMBH binary directly, stars of the dwarf galaxy are also supplied into the loss cone. After that, SMBHs can interact gravitationally with these stars and the binary loses its binding energy. In this process, three body interactions of the SMBH binary with these stars should be important (Perets et al. 2007; Perets & Alexander 2008). As a result, the hardening rate of the binary becomes high and the semi-major axis can shrink rapidly in the host galaxy.

We have also performed high resolution simulations of 200000 N-body particles with for the host galaxy. We have confirmed that the minor merger triggers the high hardening rate and the rapid shrink of the SMBH binary in the high resolution simulations. We find that the difference of time evolution of the hardening rate and the semi-major axis between with and without a minor merger becomes clear in higher resolution simulations. This is because timescale of the two body relaxation of N-body particles becomes longer in the 200000 N-dody simulations. This result indicates that effects of the minor merger appear clearly in the realistic stellar system in which the two body relaxation time is larger than the Hubble time.

It is important for our scenario that the dwarf galaxy is enough compact to come close to the galactic central region. In the hierarchical galaxy formation scenario, such minor mergers are expected to occur frequently. Therefore, we emphasize that our scenario is one of the effective processes to trigger the rapid orbital decay of the SMBH binary and helps its coalescence within the Hubble time together with other previous proposed mechanisms.

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Fig. 1. The time evolution of the binding energy (left) and the semimajor axis (right) of the SMBH binary in the host galaxy. The red and blue lines are for the cases of $N_{\rm host} = 100000$ and $N_{\rm host} = 200000$, respectively, where $N_{\rm host}$ is the particle number of the host galaxy.



Fig. 2. Distributions of the field stars in the host galaxy of $N_{\text{host}} = 100000$ in the (J, E) plane at T = 0 (left) and at T = 30 (right) at which the loss cone depletion is already established.

carried out on GRAPE system at Center for Computational Astrophysics, CfCA, of National Astronomical Observatory of Japan.

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Fig. 3. The time evolution of the binding energy (left) and the semimajor axis of the SMBH binary (right) in the cases of the zero impact parameter (Run 1-3). For comparison, the result without a minor merger is also shown by the light blue line.



Fig. 7. The time evolution of the binding energy (left) the semi-major axis of the SMBH binary (right) in the case that particle numbers are $N_{\rm host} = 200000$ and $N_{\rm dwarf} = 20000$. For comparison, the result without a minor merger is also shown by the blue line.



Fig. 4. Distributions of the field stars in the host galaxy (left) and the dwarf galaxy (right) in the (J, E) plane at T = 31 in Run2.



Fig. 5. The time evolution of the binding energy (left) and the semimajor axis of the SMBH binary (right) in the cases of the nonzero impact parameter (Run 4-8). For comparison, the result without a minor merger is also shown by the light blue line.



Fig. 6. Distributions of the field stars in the host galaxy (left) and the dwarf galaxy (right) in the (J, E) plane at T = 40 in Run5.



Fig. 8. The time that a dwarf galaxy sinks from 50 kpc to 100 pc from the galactic center (left). The horizontal axis shows the spin parameter, λ . The circles, triangles, and squares denote the cases that the masses of the dwarf galaxies are $M_{\rm dwarf} = 10^7 M_{\odot}$, $10^8 M_{\odot}$, and $10^9 M_{\odot}$, respectively. The angular momentum, J_d , of the dwarf galaxy of $M_{\rm dwarf} = 10^9 M_{\odot}$ at the time when the dwarf galaxies with the initial spin parameter from $\lambda = 0.01$ to $\lambda = 0.04$ pass through r = 1 from the center of the host galaxy in our unit (right).

 Table 1. Dwarf galaxy models and the particle number of the host galaxy and the dwarf galaxy.

Run	(x,y,z)	(v_x, v_y, v_z)	W_0	J_d	$N_{\rm host+dwarf}$
1	(0, -1, 0)	(0.0, 0.7, 0.0)	9	0.0	110000
2	(0, -1, 0)	(0.0, 0.7, 0.0)	11	0.0	110000
3	(0, 0, -1)	(0, 0.0, 0.7)	11	0.0	110000
4	(0, -1, 0)	(0.36, 0.6, 0.0)	9	0.36	110000
5	(0, -1, 0)	(0.36, 0.6, 0.0)	11	0.36	110000
6	(0, -1, 0)	(0.0, 0.6, 0.36)	11	0.36	110000
7	(0, -1, 0)	(0.6, 0.36, 0.0)	9	0.6	110000
8	(0, -1, 0)	(0.6, 0.36, 0.0)	11	0.6	110000
9	(0, -1, 0)	(0.0, 0.7, 0.0)	11	0.0	220000
10	(0, -1, 0)	(0.36, 0.6, 0.0)	11	0.36	220000