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

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Abstract

We studied the possibility that minor mergers can resolve the loss cone depletion problem, which is a difficulty that occurs in the coalescence process of a supermassive black hole (SMBH) binary, by performing numerical simulations with a highly accurate N-body code. We showed that a minor merger of a dwarf galaxy disturbs stellar orbits in the galactic central region of the host galaxy where loss cone depletion has already been 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, shrinking of the separation of the SMBH binary is accelerated. Our numerical results strongly suggest that minor mergers are one of the important processes to reduce the coalescence time of the SMBH binary to 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 & Funato 2004).

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

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

To resolve this problem, several ideas to accelerate the orbital decay of the binary are proposed. Gaseous torque in a massive gas disk is proposed for the wet merger cases (Escala et al. 2004, 2005; Dotti et al. 2006, 2007; Hayasaki 2009). In the dry merger cases, which are observed in nearby 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 a triple SMBH system, two SMBHs coalesce through a three-body instability and the Kozai mechanism; the coalescence possibility is roughly 50% (Iwasawa et al. 2006). Perets, Hopman, and Alexander (2007) and Perets and Alexander (2008) have proposed the role of massive perturbers. In their analytical studies, a possibility was shown 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 a rapid coalescence of the SMBH binary. They pointed out the importance of three-body interactions between the SMBH binary and the stars. These ideas have a 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 in which a minor merger triggers a rapid shrinking of the SMBH binary. A similar idea...
was studied by Perets, Hopman, and Alexander (2007) and Perets and Alexander (2008). Our scenario is as follows. If a dwarf galaxy is sufficiently compact, 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 also be supplied into the loss cone. In this way, gravitational interactions of the SMBH region, stars of the dwarf galaxy will also be supplied into 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 also be supplied into the loss cone. In this way, gravitational interactions of the SMBH region, stars of the dwarf galaxy have also been observed in nearby galaxies (Kormendy & Djorgovski 1989).

For the stellar distribution of the dwarf galaxy, we also assume the King model. In all of our models, the dwarf galaxies are assumed to be compact enough to be able to come close to the galactic central region without destruction by the tidal force of the host galaxy. Its mass is $M_{\text{dwarf}} = 0.1$. 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 based on a cosmological simulation (Kase et al. 2007). In order to investigate the 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 the initial angular momenta are given in Table 1. For the motion of the dwarf galaxy, two cases are considered. One is the zero impact-parameter case, and the other 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, $J_1$, valued are assumed to be 0.36 and 0.6, which are in the expected range from cosmological simulations, as discussed in subsection 4.1. In the models from Run 1 to Run 3 and in Run 9, the dwarf galaxy passes through the SMBH binary directly with a 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, the dwarf galaxies move in a prograde sense. In Run 6, they move in an 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 nearby galaxies (Kormendy & Djorgovski 1989). Their cores can be close within $r = 0.2$ from the center of the host galaxy, which is its core radius, without destruction by the tidal force of the host galaxy.

2. Simulation

2.1. Simulation Model

The simulation process is described as follows. 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 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 a 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 subsection 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 $M_{\text{SMBH}} = 0.01$. The 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 as that of Makino and Funato (2004).

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

| Run | $(x, y, z)$ | $(v_x, v_y, v_z)$ | $W_0$ | $J_1$ | $N_{\text{host}+\text{dwarf}}$ |
|-----|-------------|-------------------|------|-------|------------------|
| 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   | $(0, 0, -1)$ | $(0.0, 0.0, 0.7)$ | 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           |

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 $5.51 \times 10^7$ yr.
2.3. Simulation Method

We performed $N$-body simulations of two SMBHs, field stars in the host galaxy, and stars in the dwarf galaxy. From Run 1 to Run 8, the number of $N$-body particles was 100,000 for the stellar component in the host galaxy and 10,000 for that in the dwarf galaxy, respectively. In order to investigate the effects of the number of particles, we also performed simulations in Run 12 and Run 13 by using 200,000 and 20,000 particles for the host galaxy and for the dwarf galaxy, respectively.

The equations of motion for SMBHs and field stars are

\[
\frac{d^2 \mathbf{r}_{\text{BH},j}}{dt^2} = \mathbf{a}_{\text{BH},j} + \mathbf{a}_{\text{BB},j},
\]

and

\[
\frac{d^2 \mathbf{r}_{\text{f},j}}{dt^2} = \mathbf{a}_{\text{f},j} + \mathbf{a}_{\text{BB},j},
\]

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

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

\[
x_p(t_0 + \Delta t) = x_0(t_0) + v_0(t_0) \Delta t + \frac{1}{2} a_0(t_0) \Delta t^2 + \frac{1}{6} \dot{a}_0(t_0) \Delta t^3,
\]

and

\[
v_p(t_0 + \Delta t) = v_0(t_0) + a_0(t_0) \Delta t + \frac{1}{2} \dot{a}_0(t_0) \Delta t^2.
\]

The correctors are

\[
x_c(t_0 + \Delta t) = x_p + \frac{1}{24} a^{(2)} \Delta t^4 + \frac{1}{120} a^{(3)} \Delta t^5,
\]

and

\[
v_c(t_0 + \Delta t) = v_p + \frac{1}{6} a^{(2)} \Delta t^3 + \frac{1}{24} a^{(3)} \Delta t^4.
\]

Here, $a^{(2)}$ and $a^{(3)}$ are

\[
a^{(2)} = -6(a_0 - a_1) - \Delta t (4 \dot{a}_0 + 2 \dot{a}_1),
\]

and

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

where $a_1$ and $\dot{a}_1$ are 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

\[
\Delta t_i = \sqrt{\frac{\eta (a_i |a_i^{(2)}| + |\dot{a}_i|^2)}{|a_i| |a_i^{(2)}|^2 + |a_i^{(3)}|^2}},
\]

where $\eta$ is a parameter that controls the integration accuracy. In our simulations, we adopted $\eta = 0.005$ for SMBHs and $\eta = 0.02$ for the field stars, respectively. The acceleration and the time derivative of the acceleration by field stars were calculated by GRAPE-6 (Makino et al. 2003), which is a special-purpose hardware to make those calculations very fast. Those by SMBHs were calculated by a host computer in order to make the energy error small. In all of our simulations, the error of the total energy was 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 dynamical friction from the field stars. As a result, the semi-major axis shrinks rapidly. After $T = 20$, the hardening rate, which is defined by $\beta = |\Delta E_{b}/|\Delta t|$ becomes very low and is almost constant. They were about $\beta = 0.0008$ and $\beta = 0.0006$ in simulations with $N_{\text{host}} = 100,000$ and $N_{\text{host}} = 200,000$, respectively. Thus, the semi-major axis hardly shrinks.

The reason that the hardening rate becomes low is loss cone depletion. As evidence of this, in figure 2 we show the distribution of star particles at $t = 0$ and $T = 30$ in the $(J, E)$ 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 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 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 a simulation with a larger number of particles. This property is reported by Makino and Funato (2004).

3.2. Effects of a Minor Merger

We added the dwarf galaxy to the host galaxy at $T = 30$ when the loss cone depletion was already realized.

3.2.1. Minor mergers of zero impact parameter

In figure 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 a 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 $T = 60$ is $\beta = 0.0015$–$0.0016$ in all of these models, which is about 2.0-times higher than that in the case without a minor merger, $\beta = 0.0008$. Although the core of the dwarf galaxy was destroyed by the tidal force of the SMBHs after the first encounter with the binary in these simulations, the high hardening rate continued. In these cases, the minor merger reduced the binding energy of the binary effectively. As a result, the rapid orbital decay of the binary occurred, and the semi-major axis shrank rapidly. The rate of the shrink became similar to the case without a minor merger after about $T = 45$.

The high hardening rate and the rapid shrink of the
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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 Run 2.

Fig. 5. Time evolution of the binding energy (left) and the semi-major axis of the SMBH binary (right) in the cases of a nonzero impact parameter (Runs 4–8). For a comparison, the result without a minor merger is also shown by the dashed-and-dotted line.

semi-major axis are caused by following process. The core of the dwarf galaxy passes through the central region of the host galaxy without 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, the orbits of the star particles change, and then a large number of star particle orbits are able to pass through the loss cone.

In figure 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 figure 2, in which loss cone depletion is established. These star particles of the host galaxy are supplied into the loss cone. In the right panel of figure 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 the SMBHs.

In the case of a 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 evolutions do not depend on the compactness of the dwarf galaxy, $W_0$. The numerical results show that a 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 figure 5.

In Run 4, Run 5, and Run 6 in which the initial specific angular momentum of the dwarf galaxy is $J_d = 0.36$, the time evolution of the binding energy resembles the results of the dwarf-galaxy models with a 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 continued to the end time of our simulations. This rate is much higher than in the case without a minor merger, and a little lower than that of the dwarf-galaxy models with a zero impact parameter.

The distribution of the star particles in the $(J, E)$ plane at $T = 40$ in Run 5 is shown in figure 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 $E$ increases compared with the right panel of figure 2. The number of such star particles is almost similar to the cases of the dwarf galaxy models with a 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 a zero impact parameter. In these cases, the SMBH binary loses binding energy mainly by disturbed stars of the host galaxy. Since there are a few star particles of the dwarf galaxy that interact with the binary, the hardening rate is slightly lower than that in the dwarf galaxy models with a zero impact parameter.

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

For $J_d = 0.36$, the time evolution of the binding energy and that of the semi-major axis do 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; as examples, the core was destroyed at about $T = 35$ in Run 4 and at about $T = 45$ in Run 5.

In Run 7 and Run 8, in which the initial specific angular momentum of the dwarf galaxy was $J_d = 0.6$, an increase of the hardening rate of the binary was delayed until the dwarf galaxy came close to the galactic central region. After the core was 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 became high, similarly to those in Runs 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 the orbits of star particles by its gravitational potential, and such star particles are supplied into the loss cone.

### 3.2.3. Effects of the particle number

We performed simulations with $N_{\text{host}} = 200000$ and $N_{\text{dwarf}} = 20000$ in order to investigate the effects of the particle number. The dwarf galaxy was added to the host galaxy at $T = 35$ when the semi-major axis of the SMBH binary had a similar scale to that at $T = 30$ in a simulation with $N_{\text{host}} = 100000$. The dwarf galaxy models correspond to Run 2 and Run 5. The time evolution of the binding energy and the semi-major axis of the binary is shown in figure 7.

The time evolution of the binding energy and the semi-major axis of the binary was similar to that of $N_{\text{host}} = 100000$. The hardening rate became high after the dwarf galaxy came close to the galactic central region. The average hardening rates from $T = 35$ to $T = 60$ were $\beta = 0.0014 - 0.0015$ 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 shrunk rapidly. This result confirms that a minor merger triggers rapid shrinking of a SMBH binary in higher-resolution simulations.

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

4.1. Minor Mergers of the Compact Dwarf Galaxies

We demonstrate that the 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, $\rho_{\text{DM}}(z) \propto (1+z)^{-3}$. Therefore, many compact dwarf galaxies are expected to form in the early universe and merge to their host galaxy. This has been confirmed by the cosmological numerical simulations of galaxy formation (e.g., Saitoh et al. 2006).

To trigger rapid shrinking of a SMBH binary, such compact dwarf galaxies need to come close to the central region of a host galaxy. To investigate this possibility, we calculated the motions of the dwarf galaxies with various initial orbital parameters, which were in the range expected from the cosmological numerical simulations. Here, the fourth-order Runge–Kutta method was used for the time integration. We assumed that the dark halo and stellar potentials of the host galaxy were fixed. For the dynamical friction force, we used the formula given by Fukushige, Ebisuzaki, and Makino (1992). The initial position of the dwarf galaxy was set at 50 kpc from the center of the host galaxy, which is the vicinity of the virial radius of the dark halo. The initial parameter of the nondimensional orbital angular momentum of the dwarf galaxy was 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 figure 8. A dwarf galaxy with $10^8 \, M_\odot$ can move to the galactic center for a spin parameter of $\lambda = 0.01$–0.04 within $2 \times 10^9 \, \text{yr}$. Such dwarf galaxies can come close to the galactic center within much less than $10^{10} \, \text{yr}$. For dwarf galaxies with $10^8 \, M_\odot$, they can come close to the center within $10^{10} \, \text{yr}$ in the case of spin parameters of $\lambda = 0.01$ and $\lambda = 0.02$.

The right panel of figure 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 a larger $\lambda$, 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 a mass of more than $10^8 \, M_\odot$, and a $\lambda$ smaller than $\lambda = 0.03$.

4.2. Conclusions

We performed N-body simulations, and showed that a minor merger is an effective process to resolve the loss cone depletion problem. If the core of a 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 also performed high-resolution simulations of 200000 N-body particles for the host galaxy. We confirmed that a minor merger triggers a high hardening rate and rapid shrinking of the SMBH binary in high-resolution simulations. We found that the difference in the 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 the timescale of the two-body relaxation of N-body particles becomes longer in the 200000 N-body simulations. This result indicates that the effects of a minor merger appear clearly in a 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...
sufficiently 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 a 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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References

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
Berczik, P., Merritt, D., Spurzem, R., & Bischof, H.-P. 2006, ApJ, 642, L21
Dotti, M., Colpi, M., & Haardt, F. 2006, MNRAS, 367, 103
Dotti, M., Colpi, M., Haardt, F., & Mayer, L. 2007, MNRAS, 379, 956
Escala, A., Larson, R. B., Coppi, P. S., & Mardones, D. 2004, ApJ, 607, 765
Escala, A., Larson, R. B., Coppi, P. S., & Mardones, D. 2005, ApJ, 630, 152
Fukushige, T., Ebisuzaki, T., & Makino, J. 1992, PASJ, 44, 281
Hayasaki, K. 2009, PASJ, 61, 65
Iwasawa, M., Funato, Y., & Makino, J. 2006, ApJ, 651, 1059
Kase, H., Makino, J., & Funato, Y. 2007, PASJ, 59, 1071
Kormendy, J., & Djorgovski, S. 1989, ARA&A, 27, 235
Makino, J. 1991, PASJ, 43, 859
Makino, J., & Aarseth, S. J. 1992, PASJ, 44, 141
Makino, J., Fukushige, T., Koga, M., & Namura, K. 2003, PASJ, 55, 1163
Makino, J., & Funato, Y. 2004, ApJ, 602, 93
Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21
Matsubayashi, T., Makino, J., & Ebisuzaki, T. 2007, ApJ, 656, 879
Perets, H. B., & Alexander, T. 2008, ApJ, 677, 146
Perets, H. B., Hopman, C., & Alexander, T. 2007, ApJ, 656, 709
Saitoh, T. R., Koda, J., Okamoto, T., Wada, K., & Habe, A. 2006, ApJ, 640, 22
Sharma, S., & Steinmetz, M. 2005, ApJ, 628, 21
Whitaker, K. E., & van Dokkum, P. G. 2008, ApJ, 676, L105