EFFECTS OF A SUPERMASSIVE BLACK HOLE BINARY ON A NUCLEAR GAS DISK

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ABSTRACT

We study the influence of a galactic central supermassive black hole (SMBH) binary on gas dynamics and star formation activity in a nuclear gas disk with three-dimensional tree+SPH simulations. Because of the orbital motions of the SMBHs, there are various resonances between the gas motion and SMBH binary motion. We show that these resonances create characteristic structures of gas in the nuclear gas disk, for example, elongated or filament structures, gaseous spiral arms, and/or small gas disks around the SMBHs. In these dense gaseous regions, active star formation is induced, and as a result, many starbursts are formed in the nuclear region.

Subject headings: black hole physics — galaxies: active — galaxies: nuclei — galaxies: starburst — hydrodynamics

1. INTRODUCTION

In recent high-resolution observations (e.g., with the Chandra X-Ray Observatory), there is evidence for supermassive black hole (SMBH) binaries in several galaxies, e.g., NGC 6240 (Komossa et al. 2003), Arp 220 (Clements et al. 2002), M83 (Thutte et al. 2000; Sakamoto et al. 2004; Mast et al. 2006), and 3C 66B (Sudou et al. 2003). In particular, NGC 6240 has been well observed in a wide range of wavelengths (Tacconi et al. 1999; Komossa et al. 2003). In the high-resolution X-ray observation by Chandra, two strong peaks in the hard X-ray are detected in the galactic center, which is strong evidence of a SMBH binary (Komossa et al. 2003). In radio continuum, near-infrared, and soft X-ray observations of this galaxy, a nuclear starburst has been detected (Lira et al. 2002; Pasquali et al. 2004). Nuclear gas-rich disks have been observed around the SMBH binaries in NGC 6240 (Tacconi et al. 1999) and Arp 220 (Scoville et al. 1997; Sakamoto et al. 1999).

SMBH binaries in galactic central regions are expected to be formed by merging galaxies, each of which has a SMBH in its galactic center. After the galaxies merge, the SMBHs sink into the center by dynamical friction between the SMBHs and field stars (Ebisuzaki et al. 2001; Escala et al. 2004, 2005). These SMBHs form a SMBH binary and finally merge due to the emission of gravitational waves (Matsubayashi et al. 2004; Enoki et al. 2004; Escala et al. 2004, 2005). In explaining this process, Escala et al. (2004, 2005) have shown the important role of dynamical interaction between SMBHs and gas, especially in very gas-rich regions.

Kazantzidis et al. (2005) have made simulations of the merging process of two disk galaxies with SMBHs at each galactic center. Their results indicate that a large amount of gas flows into the center of merging galaxies, and a starburst is triggered. They also show that in the process, a SMBH binary is formed in the center of the merging galaxies, and a nuclear gas disk with a radius of 1–2 kpc is formed at the galactic center. The effects of a SMBH binary on a nuclear gas disk have not yet been studied, and they may be very important regarding star formation in the galactic center.

Since the gravitational potential of a SMBH binary has a non-axisymmetric component, we expect that gas motion in a nuclear gas disk will be strongly influenced by a SMBH binary. A change of gravitational potential due to the orbital motions of the SMBHs may induce resonance phenomena in the disk, as in barred galaxies (Athanassoula 1992). It has been suggested that these resonances trigger nuclear starbursts in barred galaxies (Fukunaga & Tosa 1991; Wada & Habe 1992, 1995; Elmegreen 1994; Fukuda et al. 1998). In the case of a SMBH binary, similar resonances may trigger active star formation in the nuclear gas disk. Moreover, the SMBH binary may yield some peculiar gaseous features in the nuclear disk, which can be used as evidence of a SMBH binary.

In this paper, we study the influence of a galactic central SMBH binary on gas motion in a nuclear gas disk using hydrodynamic simulations in a three-dimensional tree+smoothed particle hydrodynamics (SPH) code. We show that the resonances due to a SMBH binary can trigger the formation of gas concentrations in the disk, as a result of which the star formation rate (SFR) increases.

In § 2, we present our simulation model; in § 3, we present the results of our simulations; and in § 4 we summarize our results and give discussion.

2. SIMULATION MODEL

To study the influence of a galactic central SMBH binary on a nuclear gas disk, we simulate the motion of gas and SMBHs in a model galaxy using a tree+SPH code.

2.1. Model Galaxy and a SMBH Binary

We assume a model galaxy in which the gravitational potential in the nuclear region is similar to that of NGC 6240. We also assume a spherical stellar mass distribution, which is consistent with the observed rotation curve in the inner region of the galaxy. The rotation curve of CO gas has been obtained for the galactic central region by Tacconi et al. (1999). We adopt the King model for the stellar component,

$$\rho_{\text{star}}(r) = \frac{\rho_{\text{star}, 0}}{(1 + r/r_{\text{star}, 0})^{3/2}},$$  \hspace{1cm} (1)
where \( \rho_{\text{star,0}} = 15 \ M_\odot \text{ pc}^{-3} \) and \( r_{\text{star,0}} = 0.5 \text{ kpc} \), which is consistent with observations.

In our simulations, we set a SMBH binary in the central region of this model galaxy. Each SMBH is modeled by the Plummer potential in order to avoid numerical singularity in its gravitational potential. Our model parameters for the SMBH binary are shown in Table 1. We assume two cases for the masses of the SMBHs. Since the masses of the nuclei in NGC 6240 are estimated to be \( \approx 5 \times 10^8 \ M_\odot \) (Tacconi et al. 1999), in the first case, the mass of each SMBH is \( 5 \times 10^8 \ M_\odot \), and in the second case, the mass of each SMBH is \( 1 \times 10^8 \ M_\odot \). We assume four cases for the initial orbits of the SMBHs. In the first case, both SMBHs move initially in a circular orbit, and in the other three cases, both SMBHs move initially in elliptical orbits. The direction of motion of the SMBHs in each case is the same as the direction of rotation of the gas disk. We assume that the initial distance of each SMBH is 350 pc from the galactic center, and the initial positions of the SMBHs are at opposite sides of the galactic center. The separation between SMBHs is about 750 pc in NGC 6240 (Tacconi et al. 1999).

Initially the nuclear gas disk is assumed to be of uniform density, with a radius of 2 kpc. A gas disk of similar size is obtained by galaxy merger simulations with SMBHs (Kazantzidis et al. 2005). Its thickness is 500 pc, and its temperature is \( 10^3 \text{ K} \). The mass of gas within 2 kpc is \( 2 \times 10^8 \ M_\odot \). The gas disk rotates with a circular velocity and is in gravitational equilibrium in the model galaxy.

### 2.2. Effect of a SMBH Binary on Gas Dynamics

The gravity of a SMBH binary has a nonaxisymmetric component, as in a barred potential. In barred galaxies, it has been shown that resonances between gas motion and a rotating nonaxisymmetric gravitational potential are important for gas dynamics. In a weak barred potential, the inner Lindblad, corotation, and outer Lindblad resonances can be shown by epicycle approximation. These resonances play an important role in the formation of gaseous ridges and spiral arms in barred galaxies (e.g., Athanassoula 1992).

If the SMBHs are rotating in circular orbits, the gravitational potential will change with the pattern speed, \( \Omega_{\text{BH}} \), which is the orbital angular velocity of the SMBHs. In this case, we expect resonances between the gas motion and the SMBH binary motion.

When the orbits of the SMBHs are elliptical, the major axes of the elliptical orbits shift with time. In this case, due to the shift of the major axis of each elliptical orbit, the time variation of the gravitational potential is different from the circular orbit case. The angular velocity of this shift, \( \Omega_\gamma \), may be slower than \( \Omega_{\text{BH}} \). In this case, we expect additional resonances similar to the Lindblad and corotation resonances. However, the time variation of this gravitational potential is very complicated. Therefore, we need to make numerical simulations of the gas that include a SMBH binary.

We show the resonances in our simulation models in Figure 1. Figure 1 shows the angular frequency of circular rotating gas motion in the model galaxy potential, \( \Omega_{\text{BH}} \), and \( \Omega_\gamma \). In model 1, the SMBHs move in a circular orbit. In this model, we expect corotation and outer Lindblad resonances between the gas motion and the SMBH binary motion for \( \Omega_{\text{BH}} \). In models 2, 3, and 4, the SMBHs move in elliptical orbits. In these models, \( \Omega_\gamma \) is smaller than \( \Omega_{\text{BH}} \), as shown in Figure 1. We can expect resonances due to low \( \Omega_\gamma \).

### 2.3. Numerical Method

We use a tree+SPH code with GRAPE-5 to simulate the motion of gas and the SMBH binary. In the code, we solve for the gravitational force of the gas and the SMBHs, using the combination of the tree method (Appel 1985) and GRAPE-5 (Sugimoto et al. 2000), and we solve for the hydrodynamic evolution using the SPH method (Lucy 1977; Gingold & Monaghan 1977). Neighbor searching is accelerated by the combination of GRAPE and the reordering method (Saitoh & Koda 2003). We consider the self-gravity of the gas in a fixed stellar potential. Radiative cooling, star formation, and thermal heating from supernovae are also considered. We assume the Salpeter initial mass function for newly formed stars. The motions of newly formed star particles are

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**TABLE 1**

| Model | Mass of SMBH1 (\(M_\odot\)) | Mass of SMBH2 (\(M_\odot\)) | Eccentricity of SMBH’s Orbit | Semimajor Axis of SMBH Orbit (pc) |
|-------|--------------------------|--------------------------|-----------------------------|-------------------------------|
| 0...... | \(5 \times 10^8\) | \(5 \times 10^8\) | 0.00 | 350 |
| 1...... | \(5 \times 10^8\) | \(5 \times 10^8\) | 0.67 | 350 |
| 2...... | \(5 \times 10^8\) | \(5 \times 10^8\) | 0.82 | 350 |
| 3...... | \(5 \times 10^8\) | \(5 \times 10^8\) | 0.94 | 350 |
| 4...... | \(1 \times 10^8\) | \(1 \times 10^8\) | 0.64 | 350 |
| 5...... | \(1 \times 10^8\) | \(1 \times 10^8\) | 0.82 | 350 |
| 6...... | \(1 \times 10^8\) | \(1 \times 10^8\) | 0.93 | 350 |

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**Fig. 1.** Frequencies as a function of radial distance in the model galaxy, where \( \Omega_{\text{BH}} \) is the angular speed of the SMBHs in a circular orbit of radius 350 pc and \( \Omega_\gamma \) is the angular speed of the orbital precessions. In our models, \( \Omega_{\text{BH}} = 438 \text{ km s}^{-1} \text{ kpc}^{-1} \), and \( \Omega_\gamma = 52, 52, \) and 57 km s\(^{-1}\) kpc\(^{-1}\) for models 2, 3, and 4, respectively.
followed within a fixed stellar gravitational force and the gravity of gas, SMBHs, and other newly formed stars.

A SPH kernel is defined by

\[
W(x, h) = \frac{1}{4\pi h^3} \left\{ \begin{array}{ll}
4 - 6x^2 + 3x^3, & 0 \leq x \leq 1, \\
(2 - x)^3, & 1 \leq x \leq 2, \\
0, & 2 \leq x,
\end{array} \right.
\]

where \( h \) is the particle’s smoothing length, \( x = r_j/h \), and \( r_{ij} = |r_j - r_i| \). The equations for the motion and energy of the \( i \)th SPH particle are

\[
\frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i, 
\]

\[
\frac{dv_i}{dt} = -\sum_j m_j \left( \frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij} \right) \nabla W(x, h) - \nabla(\Phi_{\text{star}} + \Phi_{\text{SMBH}} + \Phi_{\text{gas}}),
\]

\[
\frac{du_i}{dt} = \sum_j \left( \frac{P_i}{\rho_i^2} + \frac{1}{2} \Pi_{ij} \right) \mathbf{v}_j \cdot \nabla W(x, h) + \frac{\mathcal{H}_i - \Lambda_i}{\rho_i},
\]

where \( P_i \) and \( \rho_i \) are the pressure and density, \( \Pi_{ij} \) is the artificial viscosity, of which the viscous parameters are \( \alpha = 1 \) and \( \beta = 2 \) (Monaghan & Gingold 1983; Monaghan 1992), \( \mathcal{H}_i \) is the supernovae heating rate by newly born stars, and \( \Lambda_i \) is the radiative cooling function of H/He for \( T > 10^4 \) K and molecular gas for \( 10^3 < T < 10^4 \) K (Spaans & Norman 1997). The metal line cooling is not considered in our simulations; we find that it does not affect our results, since the temperature of the gas in our simulations is lower than \( 10^5 \) K. We employ the shear-reduced technique in the artificial viscosity (Balsara 1995).

Our star formation algorithm is similar to that of Katz (1992), Katz et al. (1996) and Saitoh & Wada (2004), but for higher density criterion. An SPH particle is changed to a collisionless star particle if it satisfies all of the following conditions: (1) it exists within a higher number density than that of typical CO clouds \( (n_{\text{H}} > 200 \text{ cm}^{-3}) \), in order to avoid the star formation in the low gas-density regions; (2) it meets the Jeans criterion; and (3) it is within a collapsing region \( (\nabla \cdot \mathbf{v} < 0) \). The star formation efficiency is 0.033.

We use 50,000 SPH particles. Since we assume that the total mass of the nuclear gas disk within 2 kpc is \( 2 \times 10^9 M_{\odot} \), the mass of each SPH particle is \( 4 \times 10^4 M_{\odot} \). The gravitational softening lengths of SPH particles and SMBHs are 170 and 50 pc, respectively. We employ the second-order leapfrog method for time integration. We also calculate using 100,000 SPH particles to confirm our results.

### 3. RESULTS

We show the numerical results of gas motion in a nuclear gas disk with a SMBH binary. In the model galaxy without a SMBH binary, gas evolution in the gas disk is rather quiet. On the other
hand, in the model galaxy with a SMBH binary of $5 \times 10^8 M_\odot$, resonances due to the SMBH binary induce a large peculiar gas motion in the gas disk. Gas motion is particularly affected by SMBH binaries with highly eccentric orbits. However, in the model galaxy with a SMBH binary of $1 \times 10^8 M_\odot$, the effects of the SMBH binary are not strong. This can be explained by the fact that the mass of the smaller SMBH is only 2.4% of the dynamical mass of the model galaxy within 500 pc, $4.1 \times 10^9 M_\odot$. Below we show the results for the case of SMBHs of $5 \times 10^8 M_\odot$.

3.1. The Circular Orbit Case

We show the results of the model with a SMBH binary in which each SMBH moves in a circular orbit (model 1). In this case, we expect to see a corotation resonance ($r_{\text{CR}} \sim 350$ pc) and outer Lindblad resonance ($r_{\text{OLR}} \sim 900$ pc), as shown in Figure 1 (see § 2.2).

Our numerical result shows that SMBHs influence the gas motion of the nuclear disk and excite active star formation in the nuclear region. In Figure 2 (left), we show the gas surface density and star formation sites at $1.5 \times 10^7$ yr in model 1. At that time, the effects of resonances appear in the gas distribution. Gaseous ridge structures appear at the upstream side of the SMBH binary. Gaseous spiral arms are formed within 700–900 pc, which is in the vicinity of the radius of, and may be caused by, the outer Lindblad resonance. These ridge and spiral arm structures resemble those of barred galaxies (Athanassoula 1992). After the formation of the ridges, gas is accumulated into them, and the gas mass in the ridges increases with time. The gaseous ridges change their shape, and an elongated gas-rich region is formed between the SMBHs, as shown in Figure 2 (right). The major axis of the elongated region is parallel to the SMBH position angle; its semimajor axis is about 500 pc, and the minor axis is about 300 pc. In the elongated region, the gas is radiatively cooled, and many dense clumps are formed due to gravitational instability. Star formation occurs in these clumps, since they satisfy the star formation criteria given in

![Fig. 3.](image1) Time variation of the SFR within 500 pc ($M_\odot$ yr$^{-1}$) for our models. The dot-dashed, dotted, short-dashed, long-dashed, and solid lines show the SFR in models 0, 1, 2, 3, and 4, respectively.

![Fig. 4.](image2) Same as Fig. 2, but for model 3.
§ 2.3. As a result, star formation becomes very active in these dense gas regions, as shown in Figure 2 (right). After the active star formation stage, the mass of gas decreases with time in the nuclear disk, since a large amount of gas is used in star formation. These features are very different from the case without a SMBH binary, in which the gas surface density is axisymmetric, the gas concentration does not occur in the galactic center, spiral arms are not formed, and star formation is not active in the central region.

The time variation of the SFR within a 500 pc radius is shown in Figure 3. Active star formation has continued from $2 \times 10^7$ to $6 \times 10^7$ yr, and the mean SFR in this period is about $1 M_\odot$ yr$^{-1}$, which is much higher than that of model 0. The duration of the starbursts is less than $10^8$ yr, after which the SFR declines gradually. This is because most of the gas transforms into stars, and then gas is deficient in the galactic central region. After the active star formation stage, the total mass of newly formed stars is about $4.8 \times 10^7 M_\odot$ within 500 pc. This is 34% of the initial gas mass within 500 pc, which is about $1.4 \times 10^8 M_\odot$.

### 3.2. The Elliptical Orbit Cases

Here we discuss the results of the models with a SMBH binary in which each SMBH moves in an elliptical orbit (models 2, 3, and 4). With each model 2–4, we increase the eccentricity of the SMBH orbits, as shown in Table 1. In these cases, the major axis of the elliptical orbit shifts with time. As shown in § 2.2, the shift may excite an additional resonance for $\Omega_d$, which is the angular velocity of the shift. We show that in these cases, the gas morphology and the star formation sites differ from the circular orbit case (§ 3.1).

In model 3, the eccentricity of the SMBH orbit is about 0.82. At first, the gas ridge structures form parallel to the major axis of the SMBH binary. Spiral arms also form around the binary, as in model 1. When the SMBHs are close to each other, a barlike dense gas structure is formed between SMBHs due to the increase of the nonaxisymmetric component of the gravitational potential of the SMBH binary, as shown in Figure 4 (left). After that, the dense gas bar is elongated by the gravity of the receding SMBHs, and a gas filament structure is formed between them. In this process, some of the gas in the filament is captured by the gravity of the SMBHs, and as a result, the gas becomes dense in the filaments, spiral arms, and dense regions around the SMBHs. In these dense regions, gas radiatively cools, and star formation becomes active, as shown in Figure 4 (right). The regions of active star formation are more compact than in model 1, although the SFR within 500 pc is similar, as shown in Figure 3.

After several orbital rotations of the SMBHs, small gas disks form around them, and active star formation occurs in the disks, as shown in Figure 5. The total gas and stellar mass in the small disk around each SMBH is $\sim 3 \times 10^7 M_\odot$ at $2 \times 10^8$ yr. Such gas disks are not formed around SMBHs in model 1. The process of gas disk formation around the SMBHs is as follows. After the SMBHs pass through each other, the dense gas component is captured by the SMBHs and is distributed among them, as shown in Figure 4 (right). A part of the accumulated gas around the SMBHs evolves into small gaseous disks. In the circular orbit case, the SMBHs cannot capture much gas, probably because they are not close to each other, and the dense gas filament is not formed. Therefore, not much gas can be accumulated into the regions around the SMBHs by the SMBHs' gravity, and the gas disks are hardly formed around the SMBHs in model 1. The massive gas disks and active star formation around the SMBHs are typical features of the elliptical orbit case.

Next, we discuss the results of model 4, in which the eccentricity of the orbits of both SMBHs is very high, at about 0.93. Figure 6 (left) shows the gas surface density and star formation sites in the model at $t = 5 \times 10^7$ yr during the active star formation stage. The figure shows that the evolution of the gas and star formation sites is similar to model 3. Figure 3 shows that the SFR is also similar to model 3.

After several orbital rotations of the SMBHs, gas disks are also formed around them in model 4, as in models 2 and 3, as shown in Figure 6 (left). However, after about $1.5 \times 10^8$ yr, the gas disks around the SMBHs are destroyed, as shown in Figure 6 (right). This is induced by the strong tidal force due to the extra SMBH, when the SMBHs are close to each other.

The tidal force also affects the orbital angular momentum of each SMBH, which may be important for the coalescence of the SMBHs. When the tidal force destroys the gas disks around the SMBHs, the disrupted part of the disks gains angular momentum from the SMBHs. As a result, each SMBH loses its orbital angular momentum. In the other models, the angular momentum is not decreased as much as in model 4. This may be due to the fact that the destruction of the disks around the SMBHs by tidal force does not occur in these other models.

Since a large part of orbital angular momentum of the SMBHs disappears with time, violent irregular motions of the SMBHs appear in model 4. In the early stage, the SMBHs move in their original elliptical orbits, similar to the other models, as shown in Figure 7 (left). After about $3 \times 10^7$ yr, since the SMBHs lose their angular momentum due to tidal interaction, the motions of the SMBHs begin to deviate from their original elliptical orbits, and the position of each SMBH becomes asymmetric to the galactic center. Thus, after about $1.0 \times 10^8$ yr, the angular momentum of
each SMBH is exchanged with that of the other SMBH (due to their respective gravitational forces). As a result, after about $1.5 \times 10^8$ yr, large irregular motions of the SMBHs are induced, as shown in Figure 7 (right). We check this result by a simulation with a half time step for the motions of the SMBHs. Similar violent irregular motions of SMBHs are obtained in this test simulation. We also check this result with a simulation of a SMBH binary without gas. In the test simulation, the SMBHs continue to move in their original elliptical orbits; thus, we conclude that the irregular motion in the elliptical orbit case is not an artifact.

![Surface Density Map: t = 50 x 10^6 yr](image1)

![Surface Density Map: t = 200 x 10^6 yr](image2)

**Fig. 6.**—Same as Fig. 2, but for model 4.

![Orbit of the SMBH in model 4](image3)

**Fig. 7.**—Orbit of the SMBH in model 4, from $t = 0$ to $3 \times 10^7$ yr (left) and from $t = 1.7 \times 10^8$ to $2 \times 10^8$ yr (right).
4. SUMMARY AND DISCUSSION

We study the influence of a galactic central SMBH binary on gas dynamics in the nuclear gas disk using numerical simulations. We calculate various cases for initial circular and elliptical SMBH orbits. We have shown that in all cases, the SMBH binary has a large influence on gas motion in the gas disk. The SMBH binary induces some resonances in the gas motion in a nuclear gas disk. As a result of these resonances, various dense gas structures are formed in the nuclear gas disk, and gaseous spiral arms are formed near the vicinity of the outer Lindblad resonance. In these dense gas regions, star formation becomes very active. In the case of a SMBH binary with a highly eccentric orbit, narrow gaseous filaments and dense clump structures are well developed, and active star formation occurs in these regions. These features can be strong evidence of the existence of a SMBH binary. It is very interesting to compare these features with very high resolution observations of galaxies that are proposed to have a SMBH binary. Dense gas structures and the distribution of star formation sites will inform us of the dynamical state of the SMBH binary. It should be noted that these features do not appear, where the SMBH mass is smaller than about $1 \times 10^8 M_\odot$ in our model. We note that when we compare the overall SFRs of ultraluminous infrared galaxies, the SFRs induced by the SMBH binary are not high. However, the SFR is as high as that of nuclear starbursts in nearby starburst galaxies.

In our simulations, gaseous ridges are formed by shocks. In the case of elliptical-orbit SMBHs, there are collisions between gas clumps in the galactic center, which may cause these shocks. The H$_2$ emission line is expected to be excited in the shocks. Van der Werf et al. (1993) and Sugai et al. (1997) have observed bright H$_2$ emission lines in the galactic central region of NGC 6240, and they conclude that the H$_2$ emission is excited by shocks.

From our numerical simulations, small gas disks are formed around SMBHBs in the elliptical orbit cases. Such gas disks around SMBHBs have been observed in Arp 220, which has a double nucleus in the galactic center (Sakamoto et al. 1999). In our simulations, star formation is very active in the small gas disks around the SMBHBs. The active star formation in the gas disks around the SMBHBs may correspond to the radio continuum sources observed around the SMBHBs in NGC 6240 (Taccioni et al. 1999). Chandra observed hard X-rays from the double nucleus in NGC 6240. It is possible that active galactic nucleus (AGN) activity can be excited by gas accretion onto SMBHBs in the small gas disks. If AGN activity is highly excited, and AGN feedback becomes very strong, active star formation will be quenched (Matteo et al. 2005).

Since active star formation occurs in very compact regions in the highly eccentric elliptical orbit cases, we expect that these newly formed stars will concentrate in compact massive star clusters. If these star clusters interact gravitationally with the SMBH binary, the interaction may induce the loss of orbital angular momentum of the SMBHBs due to the instability of the three-body problem in which the SMBHBs and the star cluster interact with each other, and ejection of the star cluster occurs. If these star clusters are massive enough, this process may be very effective, and the binary could evolve into a more tightly bound state. This process may have an important role in the merging process of SMBHBs.

Escala et al. (2005) studied the effect of the hydrodynamic drag force from dense gas on the evolution of a SMBH binary using numerical simulations. They have shown that after the SMBHBs gradually fall into the galactic central dense gas region through dynamical friction, the effect of hydrodynamic drag becomes very large in the central region. They suggested that, finally, the SMBHBs can be close enough to merge via the hydrodynamic effect. In their simulations, they do not consider the effects of radiative cooling and star formation on the gas. However, many dense clump structures will be formed through the effect of radiative cooling, and their distribution is more complicated. The dense clumps may interact with the SMBHBs and play an important role in their coalescence. Moreover, active star formation will occur in the clumps, and the gas mass will decrease in the galactic central region. After the active star formation, it is not clear whether enough gas will remain in the galactic center for hydrodynamic interaction with the SMBHBs. Further simulations of the evolution of a SMBH binary in a more realistic model are needed.

In our simulations, we did not consider the dynamical friction between field stars and the SMBHBs. Dynamical friction induces the decay of the orbital radii of the SMBHBs. If the timescale of dynamical friction is larger than the timescale of the rotational motion of the SMBHBs, the resonances between the SMBHB motions and the gas motion will be effective. In this case, a process similar to that observed in our simulations will occur. On the other hand, if the dynamical friction timescale is smaller than the rotation timescale, the orbits of the SMBHBs will shrink very rapidly, and resonance phenomena are not important.

We have assumed that initially, a gas disk is circularly rotating. However, since a galaxy with a SMBH binary is expected to form through the merging of galaxies with SMBHBs, gas motion is more complex. To simulate a more realistic evolution of a galaxy with a SMBH binary, in a future work we will study the merging process of galaxies with SMBHBs. In this process, radiation drag (Kawakatu et al. 2005) and the influence of AGN feedback (Springel et al. 2005) should be considered.

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