Binary Black Hole Accretion Flows in Merged Galactic Nuclei

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Abstract

We study the accretion flows from the circumbinary disks onto the supermassive binary black holes in a subparsec scale of the galactic center, using a smoothed particles hydrodynamics (SPH) code. Simulation models are presented in four cases of a circular binary with equal and unequal masses, and of an eccentric binary with equal and unequal masses. We find that the circumbinary-hole disks are formed around each black holes regardless of simulation parameters. There are two-step mechanisms to cause an accretion flow from the circumbinary disk onto supermassive binary black holes: First, the tidally induced elongation of the circumbinary disk triggers mass inflow towards two closest points on the circumbinary disk from the black holes. Then, the gas is increasingly accumulated on these two points owing to the gravitational attraction of black holes. Second, when the gas can pass across the maximum loci of the effective binary potential, it starts to overflow via their two points and freely infalls to each black hole. In circular binaries, the gas supply undergoes the periodic on/off transitions during one orbital period because of the variation of periodic potential. The gap starts to close after the apastron and to open again after the next periastron passage. Due to this gap closing/opening cycles, the mass-capture rates are eventually strongly phase dependent. This could provide observable diagnosis for the presence of supermassive binary black holes in merged galactic nuclei.

Key words: accretion, accretion disks – black hole physics – binary black holes – galaxies:nuclei

1. Introduction

There is growing evidence that most galaxies have the supermassive black holes at their centers (Kormendy & Richstone 1995; see also Rees 1984 for a classical review). The remarkable evidence for supermassive black holes is provided by the existence of a gas disk with Keplerian rotation on a subparsec scale found by the radio observations (Miyoshi et al. 1995) and by the asymmetric iron line profile discovered by the X-ray observations (Tanaka et al. 1995). In the vicinity of a supermassive black hole, the gas in the disk is heated up and produces very high luminosity by efficiently transforming their gravitational energy into radiation (e.g., Lynden-Bell 1969). Thus, such rotating gas disks with accretion flow are considered as the energy sources of active galactic nuclei (AGNs) and quasars.

Recently, it has been widely accepted that the supermassive black holes play an important role not only in the activities of AGNs and quasars but also in the formation and global evolution of galaxies (Silk & Rees 1998; Kaufmann & Haehnelt 2000; Di Matteo et al. 2005; Merritt 2006, and references therein). The discovery of the tight correlation between black hole mass and the velocity dispersion of the bulge component of galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000) supports the scenario that the black holes have grown up in mass through the hierarchical galaxy mergers, just as galaxies themselves did. If this scenario is correct, the supermassive binary black holes (BBHs) will be inevitably formed during the course of galaxy mergers (Milosavljević & Merritt 2001).

There are actually a number of observational indications that some galaxies harbour supermassive BBHs at their centers. Main results are listed as follows (see also Komossa 2003; 2006);

- Periodic optical and radio outbursts (e.g., OJ287) (Sillanpää et al. 1988; Lehto & Valtonen 1996; Valtaoja et al. 2000; Valtonen et al. 2006).
- Wiggled patterns of the radio jet indicating precessional motions on a parsec scale (Yokosawa & Inoue 1985; Roos et al. 1993; Britzen et al. 2001; Abraham & Carrara 1998; Lobanov & Roland 2005).
• X-shaped morphology of radio lobes (Merritt & Ekers 2002).
• Double peaked broad emission lines in AGNs (Gaskell 1996; Ho et al. 2000).
• Double compact cores with the flat radio spectrum (Maness et al. 2004; Rodríguez et al. 2006).
• Orbital motion of the compact core (Sudou et al. 2003).

It is believed that the supermassive BBHs evolve mainly via three stages (Begelman et al. 1980; Yu 2002). Firstly, each of black holes sinks independently towards the center of the common gravitational potential due to the dynamical friction with neighboring stars. When the separation between two black holes becomes as short as 1 pc or so, angular momentum loss by the dynamical friction slows down due to the loss-cone effect and a supermassive hard binary is formed. This is the second stage. Finally, when the semi-major axis of the binary decreases to less than 0.01 pc, gravitational radiation dominates and then a pair of black holes, eventually, merge into a single supermassive black hole.

If there is the gas orbiting around the supermassive BBHs in the second evolutionary stage, one will be able to observe a signal arising from the interaction between the binary and its surrounding gas (i.e. a circumbinary disk). This disk-binary interaction could be also the predominant candidate to resolve the loss-cone problem (Armitage & Natarajan 2002; 2005; see also Artymowicz 1998). An orbital angular momentum of the supermassive BBHs is transferred to the circumbinary disk, by which the gas around the supermassive BBHs will be swept away. In addition, we expect that the mass inflow will take place from the circumbinary disk to the supermassive BBHs, leading to the formation of accretion disks around each of black holes (i.e. circumblack-hole disks). A final configuration could be three-disk systems; one circumbinary disk and two circumblack-hole disks (see Fig. 1 for a schematic view of supermassive BBHs).

Such three-disk systems have been also discussed in the context of binary star formation, where the binary is composed of young stars. Artymowicz & Lubow (1996a) found that the material can infall on to the central binary through the gap between the circumbinary disk and the central binary, and that its accretion rate modulates with the orbital phase. Since then, the theory of the young binary star formation has been extensively studied (Artymowicz & Lubow 1996b; Lubow & Artymowicz 1996; Bate & Bonnell 1997; Lubow & Artymowicz 2000; Günther & Kley 2002; Günther & Kley 2004; Ochi et al. 2005). Some basic processes involved with the disk-binary interaction have been revealed through these researches. Despite its significance, however, it is poorly known how the material accretes onto supermassive BBHs from the circumbinary disk under the realistic situations. Artymowicz & Lubow (1996a) only discussed briefly the quasi-periodic behavior of optical/infrared outbursts in a blazar OJ287 in terms of the strong phase-dependent accretion onto supermassive BBHs (see also Artyomowicz 1998).

In this paper, therefore, we elucidate the theory of accretion processes in supermassive binary black-hole systems by performing smoothed particle hydrodynamics (SPH) simulations. Our ultimate goal is to give an observable diagnosis for the presence of supermassive BBHs in central region of merged galaxies. The simulation should ideally take account of all the processes at work in the three-disk systems, including the circumbinary disk evolution around the supermassive BBHs, the mass transfer from the circumbinary disk to the individual black holes, and the accretion onto each of black holes. Such a simulation, however, would require an enormous computational time. Therefore, we confine ourselves to simulate only the accretion flow from the circumbinary disk onto the supermassive BBHs. Detailed structure and evolution of the circumblack-hole disks will be reported in a subsequent paper.

The plan of this paper is as follows: We first describe our numerical model in Section 2. Then, our numerical results will be reported in Section 3 for the basic processes involved with mass accretion onto the circular, equal-mass binary, and in Section 4 for the effects of the orbital eccentricity and the unequal masses of the binary. We then discuss the observational implications and the related issues in Section 5. Section 6 is devoted to conclusions.

2. Our Models, Basic Equations, and Numerical Procedures

Simulations presented here were performed with a three-dimensional (3D) SPH code. The SPH code is basically the same as that used by Hayasaki & Okazaki (2004; 2005; 2006), and is based on a version originally developed by Benz (Benz 1990; Benz et al. 1990). The SPH equations with the standard cubic-spline kernel are integrated using a second-order Runge-Kutta-Fehlberg integrator with individual time steps for each particle (Bate et al. 1995), which results in saving an enormous computational time when a large range of dynamical timescales are involved. We first give the basic equations and then describe the implementations to the SPH code.
2.1. Basic Equations

2.1.1. Mass Conservation

In the SPH calculations, each particle has a density distribution over a spatial scale of the smoothing length, $h$, around its center. Hence, the density at the position of particle $i$ ($i = 1, 2, \cdots$) is given by a weighted summation over the masses of the particle $i$ itself and its neighboring particles (hereafter, neighbors),

$$\rho_i = \sum_j m_j W(r_{ij}, h_{ij}).$$

(1)

Here $m_j$ is the mass of the particle $j$, $N_{nei}$ is the number of the neighbors of the particle $i$, $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ is the distance between the particles $i$ and $j$, $h_{ij} = (h_i + h_j)/2$ is the mean smoothing length, and $W$ is the kernel. We adopt the standard cubic-spline kernel $W$ the mean smoothing length, and of the neighbors of the particle $i$.

Gingold 1983), viscosity with the following standard form (Monaghan & McCray and secondary black holes, respectively, $M_i$ is the mass of the particle $i$, $\alpha$ where $\alpha$ is the viscosity parameter. $\alpha$ is a constants, respectively.

2.1.2. Momentum Equation

The momentum equation for the fluid under a gravity in the inertia frame is written by

$$\frac{d\mathbf{v}_i}{dt} = -\nabla P + \mathbf{F}_{\text{vis}} - \nabla \phi,$$

(3)

where $d/dt$ is the Lagrangian derivative, $\mathbf{v}$ is the velocity field, $P$ is the pressure, $\mathbf{F}_{\text{vis}}$ is the viscous force, and $\phi$ is the gravitational potential by the BBHs. Self-gravity of the gas particles is neglected. The corresponding SPH momentum equation for the $i$-th particle in the potential of a pair of black holes is then

$$\frac{d\mathbf{v}_i}{dt} = -\sum_{j} m_j \left( \frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij} \right) \nabla W(r_{ij}, h_{ij})$$

$$+ \frac{GM_p(\mathbf{r}_i - \mathbf{R}_p)}{|\mathbf{r}_i - \mathbf{R}_p|^3} - \frac{GM_s(\mathbf{r}_i - \mathbf{R}_s)}{|\mathbf{r}_i - \mathbf{R}_s|^3}$$

(4)

where $\mathbf{v}_i$ is the velocity of the $i$-th particle, $G$ is the gravitational constant, $M_p$ and $M_s$ are the masses of the primary and secondary black holes, respectively, $\mathbf{R}_p$ and $\mathbf{R}_s$ are the position vectors of the primary and secondary black holes, respectively, and $\Pi_{ij}$ is the SPH artificial viscosity with the following standard form (Monaghan & Gingold 1983),

$$\Pi_{ij} = \begin{cases} \frac{\alpha_{SPH}(\mu_{ij} + \beta_{SPH}v^2_{ij})/\rho_{ij}}{
u_{ij} \cdot r_{ij} \leq 0} & \nu_{ij} \cdot r_{ij} \leq 0 \leq 0 \\ 0 & \nu_{ij} \cdot r_{ij} > 0 \end{cases}$$

(5)

where $\alpha_{SPH}$ and $\beta_{SPH}$ are the linear and non-linear artificial viscosity parameters, respectively. $\rho_{ij} = (\rho_i + \rho_j)/2$, $v_{ij} = \mathbf{v}_i - \mathbf{v}_j$ and $\mu_{ij} = h_{ij} v_{ij} \cdot r_{ij}/(r_{ij} + \eta_{ij})$ with $\eta_{ij}^2 = 0.01 h_{ij}^2$. The connection with the disk viscosity will be described in subsection 2.2.3.

2.1.3. Equation of State

The pressure term $P$ in the momentum equation is calculated by the isothermal equation of state;

$$P_i = c_s^2 \rho_i,$$

(6)

where $c_s$ is the isothermal sound speed of the gas. We do not need to explicitly solve an energy equation.

2.2. Disk Viscosity

Viscosity is essential in the disk simulations, while the SPH formalism already contains the artificial viscosity. There is an approximate relation connecting the Shakura-Sunyaev viscosity parameter $\alpha_{SS}$ and the SPH artificial viscosity parameter $\alpha_{SPH}$. The outline of formalism is presented below in the same procedure as that of Section 2.1 of Okazaki et al. (2002).

Meglicki, Wickramanashige & Bicknell (1993) found that the SPH viscous force becomes

$$F_{\text{vis}} = \frac{1}{10} \alpha_{SPH} c_s h [\nabla^2 \mathbf{v} + 2 \nabla (\nabla \cdot \mathbf{v})]$$

(7)

in the 3D continuum limit of equation (5), assuming that the density varies on a length-scale much larger than that of the velocity. This implies that the shear viscosity $\nu$ and the bulk viscosity $\nu_{bulk}$ are given by

$$\nu = \frac{1}{10} \alpha_{SPH} c_s h$$

(8)

and

$$\nu_{bulk} = \frac{5}{3} \nu,$$

(9)

respectively.

According to the $\alpha$ viscosity prescription (Shakura & Sunyaev 1973), on the other hand, the shear viscosity is written as

$$\nu = \alpha_{SS} c_s H,$$

(10)

where $H$ is the disk scale-height and $\alpha_{SS}$ is the viscosity parameter. From the combinations of equations (8) and (10), we find the relation connecting $\alpha_{SPH}$ and $\alpha_{SS}$ as

$$\alpha_{SS} = \frac{10^{10}}{10^{10}} \alpha_{SPH} \frac{h}{H}$$

(11)

as long as $\nabla \cdot \mathbf{v} = 0$ holds. However, we usually find $\nabla \cdot \mathbf{v} \neq 0$ in general flows. Moreover, the viscosity is artificially tuned off for divergent flows in our model (see equation 5). Therefore, equation (11) should be taken as a rough approximation to relate $\alpha_{SPH}$ to $\alpha_{SS}$. We adopt a constant value of $\alpha_{SS} = 0.1$ throughout the simulations. Hence, $\alpha_{SPH} = 10 \alpha_{SS} H/h$ is variable in space and time, while $\beta_{SPH} = 0$ everywhere.

2.3. Initial Settings

We put a pair of black holes on the $x$-$y$ plane with the semi-major axis of the binary orbit being along the $x$-axis initially and the center of mass being at the origin. In the case of an eccentric binary, we set a pair of black holes initially with the minimum separation (i.e., at the periastron). That is, black holes are initially at $(x, y) =
We assume that the black holes are both Schwarzschild black holes. The masses of the primary and the secondary black holes are $M_p$ and $M_s$, respectively. The binary has the mass ratio $q = M_p/M_s$, and the total mass $M_{\text{tot}} = M_p + M_s = 10^{4} M_{\odot}$. The black holes are modeled by sink particles with the fixed accretion radius of $r_{\text{acc}} = 0.2a$ which are $\sim 8.0 \times 10^3$ times as large as the Schwarzschild radius. Numerically, we take away all the particles which enter the region inside $r_{\text{acc}}$. To ensure that the simulation results do not depend on the accretion radius, we also performed a simulation with $r_{\text{acc}} = 0.1a$, finding no qualitative and quantitative differences within estimated errors of $\sim 13\%$.

The circumbinary disk is initially set around the common center of mass of the supermassive BBHs, which is coplanar with the binary orbital plane. It has a radially random density profile over a width of $0.05a$ and a vertically isothermal, thin disk density profile. Its initial mass is $1.0 \times 10^{-3} M_{\odot}$. The disk temperature is assumed to be $T = 5000 K$ everywhere. Note that this temperature roughly corresponds to the typical effective temperature of a standard disk around a single black hole with $10^8 M_{\odot}$ (Kato et al. 1998). The disk material is rotating around the origin with the Keplerian rotation velocity. The gas particles are added randomly at the radius of the initial outer edge of the circumbinary disk, at a constant rate, $M_{\text{inj}} = 1.0 M_{\odot} \text{yr}^{-1}$ in all the calculated models.

The inner edge of the circumbinary disk depends on the orbital eccentricity. In the circular binary, we take the radius of $r = 1.85a$ corresponding to the tidal truncation radius where the tidal torque of the binary equals to the viscous torque of the circumbinary disk. A circumbinary disk around a circular binary is truncated at this radius (Papaloizou & Pringle 1977). The tidal truncation radii for circular binaries with non-extreme masses are distributed between $r/a = 1.68$ and $r/a = 1.78$ (see Table 1 of Artymowicz & Lubow 1994). In the eccentric binary, on the other hand, we take the (2,1) corotation radius at $r = 2.75a$ (see section 4.1 for the detailed explanation).

We set an outer calculation boundary at $r = 6.0a$, which is sufficiently far from the disk region so that the outer boundary should not affect the flow dynamics in the supermassive BBH systems. The SPH particles passing outward across the outer boundary are removed from the simulation.

### Simulation Implementations

In our code, the accretion flow is modeled by an ensemble of gas particles, each of which has a negligible mass chosen to be $1.0 \times 10^{-7} M_{\odot}$ with a variable smoothing length. We have carried out several simulations with different parameters. The parameters adopted by the calculated models are summarized in Table 1.

To check if the number of SPH particles used in this study is large enough, we also performed the same simulation as in model 1 but with about a half as many particles, finding no appreciable changes. In order to see the validity of the simulations, we also checked several simulation values, such as the ratio of the smoothing length to the disk scale-height $h/H$, the ratio of the smoothing length to the disk radius $h/r$, and the relative disk scale-height $H/r$, respectively. Here the disk scale-height $H$ is defined as the half thickness at which the density decreases by a factor of $e^{-1/2}$. We have found $h/r \ll 1$ in the range of $1.68a \leq r < 4.0a$; that is, the radial structure of the circumbinary disk is well resolved. We also found $h/r \sim 0.03$ at the inner edge of the disk, which ensures the justification of the size of accretion radius, $r_{\text{acc}} = 0.2a$. The disk is geometrically thin because of $H/r < 0.01$ over the whole radial region, as expected from the standard disk theory. However, the vertical structure of the disk is not resolved by our SPH simulations, since we find $h/H > 1$. We, hence, focus our discussion on the radial structure and the detailed explanation of vertical structure is beyond the scope of the present paper.

### Circular Binary with Equal-Mass Black Holes

In this section we consider the accretion onto the circular, equal-mass binary from the circumbinary disk (model 1) for understanding its basic characteristics.

#### 3.1. Overall Evolution

We first overview the global evolution of the supermassive BBH systems. Fig. 2 gives snapshots of the accretion flow in 6 evolutionary stages. These are density contours in the rotation frame co-rotating with the supermassive BBH. Both of the black holes and the circumbinary disk are rotating in the anti-clockwise direction, although the former are rotating more rapidly than the latter according to the Kepler’s law. A pair of the solid circles denote the accretion radii of black holes, which we set at $r_{\text{acc}} = 0.2a$ from the center of the black holes. The dotted circle and dashed circle represent the tidal truncation radius, $r_{\text{trunc}} = 1.68a$ (see section 2.3), and a trapping radius for material, $r_{\text{trap}}/a = 1.19841$, respectively. The trapping radius is defined as the distance from the center of mass to the outer Lagrange point, $L_2$. This is also the same as that from the center of mass to the $L_3$ point in the case of a circular binary with equal masses. This circle approximately points the loci of the maximum in the radial profile of the effective potential (e.g. Kitamura 1970). In other words, when the material once flows inside this circle, it can freely fall towards either of the black holes.

Let us see the disk evolution, following each panel in Fig. 2. Although starting with a circular shape around the center of mass at $t = 0$ [panel (a)], the disk shape begins to be elongated [see panel (b) at $t = 0.35$]. Such deformation continues to grow as the time goes on, and eventually the inner edge of the circumbinary disk touches...
the circle of the trapping radius at two points at $t = 0.54$ [see points P and Q in panel (c)]. Then, gas starts to flow towards the black holes across these two points (particularly, via the point Q), being gravitationally attracted by the black holes. But this inflow is only a transient one for $0 \leq t < 1$. Subsequently, the gas is gradually accumulated on the two points as shown in panel (d). After $t = 3.75$, the gas starts to continuously overflow via points P and Q. The gas inflow will eventually form an accretion disk (i.e., circumblack-hole disks) around each black hole. The possibility of circumblack-hole disk formation will be discussed in section 3.4.

### 3.2. Why is the Disk Elongated?

Fig. 2 clearly demonstrates that the disk elongation triggers mass inflow towards the black holes. Then, what is the key physics underlying the disk deformation? To understand the physics, we performed the pressure-less particle simulation, in which we dropped all the terms related to pressure and viscosity ($P_i = \Pi_{ij} = 0$ in equation 4), adopting the same parameters as those in model 1. The resultant evolution is very much similar to those we obtained in model 1, including the angle of the elongation, in the initial evolutionary stage for $0 < t < 1$. This examination unambiguously proves that the key physics causing the disk elongation should be of kinematics origin; that is, the potential of the supermassive BBHs is dominated by the $m = 2$ Fourier component of the binary potential. This $m = 2$ Fourier component causes the $m = 2$ mode to be excited on the circumbinary disk, which eventually makes the circumbinary disk elongated.

Why is, then, the semi-major axis of the elongated disk misaligned with the line connecting the primary and the secondary black holes as seen in panel (b) of Fig. 2? In the present case, both the binary and the circumbinary disk rotates with the different angular frequency, where the angular frequency of the binary is always faster than that of the circumbinary disk. The system evolves towards the synchronous rotation with the resonance between the angular frequency of the binary and that of the circumbinary disk, which causes the dissipation on the circumbinary disk. Therefore, we interpret that the misalignment is due to the the resonance friction induced by the difference between the binary frequency and the frequency of the disk-inner edge.

After the disk starts to be elongated, the disk material is accumulated in the two closest points on the circumbinary disk by the gravity force of black holes. A pair of bumps (i.e., the tidal bulges) are, then, formed at the disk inner edge, as shown in panel (c) of Fig. 2.

Next, let us examine the radial structure of the circumbinary disk. The left panel of Fig. 3 shows the radial distributions of the surface density and radial velocity at $t = 39.5$ in model 1. The solid line, the dashed line and the dash-dotted line show the surface density (in units of g cm$^{-2}$), the radial velocity normalized by the free-fall velocity, and the tidal truncation radius, $r_{\text{trunc}} = 1.68a$, respectively. A positive (or negative) radial velocity indicates an outward (inward) flow. Clearly, the radial motion of the gas in the circumbinary disk is mostly outward, whereas it is inward inside the tidal truncation radius. Note that the upwardly convex shape of the surface density distribution may be due to an artifact of our way of mass injection (recall that we inject mass to the radius of $r_{\text{inj}} = 1.73a$). However, it is unlikely that our treatment will seriously influence the mass inflow rate at the disk inner edge, since the circumbinary disk evolves on much longer timescale than the orbital period.

### 3.3. Mass Supply and Mass Capture

Let us next see long-term evolution of the mass supply from the circumbinary disk and the mass capture by the black holes. Fig. 4 illustrates the initial evolution of the mass-supply rate (upper) and the capture rates with (lower), together with that of the circumbinary disk mass (upper) and of total mass captured by black holes (lower), during $0 \leq t \leq 20$ in model 1. The mass-capture rate is defined by how much the material is captured by each black hole at the accretion radius $r_{\text{acc}} = 0.2a$ in units of $M_\odot$ yr$^{-1}$. The solid line, the dashed line and the dash-dotted line show the mass-capture rates by the primary black hole and by the secondary black hole, and the disk mass, respectively. We see in this figure that the disk mass steadily increases until $t = 15$ and then stays nearly constant afterwards. Both mass-capture rates by the black holes also increase until $t = 15$ and saturate afterwards but show substantial fluctuations. We can thus safely conclude that mass supply and accretion flow reach their quasi-steady state after $t \simeq 15$.

To investigate how the results depend on an initial disk-width, we performed another simulation with the same simulation parameters as those of model 1, but with an initially more extended circumbinary disk; the disk-inner edge is at 1.68a and the disk-outter edge is at 2.0a. As

### Table 1. Summary of model simulations. The first column represents the model numbers. The second column is the run time in units of $P_{\text{orb}}$. The third column is the number of SPH particles at the end of the run. The mass ratio and the eccentricity are given in the fourth column and the fifth column, respectively. The last column is the initial radius of the inner edge of the circumbinary disk.

| Model | Run time ($P_{\text{orb}}$) | $N_{\text{SPH}}$ (final) | Mass ratio | Eccentricity | Initial disk-inner edge |
|-------|-----------------------------|---------------------------|------------|--------------|------------------------|
| 1     | 40                          | 64023                     | 1.0        | 0.0          | 1.68                   |
| 2     | 60                          | 92633                     | 1.0        | 0.5          | 2.75                   |
| 3     | 40                          | 73975                     | 0.5        | 0.0          | 1.75                   |
| 4     | 60                          | 64921                     | 0.5        | 0.5          | 2.75                   |
Fig. 2. Snapshots of accretion flow from the circumbinary disk onto the supermassive BBHs in model 1. The origin is set on the center of mass of the binary and all panels are shown in a binary rotation frame. Each panel shows the surface density in a range of three orders of magnitude in the logarithmic scale. The solid circle denotes the accretion radius of the primary black hole and the secondary black hole, respectively. The dashed and dotted circle represents the tidal truncation radius and the outer Roche-lobe radius of $q = 1.0$ along with $L_2$ and $L_3$, respectively. Annotated in each panel are the time in units of $P_{\text{orb}}$ and the number of SPH particles $N_{\text{SPH}}$. 
Fig. 3. Radial distributions of the surface density (dashed line) and radial velocity (solid line) normalized by the free-fall velocity at $t = 39.5$ in model 1. The vertical dash-dotted line indicates the position of the tidal truncation radius $r_{\text{trunc}} = 1.68a$. A positive (or negative) radial velocity means the outward (inward) flow.

3.4. Circumblack-hole Disk Formation

Hayasaki & Okazaki (2004) discussed the possibility of the accretion disk formation around the neutron star in a Be/X-ray binary using the data of SPH particles captured by the neutron star. In this subsection, we discuss a possibility of the circumblack-hole disk formation around each black hole in model 1, adopting a similar approach as that in section 2.3 of (Hayasaki & Okazaki 2004).

The material captured at $r_{\text{acc}}$ has a specific angular momentum $J$, by which we can infer the circularization radius of the gas particles, $R_{\text{circ}} = J^2_i / GM_i$, where suffix $i = p$ refers to the primary black hole and $i = s$ to the secondary one. The upper panel of Fig 5 shows the orbital dependence of the circularization radius, where the solid line and the dashed line denote the circularization radius of the primary and the secondary, respectively. This figure clearly shows that the circularization radii largely exceed the Schwarzschild radii of the black holes. Thus, the formation of a disk around each black hole is very likely.

The lower panel of Fig 5 denotes the viscous timescale of each circumblack-hole disk evaluated at $R_{\text{circ}}$. For simplicity, we assume the circumblack-hole disk to be geometrically thin and isothermal with the Shakura-Sunyaev viscosity parameter $\alpha_{\text{SS}}$. The ratios of $\tau_{\text{vis}} / P_{\text{orb}}$ for the primary and the secondary black holes are given, respectively, by

$$\frac{\tau_{\text{vis}}}{P_{\text{orb}}} \bigg|_p = \frac{1}{2\pi \alpha_{\text{SS}} c^2} \left( \frac{R_{\text{circ}}}{a} \right)^{1/2} \frac{GM_p}{a} (1 + q)^{1/2}, \quad (12)$$

$$\frac{\tau_{\text{vis}}}{P_{\text{orb}}} \bigg|_s = \frac{1}{2\pi \alpha_{\text{SS}} c^2} \left( \frac{R_{\text{circ}}}{a} \right)^{1/2} \frac{GM_s}{a} \left( 1 + \frac{1}{q} \right)^{1/2}. \quad (13)$$

The orbital phase dependence of $\tau_{\text{vis}} / P_{\text{orb}}$ is shown in the lower panel of Fig 5. It is immediately seen that the viscous timescales in each of circumblack-holes disks are much longer than the orbital period.
4. Effects of Eccentricity and Unequal Masses

In this section, we first discuss the effects of an orbital eccentricity, which gives rise to interesting orbital-phase modulations. We then touch on the cases with unequal mass black holes.

4.1. Eccentric Binary with Equal-Mass Black Holes

The evolution of supermassive BBHs with an orbital eccentricity has been discussed (e.g. Roos 1981; Polnarev & Rees 1994; Rauch & Tremaine 1996; Quinlan & Hernquist 1997; Armitage & Natarajan 2005). The eccentricity could grow secularly due to the interaction between the black hole and its ambient stellar medium, although this feature has not yet obtained general consensus. In this section, we describe the accretion flow from the circumbinary disk onto the central binary with an eccentricity $e = 0.5$.

Fig. 6 shows snapshots of accretion flow around supermassive BBHs with eccentricity $e = 0.5$ and equal masses $q = 1.0$. Here, the dotted circle and the dashed circle correspond to the radius of the (2,1) corotation resonance and that of the (2,1) outer Lindblad resonance, respectively, where the $(m,l)$ corotation resonance radius and the $(m,l)$ outer Lindblad resonance radius are given, respectively, by $(m/l)^{2/3}a$ and $((m+1)/l)^{2/3}a$ for a circumbinary disk. Here $m$ and $l$ are the azimuthal and time-harmonic numbers, respectively, in a double Fourier decomposition of the binary potential, $\Phi(r, \theta, t) = \sum \phi_{m,l}(r) \exp[i(m\theta - l\Omega_B t)]$, where $\Omega_B$ is the orbital frequency of the binary (Artymowicz & Lubow 1994).

After the disk is set up (see panel (a) of Fig. 6), the tidal bulge is formed and the gas reaches the radius of the (2,1) outer Lindblad resonance at $t = 1.5$, as is seen in panel (b) of Fig 6. The semi-major axis of the elongated disk is not aligned with that of the binary, as well as in a circular binary (see panel (b) of Fig. 2). This phase shift of the tidal bulge occurs by the resonance friction. The unique feature seen in the case of eccentric binaries is that since the binary separation is periodically changing with time, the phase shift should also be changing with time. In addition, the gravitational attraction force to the circumbinary disk also changes periodically and is maximum for the closest parts of the disk to black holes at the phase of the maximum binary separation (i.e., at the apastron).

The material around the binary inside $r_{\text{trunc}}$ will be swept away, since it acquires angular momentum transferred from the BBHs. This transfer is induced by the resonance interaction between the binary and the circumbinary disk (see Artymowicz & Lubow 1994; 1996a; 1996b; Lubow & Artymowicz 1996; 2000). As a result, the inner edge of the circumbinary disk is truncated roughly at the (2,1) outer Lindblad resonance as seen in panels (c)-(f) of Fig 6. This supports the results of Artymowicz & Lubow...
Fig. 6. Same formats as model 1 (Fig. 2), but for model 2. The dashed circle and the dotted circle denote the \((2,1)\) outer Lindblad resonance radius and the \((2,1)\) corotation radius, respectively.
4.2. Gap Opening and Closing

Panels (c)-(f) of Fig. 6 represent sequential snapshots of accretion flows in this system for \(39 < t < 40\). While the material inside the (2,1) corotation radius is captured by the black holes, the mass outside the (2,1) corotation radius outwardly flows at \(t = 39.02\). Subsequently, most of the material is swallowed by black holes at \(t = 39.25\), whereas the gas keeps the outward flow outside the (2,1) corotation radius. The mass overflow is, then, initiated at \(t = 39.5\), and the gas falls and reaches the BBHs at \(t = 39.79\). The most conspicuous feature in the evolution of model 2 resides in this periodic on/off transitions of mass supply. In the absence of the mass inflow from the circumbinary disk a big gap appears between the disk and the black holes. We call this the gap-opening phase. When the mass inflow occurs from the circumbinary disk and then make bridges from the disk to the BBHs, the gap is closed. This is the gap-closing phase. The typical four stages in one gap-closing and opening cycle is repeated in sequential order. In model 1, in contrast, there is a continuous mass supply to the black holes (i.e., the gap is always closed).

As seen in panel (c) of Fig. 6, the circumbinary disk stops mass inflow towards its inner edge when the binary is at the periastron (phase 0), whereas the mass which already left the (2,1) corotation radius continues to fall on to each black hole by the gravitational attraction. Here, Fig. 7 displays the radial distributions of the surface density and the radial velocity in the circumbinary disks in the two different phases. The left panel shows that the radial velocity is almost everywhere outward at phase 0.25, meaning no mass inflow, whereas there is mass inflow at the apastron (phase 0.5).

We need to distinguish the following two steps to understand the orbital modulation of the mass flow stream: (1) When the binary is at the periastron, the angular momentum is much more transferred from the binary to the circumbinary disk than otherwise. Accordingly, the gas inflow is terminated after the periastron [see panel (c)]. Conversely, the mass inflow is at maximum around the apastron (phase 0.5). (2) The material which was launched from the circumbinary disk at the apastron will take some time to reach the BBHs. Hence, there arises a phase-lag between the mass-supply maximum and the mass capture maximum, which roughly corresponds to the free-fall time from the circumbinary disk to the black holes. As a result, the majority of infalling gas is captured by the black holes just before the periastron [see panel (f)]. Hence, the gap starts to be closed after the apastron and is completely closed before the periastron (at phase \(\sim 0.75\)), and then is opened again after the periastron (at phase \(\sim 0.25\)).

4.3. Mass Supply and Mass Capture

Owing to the reason mentioned above, there arises a phase delay between the moment of the maximum azimuthally-averaged mass flux and that of the maximum mass-capture rate. We next show how the mass-capture rate and the averaged mass flux vary with binary orbital motion. To reduce the fluctuation noise, these data are folded on the orbital period over \(40 \leq t \leq 60\) after the system is the quasi-steady state (\(t \geq 38\)).

The lower-left panel of Fig. 8 shows the azimuthally averaged mass flux at the (2,1) corotation radius in model 2. While the circumbinary disk has an outward flow from the periastron passage to the phase somehow before apastron, the mass is inwardly launched from the disk-inner edge from the phase somehow before apastron to the next periastron. This also supports that the gap is opening after the periastron and the gap is closing after the apastron in the eccentric binary.

The lower-right panel of Fig. 8 represents the orbital-phase dependence of the mass-capture rate and the corresponding luminosity normalized Eddington luminosity with total black hole mass \(10^8 M_\odot\); i.e., \(L_E \sim 10^{46}\) erg s\(^{-1}\), in model 2. Despite the fact that we continuously inject mass to the circumbinary disk at a rate of \(M_{\text{inj}} = 1.0 M_\odot \text{yr}^{-1}\), which would produce about the Eddington luminosity for \(\eta \sim 0.1\), the calculated luminosity is substantially sub-Eddington. This is because the majority of the injected mass is lost in this system. The solid line and dashed line denote the mass-capture rate by the primary black hole and by the secondary one, respectively. This figure clearly shows that the mass-capture rate significantly modulates with the orbital motion. The peak of mass-capture rate is located in before the periastron passage. Furthermore, the ratio of the lowest mass-capture rate to the highest one during one orbital period is \(\sim 1/10\).

In the context of the young binary star formation, a couple of simulations with the similar mass ratio and orbital eccentricity as those of model 2 were performed by Artymowicz & Lubow 1996a and Günther & Kley 2002. They are the non-dimensional, high-eccentricity system with \((q,e) = (1.27,0.5)\) by Artymowicz & Lubow 1996a and AK Sco system with \((q,e) = (0.987 \pm 0.007, 0.469 \pm 0.004)\) by Günther & Kley 2002, respectively. The orbital modulation of mass accretion rates in both cases are well corresponding to that of model 2. The ratios of the lowest mass accretion rate to the highest one are the factor 7-8, which is lower than that of model 2 because of their smaller accretion radii.

For comparison purpose, we give the same but for model 1 in the upper panels of Fig. 8. This figure clearly represents that the circumbinary disk continues to supply the gas to its inner regions over the whole orbital period. Then, the gas falls onto each black hole with fluctuations. This behavior is mainly caused by the overflow as seen in the last two panels of Fig 2.

4.4. Unequal Masses

Finally, we discuss the cases of unequal mass black holes (models 3 and 4). The most common binaries are likely to possess black holes with extreme mass ratios in the case of the minor galactic mergers (Armitage & Natarajan 2002; Armitage & Natarajan 2005). If the binaries are formed as a result of a major merger, on the contrary, its mass ratio can be non-extreme and slightly deviate from
The effects of non-extreme but unequal masses on the accretion flow onto the supermassive BBHs are investigated by models 3 and 4 and are remarkably represented by the azimuthally averaged mass flux and the mass-capture rate by each black hole in Fig. 9.

Model 3 is the run with \((q,e) = (0.5, 0.0)\). It is seen from the upper panels of Fig. 9 that the mass-capture rate of the secondary black hole is much higher than that of the primary one. This is because the distance between the inner edge of the circumbinary disk and the \(L_2\) point is shorter than that between the disk inner edge and \(L_3\) point. Thus, the gas prefers to be attracted from the secondary black hole closer to the \(L_2\) point than the primary one. Here, note that the total mass-capture rate by both black holes roughly equals to the azimuthally averaged mass flux.

In model 4, which is run with \((q,e) = (0.5, 0.5)\), the lower panels of Fig. 9 indicates that the rising time of the secondary burst is earlier than that of the primary burst (burst in gas accretion onto the primary black hole). Thus, the amount of gas captured by the secondary black hole during one orbital period is more than that by the primary black hole. This is consistent with the results of model 3, i.e., the gas is easier to be captured by the secondary black hole.

5. Discussion

We have performed the SPH simulations of accretion flow around the supermassive BBHs. We find that the material overflows from the circumbinary disk via two points, freely infalls towards either of the BBHs, and is eventually captured by it. While the mass capture-rate has little orbital-phase dependence in the case of a circular binary, it exhibits significant orbital modulations in the case of an eccentric binary. In this section, we discuss the formation and evolution processes of the circumblack-hole disks, circumbinary disk evolution, shock formation near the circumblack-hole disks, and possible strategy to detect such BBH candidates exhibiting periodic light variations.

5.1. Circumblack-hole Disks

We have already discussed in section 3.4 a possibility of the formation of the circumblack-hole disks and estimated their viscous timescales at the circularization radii. In this section, we discuss whether the circumblack-hole disks are persistent or not during one orbital period and how viscous accretion processes affect the evolution and structure of the circumblack-hole disk.

Table 2 summarizes the mean mass-capture rates, the mean circularization radii, and the mean viscous timescales of all the calculated models. To reduce the fluctuation noise, the simulation data are folded on the orbital period over \(20 \leq t \leq 40\) in models 1 and 3, and over \(40 \leq t \leq 60\) in models 2 and 4. The second and the third columns denote the mean mass-capture rates of the primary and the secondary black holes, respectively. These columns clearly show that the sum of the mean mass-capture rates by the BBHs in the circular binaries is higher than that in the eccentric binaries. This implies that the circumblack-hole disks in the circular binaries are denser than those in the eccentric binaries.

We see from the fourth column and the fifth column of Table 2, which denote the mean circularization radii around each black hole, that the size of the circumblack-hole disks in the circular binaries is larger than that in the eccentric binaries. In model 3, the disk size of the secondary black hole, \(R_{\text{circ},s} = 0.42a\), is larger than the accretion radius, \(r_{\text{acc}} = 0.2a\). This means that some of the mass which enters the sphere of \(r_{\text{acc}} = 0.2a\) may finally go out, without being captured by the black hole.

For comparison with model 1, we’ve performed the other simulation model with the initially more extended circumbinary disk; the disk-inner edge 1.68a and the...
Fig. 8. Orbital-phase dependence of azimuthally averaged mass flux and mass-capture rate in models 1 (upper panels) and 2 (lower panels), respectively. The binary is at the periastron (apostron) at phase 0.0 (0.5). The data are folded on the orbital period over $20 \leq t \leq 40$ in model 1 and over $40 \leq t \leq 60$ in model 2. The mass flux is measured at the tidal truncation radius $r_{\text{trunc}} = 1.68a$ in model 1 and at the $(2,1)$ corotation resonance radius $r_{\text{trap}} \simeq 1.59a$ in model 2, respectively. The right axis shows the bolometric luminosity corresponding to the mass-capture rate with the energy conversion efficiency, $\eta = 0.1$, normalized by the Eddington luminosity with total black hole mass $M_{\text{bh}} = 1.0 \times 10^8 M_\odot$, where $\eta$ is defined by $L_{\text{acc}} = \eta \dot{M}_{\text{cap}} c^2$.

Table 2. Summary of simulation results The first column represents model numbers. The second column and the third column are the mean accretion rates of the primary black hole and those of the secondary black hole, respectively. The fourth column and the fifth column are the mean circularization radii of the primary and those of the secondary, respectively. The last two columns are the mean viscous time-scales of the primary black hole and of the secondary black hole, respectively. All quantities shown in the 2-7th columns are folded on the orbital period over $20 \leq t \leq 40$ in models 1 and 3, and $40 \leq t \leq 60$ in models 2 and 4.

| Model | $\langle M_p \rangle$ | $\langle M_s \rangle$ | $\langle R_{\text{circ},p} \rangle$ | $\langle R_{\text{circ},s} \rangle$ | $\langle t_{\text{vis},p} \rangle$ | $\langle t_{\text{vis},s} \rangle$ |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1     | $5.6 \times 10^{-2}$ | $5.7 \times 10^{-2}$ | $1.5 \times 10^{-1}$ | $1.5 \times 10^{-1}$ | $2.7 \times 10^4$ | $2.7 \times 10^4$ |
| 2     | $3.8 \times 10^{-2}$ | $3.8 \times 10^{-2}$ | $8.1 \times 10^{-2}$ | $8.5 \times 10^{-2}$ | $2.0 \times 10^4$ | $2.0 \times 10^4$ |
| 3     | $5.5 \times 10^{-2}$ | $1.8 \times 10^{-1}$ | $1.0 \times 10^{-1}$ | $4.2 \times 10^{-1}$ | $2.6 \times 10^4$ | $3.7 \times 10^4$ |
| 4     | $1.7 \times 10^{-2}$ | $2.1 \times 10^{-2}$ | $7.7 \times 10^{-2}$ | $8.4 \times 10^{-2}$ | $2.1 \times 10^4$ | $1.6 \times 10^4$ |
disk-outer edge 2.0a where the mass is injected (see Section 3.3). Although the circularization radii are less than half those of model 1, our conclusion regarding the formation of circumblack-hole disks is unchanged.

The last two columns of Table 2 represent the mean viscous time-scale of the primary black hole and of the secondary one, respectively. These are estimated by using equation 13 and 13. It is clear from these columns that the viscous time-scale is much longer than the orbital period in all the models. Thus, the circumblack-hole disks once formed, they will survive over the whole orbital phase. The viscosity in the circumblack-hole disks gives little influence on their structure and short-term evolution on the timescale of the order of the orbital period.

The phase-dependent accretion flows are likely to give a good impact on the outer edge of the circumblack-hole disks. This will be able to excite one-armed oscillations on the disk (e.g., Hayasaki & Okazaki 2005). As the one-armed waves propagates, the material on the outer region of the disk is inwardly pushed towards the central black hole. Since the propagation time-scale is roughly estimated by using $\left(\frac{\alpha_{SS}}{2\pi}\right)\tau_{vis}$, where $\tau_{vis}$ is the viscous time-scale of circumblack-hole disks (see Kato et al. 1998), as $\sim 10^{2-3}P_{orb}$, the outer region of the disk can significantly vary, whereas the inner region of the disk may remain to be unchanged. We thus expect that optical/IR radiation emitted mainly from the outer portions will exhibit significant periodic variations, whereas radio and X-ray emissions coming from the innermost region may not show such periodic and coherent variations (however, see the later Section 5.3). If this is the case, the spectral energy distributions (SEDs) will be highly time-variable on the orbital timescale.

It is likely that the mass exchanges occur via an effective L1 point between the disks around the primary and secondary black holes (e.g. Günther & Kley 2004). In addition to the phase-dependent mass inflow from the circumbinary disk, this mass exchange could also affect the evolution and structure of circumblack-hole disks. This effect cannot be treated in our simulations, however, because of the lack of sufficient resolution in the narrow region around the effective L1 point.
The right-upper (lower) panels of Fig. 8 and Fig. 9, also demonstrate that the mass-capture rate is about one-order of magnitude as low as the mass-input rate in all the models. In fact, the total mass of circumblack-hole disks, which approximately equals to the total mass captured by black holes $M_{\text{CBHDs}}$, is much lower than the mass of circumbinary disk, as shown in Fig. 4. This strongly suggests that the circumblack-hole disk has a significantly low density. Thus, we expect that the accretion flow should become radiatively inefficient in the vicinity of black holes (Kato et al. 1998).

5.2 Circumbinary Disks

We address a question; what happens if the circumbinary disk is inclined from the orbital plane of the supermassive BBHs? The mass-capture rate profile may show a two-peaked feature, because there are a couple of points in the disk-inner edge to which the BBHs approach during one orbital period. In fact, the double-peak structure is observed in the optical outbursts of OJ287 (Stothers & Sillanpää 1997). The effect of the inclination angle on the mass-capture rate profile will be also examined in a subsequent paper.

MacFadyen & Milosavljević (2006) asserted that the mass supply rate from the circumbinary disk to the BBHs exhibits a quasi-periodic modulation due to the eccentricity of the circumbinary disk, even if the binary black hole has circular orbit. The disk eccentricity is excited due to the resonance interaction between the circumbinary disk and the central binary after a few viscous time-scale of the circumbinary disk. Such a long-term evolution of the circumbinary disk could also give the time variations of the light curve of circumbinary disk itself, such as a super-lump phenomenon in Dwarf Novae systems (e.g., Murray 1998).

The circumbinary disk evolution could play a key role to resolve the loss-cone problem (e.g., Artymowicz 1998; MacFadyen & Milosavljević 2006). The disk-binary interaction gives an influence on the global evolution of the binary orbital elements, e.g., the eccentricity, the semimajor axis, the mass-ratio, the inclination angle and so on (Artymowicz et al. 1991; Bate & Bonnell 1997; Lubow & Artymowicz 2000). In the framework of the disk-binary interaction, therefore, the effects of all the orbital elements should ideally be taken account of.

In addition, it is an open problem how the gas is supplied from an outer region over several parsec to an inner, subparsec region, in the context of the supermassive BBH systems in merged galactic nuclei. The mass supply to the circumbinary disk may prevent the accretion rate from decreasing due to the viscous diffusion of the surface density. Although this viscous diffusion could be neglected in such a short-term evolution as our simulations, it should be taken account of in the mass inflow processes in the long-term evolution of the circumbinary disk over the viscous time-scale. The long-term evolution of the circumbinary disk remains as a matter to be discussed further.

Fig. 10. Orbital dependence of the radial velocity normalized by the free-fall velocity at the inner boundary, $r_{\text{acc}} = 0.2a$.

5.3 Shock Formation

Another important issue to be considered is a possible formation of shock structure. We measured the radial velocity at the inner boundary $r_{\text{acc}} = 0.2a$ in model 2 and plot its orbital-phase dependence in Fig. 10. Here, the radial velocity is normalized by the free-fall velocity. We understand that the radial velocity is on the same order of magnitude of the free-fall velocity and that it suffers the orbital modulation with the peak being around the apastron (phase 0.5). This trend contrasts with that of the mass-capture rate which exhibits a peak around the periastron (see Fig. 8). If the material infalls near circumbinale-hole disk, shock structures could be formed near the outer edge of the circumbinale-hole disks. Substantial fraction of the kinetic energy of the material will be converted to the thermal energy. Consequently, detectable soft X-rays or UV could be periodically emitted from the shock structures. Such X-rays or UV will exhibit a broad peak around phase $\sim 0.5$, whereas optical/IR radiation will show a sharp peak around phase $\sim 0.0$.

5.4 Observation Implications

Sillanpää et al. (1988) firstly proposed that the periodic behavior of the optical light-curve of OJ287 may be induced by the orbital motion of the binary black holes, that is, the tidal perturbation of the secondary black hole causes the accretion rate of the primary black hole to be enhanced. Although a number of models has been proposed during the last two decades since then (Lehto & Valtonen 1996; Katz 1997; Valtasoria et al. 2000), no widely accepted mechanism has been yet proposed for the behavior of periodic outbursts in OJ287. Furthermore, several quasars are known often to show periodic outbursts similar to those in OJ287. The existence of supermassive BBHs has been also suggested for these sources,
for example, 3C75 (Yokosawa & Inoue 1985), 3C279 (Abraham & Carrara 1998), PKS 0420-014 (Britzen et al. 2001) and 3C345 (Lobanov & Roland 2005). Such periodic behaviors in the observed light curves of these sources could be also explained by our scenario i.e., the outbursts are driven by the orbital eccentricity of BBHs in three-disk systems, as shown in the lower right panel of Fig. 8 and Fig. 9.

Multiwavelength long-term monitoring observations should be a powerful tool to probe the existence of the circumbinary disk, as well as that of supermassive BBHs. As described in Section 5.1, the photons emerging from the inner region of the disk exhibits different SEDs and time variations from those emerging from the outer region. In addition, it is expected that the shock-induced radiation should also show periodic variations at different phases from those of SEDs, as seen in Fig. 10. If we detect periodic time variations of SEDs with the different behavior at different wavelengths, it provides the strong observational evidence for the existence of supermassive BBHs in three-disk systems on a parsec/subparsec scale of the galactic center.

Finally, we give a remark on the quasi-periodicities in the light curves. These are often found in the blazar light curves (see, e.g., Kataoka et al. 2003). In this context, it is interesting to note that Negoro, Mineshige (2002) have found quasi-periodic light variations through the analysis of X-ray intensity variations from Cygnus X-1. It is well known that its X-ray curves are composed of numerous shots (or mini-flares) with a variety of flare amplitudes. By picking up only large shots they found that the light variations follow log-normal distribution. That is, if only large flaring events in the accretion flow produce blob outflow in the form of a jet, jet light curves will be quasi-periodic. This gives another possibility to produce quasi-periodicities in blazar light curves. Much more work is desirable both theoretically and observationally in this area.

6. Conclusions

For the purpose of providing the observable diagnosis to probe the existence of supermassive BBHs on a subparsec scale in merged galactic nuclei, we have carried out the SPH simulations of accretion flows from circumbinary disks onto the supermassive BBHs. Our main conclusions are summarized as follows:

(1). There are two-stage mechanisms to cause an accretion flow from the circumbinary disk onto the supermassive BBHs: First, the gas is guided to the two closest points on the circumbinary disk from the black holes by the tidal deformation of the circumbinary disk. Then, the gas is increasingly accumulated on these two points by the gravitational attraction of the black holes. Second, when the gas can pass across the maximum loci of the binary potential, the gas overflows via these two points and inspirals onto the black holes with the nearly free-fall velocity.

(2). In circular binaries, the gas continues to be supplied from the circumbinary disk onto the supermassive BBHs (i.e. the gap is always closed).

(3). In eccentric binaries, the material supply undergoes the periodic on/off transitions with an orbital period because of the periodic variations of the binary potential.

(4). While the mass-capture rates exhibit little orbital phase dependence in circular binaries, they significantly modulate with the orbital phase due to the gap opening/closing cycles, in eccentric binaries. This could provide the observable diagnosis for the presence of supermassive BBHs in three-disk systems at the galactic center.

(5). The circumbinary disks are formed around each black hole regardless of the orbital eccentricity and the mass ratio.

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