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The mass ratio distribution of MBH binaries in the hierarchical model *

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Abstract We present different mass ratio distributions of massive black hole (MBH) binaries due to different mechanisms involved in binary evolution. A binary system of MBHs forms after the merger of two galaxies, which has three stages: the dynamical friction stage, the stellar scattering or circumbinary disk stage, and the gravitational radiation stage. The second stage was once believed to be the "final parsec problem" (FPP) as the binary stalled at this stage because of the depletion of stars. Now, the FPP has been shown to no longer be a problem. Here we get two different mass ratio distributions of MBH binaries under two mechanisms, stellar scattering and the circumbinary disk interaction. For the circumbinary disk mechanism, we assume that the binary shrinks by interaction with a circumbinary disk and the two black holes (BHs) have different accretion rates in the simulation. We apply this simple assumption to the hierarchical coevolution model of MBHs and dark matter halos, and we find that there will be more equal-mass MBH binaries in the final coalescence for the case where the circumbinary mechanism operates. This is mainly because the secondary BH in the circumbinary disk system accretes at a higher rate than the primary one.

Key words: cosmology: theory — black hole physics — galaxies: interaction

1 INTRODUCTION

The coevolution of massive black holes (MBHs) and their host galaxies remains one of the main unsolved problems in studies of cosmic structure formation. However, it is well accepted that the evolution of MBHs is related to their host galaxies (Richstone et al. 1998; Ferrarese 2002). In the standard paradigm of structure formation in the Universe, mergers between galaxies appear to be frequent over the course of galaxy evolution. MBHs are driven into the center of a newly formed galaxy by mergers and then form binary systems. According to observations, we know that the BL Lacertae object OJ 287 has produced quasi-periodic optical outbursts for the last hundred years. The model for OJ 287 incorporates a smaller black hole (BH) crossing the accretion disk of a larger BH during its eccentric binary orbit (Lehto & Valtonen 1996). A binary active galactic nucleus (AGN) in the ultraluminous infrared galaxy NGC 6240 was discovered using the *Chandra X-Ray*

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Observatory by Komossa et al. (2003). In the radio galaxy B0402+679, high resolution radio imaging has revealed two radio-loud nuclei – a massive binary BH system with a projected separation of only 7.3 pc (Rodriguez et al. 2006). Wen et al. (2009) has identified 249 merging galaxies by searching for interaction features from luminous early-type galaxies released by the Sloan Digital Sky Survey (SDSS). 245 paired AGNs with unambiguous tidal features have been identified from the Seventh Data Release of SDSS (Liu et al. 2011). It is also believed that a few AGNs with double-peaked profiles of [O III]$\lambda\lambda$5007, 4959 and other narrow emission lines could be candidates of paired AGNs (Zhou et al. 2004; Wang et al. 2009; Smith et al. 2010; Fu et al. 2011; Yu et al. 2011).

The dynamical evolution of an MBH binary mainly consists of three stages (Begelman et al. 1980). At first the BHs migrate toward the center of the newly formed galaxy within a characteristic dynamical friction timescale. At the second stage, interactions with the surrounding stars or gas bring the MBHs into a bound orbit around each other to form a binary. Early on, it was believed that, theoretically, the binary will decay due to repeated gravitational slingshot interactions with stars, and finally coalescence occurs because of the fast gravitational radiation. However, as the surrounding stars are depleted, binaries with mass $10^6 \sim 10^7 M_\odot$ will stall at separations of 0.01∼1 pc (Milosavljević & Merritt 2001; Yu 2002). This is known as the final parsec problem (FPP). One approach to solve the FPP is to consider a more realistic situation in a galaxy merger, but only use a mechanism that relies on stellar dynamics. More and more numerical simulations have shown that the flatness or triaxial non-axisymmetry of galaxies could help to solve the FPP because a significant fraction of stars with centrophilic orbits could efficiently drive a binary close enough to coalesce (Yu 2002; Berczik et al. 2006; Berentzen et al. 2008; Preto et al. 2011; Khan et al. 2011; Iwasawa et al. 2011; Khan et al. 2012a,b; Gualandris & Merritt 2012; Khan et al. 2013). The other approach depends on gas being funneled into the galaxy centers as the merger of galaxies occurs. Strong gas inflows due to tidal torques produce nuclear disks. A gas disk forms around the rapidly formed MBH binary, then becomes efficient in helping transfer angular momentum out of the binary, and finally drives the binary to coalesce (Artymowicz & Lubow 1996; Gould & Rix 2000; Escala et al. 2005; Ioka & Mészáros 2005; Dotti et al. 2006; MacFadyen & Milosavljević 2008; Hayasaki et al. 2008; Mayer et al. 2008; Cuadra et al. 2009; Lodato et al. 2009; Roedig et al. 2011, 2012; Kocsis et al. 2012; Amaro-Seoane et al. 2013). In a steady, geometrically thin and self-gravitating disk model, the timescale of orbital decay is short enough for massive binaries ($M_{\rm bh} > 10^7 M_\odot$) to merge. In simulations these researchers also found that the accretion rate of the secondary BH is larger than that of the primary BH (Artymowicz & Lubow 1996 and Hayasaki et al. 2008). Because of the different accretion rates of the two BHs in the circumbinary phase, the mass ratio will tend toward unity during the interaction of the binary with the gas disk (Artymowicz & Lubow 1996).

In the evolution of MBH binaries, the eccentricity e and the mass ratio p are two important factors. Triaxial galaxies provide enough stars to binaries to avoid stalling and tend to increase the eccentricities of the MBH binaries. The high eccentricities in a way assist the MBH binaries to coalesce through gravitational wave radiation. Roedig et al. (2011) show that there exists a limiting eccentricity $e_{\rm crit}$ with a value in the interval [0.6, 0.8] in cases of subparsec (sub-pc) MBH binaries surrounded by self-gravitating gas disks. MBH binaries in triaxial galaxies have and keep high eccentricities up to $e \sim 0.95$ (Khan et al. 2012a; Preto et al. 2011). However, Khan et al. (2013) show that MBH binaries in mildly flattened galaxies all have quite low eccentricity.

The FPP could still show up in minor mergers of galaxies, in which MBH binaries have low mass ratios that are less than 0.1. In cases with $p > 0.1$, the hardening rates are essentially independent of the mass ratio p (Khan et al. 2012b). The initial 1:10 mass ratio of the binary can change significantly due to the fact that the secondary is fed at a higher rate, from a kpc separation to a pc scale (Khan et al. 2012a; Callegari et al. 2011). There are still a lot of uncertainties related to the evolution of MBH binaries, as well as the environment where mergers occur. Here we assume two situations in the simulations. In the first case, we assume that the binary shrinks to the gravitational wave radiation stage purely by stellar scattering in a non-spherical structure. In the other, we assume that the binary shrinks to the final stage by the interaction with a circumbinary disk and the secondary MBH has a higher accretion rate. Then we compare the mass ratio distributions of these two situations in the hierarchical coevolution model of MBHs and dark matter (DM) halos.

In this paper, we describe the hierarchical coevolution model of MBHs and DM halos. The physics and assumptions used in the simulations are described in Section 2. In Section 3, we give results of the mass ratio distributions of MBH binaries. We also try to compare the theoretical mass ratio distributions to the observational mass ratio distribution of the interacting galaxies from Wen et al. (2009). Finally, Section 4 summarizes and discusses the results. Throughout, we work in a flat cold DM model with a cosmological constant (ΛCDM) cosmology using cosmological parameters as follows: $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $\Omega_{\rm b}h^2 = 0.02$, $\sigma_8 = 0.93$ and $n = 1$. Here h is defined by $H_0 = h \times 100\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

2 HIERARCHICAL GROWTH MODEL OF MBHS AND DM HALOS

In this section, we use a Monte Carlo method to build up the growth and coevolution of MBH and DM halos over cosmic time under the hierarchical structure formation scenario in a ΛCDM cosmology. The algorithm is the same as that described in Volonteri et al. (2003a). From redshift $z = 20$ to the present, we create the merger history of 220 present-day halos with mass range $10^{11} < M_{\rm halo} < 10^{15}$ based on the extended Press-Schechter formalism (Lacey & Cole 1993; Cole et al. 2000). Theoretically, we assume that seed BHs in the prototype galaxies that formed at high redshift are the results of the collapse of Pop III stars. Then they follow the merger of halos, migrate into the galaxy centers by dynamical friction and accrete gas after a series of major mergers. Since most galaxies contain BHs at their centers, it is natural to form a BH binary as the satellite halo merges with a larger host. The MBH evolution history and accretion models are described in the following subsections.

2.1 The Growth of a Single MBH

In the simulation we use the light BH seed model as the seed BHs, the so-called VHM scenario (Volonteri et al. 2003a, 2006). Seed BHs with masses of $150\,{\rm M_\odot}$ are placed in the highly biased $3.5\,\sigma$ halos in the simulations at $z = 20$. They are the remnants of the metal free Pop III stars at $z \sim 20$.

Major mergers of DM halos trigger gas accretion onto the MBHs. The criterion of a major merger is set to be $M_{\rm s}/M_{\rm p} \geq 0.3$ for the mass ratio of merger halos. $M_{\rm s}$ and $M_{\rm p}$ are masses of the secondary and primary halos respectively. After mergers of DM halos (major mergers), MBHs in the galaxy centers begin to accrete gas at the Eddington accretion rate. The MBHs will keep accreting until their behavior can be described by the MBH mass and bulge stellar velocity dispersion relation, also called the $M_{\rm BH} - \sigma_*$ relation, which is regulated by feedback from star formation, and radiation and outflows of AGNs. The $M_{\rm BH} - \sigma_*$ relation for the local galaxies used here is given by Gültekin et al. (2009) as follows

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = 8.12 + 4.24\log\left(\frac{\sigma_*}{200{\rm km\,s^{-1}}}\right). \tag{1}$$

This relation is generally extrapolated to be suitable for all galaxies at any arbitrary redshift.

For major mergers, MBHs start to accrete gas after a dynamical friction time for galaxy mergers to occur (Binney & Tremaine 1987). When gas is accreted from the innermost stable circular orbit (ISCO) in a standard thin disk (SSD), the BH spin a changes with the mass M growth as follows (Bardeen 1970; King & Pringle 2006),

$$\frac{x}{x_0} = \left(\frac{M_0}{M}\right)^2, \tag{2}$$

$$a = \frac{x^{1/2}}{3}\left[4 - (3x - 2)^{1/2}\right], \tag{3}$$

in which $r = xc^2/GM$ is the radius of the ISCO expressed in Boyer-Lindquist coordinates. The radiation efficiency ϵ (or mass-to-energy conversion efficiency) of a BH with spin a is given by,

$$\epsilon = 1 - \left[1 - \frac{2}{3x}\right]^{1/2}. \tag{4}$$

From Equation (3) and Equation (4) we know that a Schwarzschild BH ($a = 0$) has a much lower radiation efficiency $\epsilon = 0.057$, while a Kerr BH has $\epsilon \sim 0.4$. We can define $f_{\rm Edd}$, the accretion ratio,

$$f_{\rm Edd} \equiv L/L_{\rm Edd}\,, \tag{5}$$

where $L_{\rm Edd} = 4\pi M_{\rm BH}\mu_e m_{\rm p} c/\sigma_T \approx 1.3\times10^{46}\mu_e M_8\ {\rm erg\ s^{-1}}$ is the Eddington luminosity, with $\mu_e, m_{\rm p}, \sigma_T, M_8$ being the mean molecular weight per electron, the proton mass, Thomson cross section, and $M_{\rm BH}$ in the unit of 10^8 solar masses respectively. The mass growth of an MBH is restricted by the radiation efficiency and the accretion ratio according to the following equation

$$M_{\rm BH}(t) = M(0)\exp\left(\frac{1-\epsilon}{\epsilon}\frac{f_{\rm Edd}}{\tau_{\rm Edd}}t\right), \tag{6}$$

where $\tau_{\rm Edd} \equiv M_{\rm BH}c^2/L_{\rm Edd} \sim 0.45\mu_e^{-1}{\rm Gyr}$ is the characteristic Salpeter timescale, which is independent of $M_{\rm BH}$. The mass and spin growth of an MBH is governed by Equations (2), (3), (4) and (6) for both possible accretion scenarios of MBHs with retrograde or prograde motion in the accretion disk.

Shapiro (2005) used the results of relativistic magnetohydrodynamical (MHD) simulations of disk accretion onto Kerr BHs to track the coupled evolution of the masses and spins of the BHs. They showed that MHD disks tend to drive BHs to a sub-maximal equilibrium spin rate of $a \sim 0.95$ and radiation efficiency $\epsilon \sim 0.2$. The spin evolution in terms of a nondimensional quantity $s = s(a)$ is given as follows

$$\frac{{\rm d}a}{{\rm d}t} = \frac{f_{\rm Edd}}{\epsilon}\frac{s}{\tau_{\rm Edd}}, \tag{7}$$

$$s = 3.14 - 3.30a \quad \text{(MHD disk)}. \tag{8}$$

We compared the mass and spin evolution of a BH between two theories, the SSD and MHD theories, assuming that they have the same accretion rate. The spin grows slower, but the mass grows faster under the MHD theory than under the SSD theory. Not only does the spin in the MHD case grow slower, but it also has a smaller upper limit of 0.95 (Shapiro 2005).

To make sure our simulations represent the actual growth of MBHs in galaxy centers, we need to get the luminosity function of active MBHs. In our simulations, the bolometric luminosity of an active BH is $L_{\rm bol} = f_{\rm Edd}\cdot L_{\rm Edd} = (\frac{1}{\epsilon}-1)\dot{M}_{\rm BH}$. We count active BHs at the redshift intervals, and weight each of them according to the Press-Schechter function. The blue band luminosity is $L_{\rm B} = f_{\rm B}\cdot L_{\rm bol}$, where $f_{\rm B} = 0.08$ is the conversion factor between blue band luminosity and bolometric luminosity (Fanidakis et al. 2011).

When a disk forms around an MBH, the MBH could align (prograde disk) or anti-align with the disk (retrograde disk) (King & Pringle 2006; King et al. 2008). We studied both prograde disk and retrograde disk scenarios. We found that a prograde MHD disk works quite well, as the luminosity functions from the simulation are in good agreement with the observational data (Croom et al. 2004) in different redshifts; the results are shown in Xu & Yuan (2012). Therefore, for a single MBH activity, we use the spin and mass evolution from the MHD results and assume that accretion disks are always prograde with respect to the MBHs in the following calculations.

2.2 The Evolution of MBH Binaries

When two halos merge, the MBHs are driven to the central regions through the dynamical friction mechanism (Binney & Tremaine 1987). Eventually, an MBH binary forms at the center of the new halo. The dynamical friction will become weak and inefficient in driving the binary closer when they get into each other's gravitational influence radius. This is called the hardening stage. There are two solutions to this subsequent evolution of the hardened binary. One is through the three-body interactions in which the binary captures passing stars and ejects them with much higher velocities in triaxial non-axisymmetric galaxies (Berczik et al. 2006; Khan et al. 2011). Triaxial galaxies provide enough stars with centrophilic orbits to avoid binary stalling. The "gravitational slingshot" mechanism shrinks the hardened binary. We assume the stellar cores are preserved during galaxy mergers (Volonteri et al. 2003b). Finally the binary shrinks to a radius where gravitational radiation takes over and two MBHs coalesce quickly afterwards. In the cases with unequal mass, the new MBH gets a recoil velocity because of the anisotropic emission of gravitational waves. If the recoil velocity exceeds the escape velocity for the halo, the MBH will become off-centered or wander nearby (Volonteri 2007). In this scenario that only involves stars, the mass ratio does not change after the hardening stage. The timescale of the stellar scattering stage used in this article is as follows,

$$t_{\rm ss} \sim 3.0 \times 10^{8}[{\rm yr}] \left(\frac{a_{\rm h}}{a}\right) \left(\frac{M_{\rm bh}}{10^{7}\, M_{\odot}}\right), \tag{9}$$

where a is the separation of the binary, $a_{\rm h}$ is the binary hardening radius (Begelman et al. 1980; Quinlan 1996), and $M_{\rm bh}$ is the mass of the binary, given by equation (7) in Hayasaki et al. (2010).

The other way for a binary to coalesce is through the interaction with the surrounding gas disk. The effects of the infalling gas have already been considered for the evolution that shrinks the binary as described in Begelman et al. (1980). As one of the promising mechanisms to solve the FPP, we applied it to our simulations. We assume that the binary does not stall at the hardening stage when the stellar scattering mechanism fails to shrink a binary with mass $M_{\rm bh} \geq 10^{7}\, M_{\odot}$. The interaction between the binary and the surrounding gas provides a way to extract energy and angular momentum from the binary. We assume the timescale of circumbinary interaction is as follows,

$$t_{\rm gas} \sim 3.1 \times 10^{8}[{\rm yr}] \frac{q}{(1+q)^2} \left(\frac{0.1}{f_{\rm Edd}}\right) \left(\frac{\epsilon}{0.1}\right). \tag{10}$$

Here $t_{\rm gas}$ is only dependent on the binary mass ratio q, the Eddington ratio $f_{\rm Edd}$ and the radiation efficiency ϵ. It is the characteristic timescale of orbital decay due to the binary interaction with a steady, axisymmetric, geometrically thin, self regulated, and self-gravitating circumbinary disk as described by equation (20) in Hayasaki et al. (2010). For MBH binaries, this timescale is less than the age of the Universe and short enough to coalesce. It has been demonstrated that more gas is accreted by the secondary BH in a binary system with a circumdisk. The secondary BH is closer to the gaseous disk and has a greater specific angular momentum. Therefore, the mass ratio of the binary tends toward unity (Artymowicz & Lubow 1996; Cuadra et al. 2009; Hayasaki & Mineshige 2008). For simplicity, here we assume the secondary BH accretes at a rate of $f_{\rm Edd} = 0.1$ with a radiation efficiency $\epsilon = 0.1$, and the primary BH does not accrete at all. When the binary becomes tightly bound, the binary orbit begins to shrink through the emission of gravitational radiation and quickly coalesces after a short time in the final stage (Peters 1964).

3 MASS RATIO DISTRIBUTIONS OF MBH BINARIES

We carry out two simulations by implementing two different dynamical processes within a comprehensive model that describes the coevolution of BHs and DM halos in a ΛCDM Universe. The mass of MBHs in the simulations grows mainly because of the accretion of gas through MHD disks.

The accretion rate is $f_{\rm Edd} = 1.0$ after a major merger of two halos. The activity will be turned off until the behavior of the MBH can be described by the $M_{\rm BH} - \sigma_*$ relationship. After the two MBHs merge as their host halos collide, they will go through three stages before the final coalescence: the dynamical friction stage, stellar scattering/circumbinary interaction stage, and the gravitational radiation stage. We studied two mechanisms involved in the second stage. For the first step, we assume that stellar scattering is the only process that operates in the second stage of the binary evolution. In the next step, we assume the interaction between the binary and a circumbinary disk dominates the orbital decay of binaries with mass $M_{\rm bh} \geq 10^7\,M_\odot$. The accretion rate and radiation efficiency for the secondary BH in the circumdisk scenario are set to $f_{\rm Edd} = 0.1$ and $\epsilon = 0.1$ respectively.

Merger trees that are based on 220 present halos cover the masses of interest and trace merger history of DM halos in a hierarchical cosmology. The comoving number density n_i of n objects of interest is scaled by the Press-Schechter weight $W^i_{\rm PS}$ (Sheth & Tormen 1999, 2002) as $n_i(z) = N_i \times W^i_{\rm PS}/N_t$, where N_i is the number of halos occupied by the objects of interest at some redshift and mass range, and N_t is the number of all halos at the same redshift and the same mass range. The MBH binaries are the ones that have just gone through a major merger, with a single MBH in each halo. A major merger means that the mass ratio of the host halos is greater than 0.1 (or 0.3) and the dynamical friction timescale is short enough for them to form a gravitationally bounded binary system. We count all binaries before and after the interaction with circumdisks in simulations at ten different mass ratio ranges and scale them by the Press-Schechter weight. Then we get the normalized distribution of MBH binaries as a function of the mass ratio q.

3.1 The Mass Ratio Distribution in Merging Galaxy Pairs

Before comparing the mass ratio distributions under different mechanisms in the second stage of evolution, we first show the mass ratio distributions of MBHs from observations. Wen et al. (2009) identified 249 mergers of close galaxy pairs with interaction features from SDSS 6. The MBH mass used here is estimated by the $M_\bullet - L$ relation ($M_\bullet$ is the MBH mass and L is the luminosity) given by Tundo et al. (2007)

$$\log M_\bullet = 8.69 - \frac{1.31}{2.5}(M_r + 22), \tag{11}$$

where M_r is the r band magnitude of paired galaxies that is listed in Wen et al. (2009). These merging galaxies are close pairs with projected separations $7 < r_{\rm p} < 50$ kpc and have clear interaction features at redshifts $z < 0.12$. It is believed that the MBHs in these galaxies are going to form MBH binaries. They can be treated as MBH binaries at the very first stage. The normalized mass ratio distribution of binaries from the galaxy pairs is shown as the solid line in Figure 1. Theoretically, the mass ratio of the binary does not change at the first stage (from kpc to pc separation), no matter what mechanism a MBH binary goes through at the second stage (from pc to sub-pc separation) of its evolution. We assume that there is no accretion activity from either MBH in the binary at the first stage. It appears weak as nuclear activities are likely to be triggered during the first stage, but we also know that only a small fraction of the paired MBHs are dual AGNs as suggested by observations (Liu et al. 2011; Yu et al. 2011). So theoretically, we could conclude that basically the mass ratio distribution of binaries with a separation on the scale of a pc is the same with that of binaries at kpc separations in simulations. Also, the stellar scattering or the interaction with a circumdisk happens at the second stage (sub-pc scale), so the mass ratio distribution can be compared with the observational ones. Although Callegari et al. (2011) assumed that the MBHs individually accrete from the gas within a smoothing length in their simulations of two galaxies merging from kpc down to the pc scale, it can be treated as individual activity for each BH and is not the case we consider here. Next we will compare it with the distributions from the theoretical result.

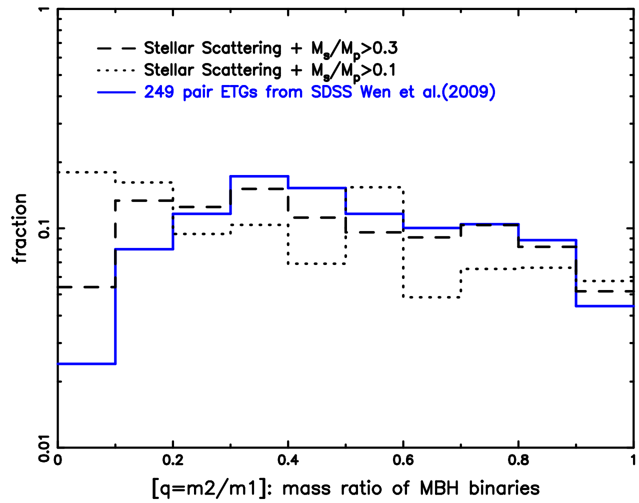

Fig. 1 Normalized mass ratio distribution of MBH binaries. The solid line is the distribution of 249 binaries that are considered to be pairs of merging galaxies (Wen et al. 2009). Dashed and dotted lines show mass ratio distributions of MBH binaries ($z < 1.0$) in models with only the stellar scattering mechanism. The dashed line is the distribution in the model with a major merger criterion of $p \geq 0.3$ and the dotted line that with a major merger criterion of $p \geq 0.1$.

3.2 Different Criteria of Major Mergers

We first carry out two sets of simulations with two different criteria for a major merger of halos. One is to set $M_{\rm s}/M_{\rm p} \geq 0.3$ for the mass ratio. The other is to set $M_{\rm s}/M_{\rm p} \geq 0.1$. Both of the simulations use the stellar scattering mechanism to shrink the binaries. However, the halo mass ratio is not the only factor deciding whether the merger of halos is a major merger or a minor merger. It is also decided by the dynamical friction timescale of the two halos to spiral into one new halo. If the dynamical time is too long for the two halos to merge together, it is not a major merger event even with a mass ratio $M_{\rm s}/M_{\rm p} \geq 0.1$. After the calculations, we compared the mass ratio distributions of MBHs redshifts $z < 1.0$ in the simulations, represented by the dashed and dotted lines in Figure 1, with the observation result. We can see that the mass ratio distribution of MBHs is related to the criterion for major mergers. There are more unequal mass MBH binaries in the case with a smaller value of major merger criterion. Comparing them with the observational data, we see that the mass ratio distribution of MBHs from the SDSS galaxy pairs is in good agreement with the theoretical result with a criterion $M_{\rm s}/M_{\rm p} \geq 0.3$ (the dashed line) in Figure 1.

3.3 The Change of Distributions due to Circumbinary Disks

In the simulation of galaxy mergers by Khan et al. (2012a) and Callegari et al. (2011), they found that the initial 1:10 mass ratio of a binary can change significantly due to the fact that the secondary is fed at a higher rate, from a *kpc* separation to a *pc* scale. That means the large scale evolution occurs in the first stage of the coalescence of an MBH binary, as described in the first section in this article. Here we check the change in mass ratio distributions of the MBH binaries due to the existence of circumbinary disks during the second stage of their evolution. We assume that the secondary MBH accretes from the circumdisk at a rate of $f_{\rm Edd} = 0.1$ and the primary MBH does not accrete. This paper is based on the fact that simulations indicate the mass ratio will tend toward unity during the

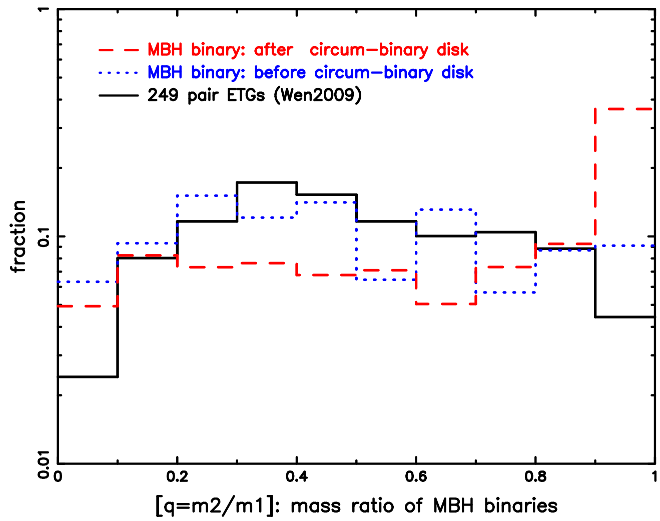

Fig. 2 Mass ratio distribution of MBH binaries. The solid line shows 249 binaries that are merging galaxy pairs (Wen et al. 2009). The dashed line shows the mass ratio distribution of MBH binaries ($z < 1.0$) after the interaction with circumdisks. The dotted line represents mass ratio distribution of MBH binaries ($z < 1.0$) before the interaction with circumdisks.

interaction of an unequal-mass binary with the gas disk (Artymowicz & Lubow 1996; Hayasaki et al. 2008). Here we check how the distribution of binary mass ratio is effected by this interaction. This is a simple toy model without other complex assumptions. The accretion rate $f_{\rm Edd} = 0.1$ of the secondary MBH in the binary system is 10 times smaller compared to the accretion rate $f_{\rm Edd} = 1.0$ of a single MBH after a major merger.

In Figure 2 we show the mass distributions of MBH binaries before and after the interaction with a circumbinary disk from our simulations. The dotted line is the mass ratio distribution of the binaries before their interaction with the circumbinary disk. The dashed line is the distribution after the interaction. The distribution is clearly shifted toward more equal-mass binaries because of the accretion of the secondary MBH. Theoretically, MBH binaries at this stage are hard to detect by modern telescopes as the separation is quite small, $a < 1$ pc. So far, the closest MBH binary is the radio galaxy B0402+679 with a projected separation of only 7.3 pc (Rodriguez et al. 2006). As technology advances, we hope that more and more close MBH binaries could be detected in the future. If circumbinary disks do exist in MBH binary systems and the secondary MBH does accrete at a higher rate, we could observe more equal-mass MBH binaries as indicated by the dashed line in Figure 2. We also investigate how important the accretion rates are to the mass ratio distribution. In the simulation we set the accretion rates for secondary and primary MBHs to $f_{\rm Edd,secondary} = 0.1$ and $f_{\rm Edd,primary} = 0.1/3$ respectively during the interaction with the binary and the circumdisk.

The mass ratio distribution for this set is shown as the dotted line in Figure 3. The solid line and dashed line represent the same quantities as in Figure 2. Even though both of the MBHs accrete during the circumbinary interaction stage with an accretion rate that is three times larger for the secondary MBH than the primary one, more equal-mass binaries are shown in the mass ratio distribution. So as long as the circumbinary interaction exists and the secondary MBH accretes at a higher rate, the mass ratio distribution will be different and have more equal-mass MBH binaries.

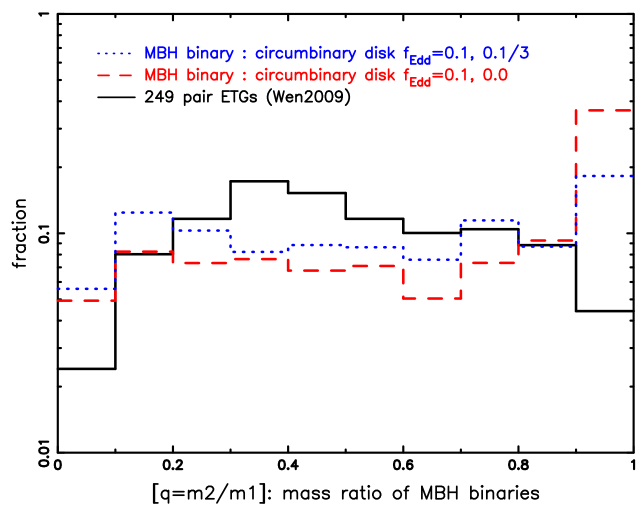

Fig. 3 Mass ratio distribution of MBH binaries. The solid line and dashed line are the same as in Fig. 2. The dotted line shows the mass ratio distribution of MBH binaries ($z < 1.0$) after the interaction with circumdisks, but the accretion rates of secondary and primary MBHs are $f_{\rm Edd,secondary} = 0.1$ and $f_{\rm Edd,primary} = 0.03$ respectively.

4 SUMMARY AND DISCUSSION

The FPP is not a problem anymore. It seems to have been solved by many authors (Yu 2002; Berczik et al. 2006; Dotti et al. 2006; Khan et al. 2011, 2013). Here we want to investigate which mechanism may be the actual one that shrinks binaries to the gravitational stage and where coalescence finally occurs. This approach may provide a way by studying the mass ratio distributions and be tested by observations. Here we simply show the mass ratio distributions of MBH binaries under two main mechanisms. We used a Monte Carlo method to build up the coevolution of MBH and DM halos under the hierarchical structure formation scenario in a ΛCDM cosmology.

Theoretical luminosity functions are compared with observations at different redshifts to make sure that they reproduce the growth history of MBHs. After constructing the coevolution model of MBHs and DM halos, we incorporated two mechanisms at the second stage of the binary evolution into the model. One is the pure stellar scattering mechanism of the MBH binaries in triaxial non-axisymmetric galaxies (Berczik et al. 2006; Khan et al. 2011). The other is the circumbinary disk mechanism that shrinks MBH binaries. We found that the mass ratio distribution of binaries under a pure stellar scattering mechanism is in good agreement with the distribution of MBHs in paired galaxies (Wen et al. 2009), with the major merger criterion of $M_{\rm s}/M_{\rm p} \geq 0.3$. With the presence of the circumbinary interaction, the mass ratio distribution will be different and have more equal-mass binaries. So, we expect different mass ratio distributions for different possible mechanisms in the history of the evolution of MBH binaries. Hopefully this can be demonstrated by observations with a future high resolution telescope. There is a lot physics that needs to be considered, such as the effects of eccentricity, and the possibilities of different timescales. All these effects may play an important role.

In this article we only study the effects of the circumdisk on the mass ratio distribution of MBH binaries with mass ratio close to 0.1 and > 0.1. Cases where the binaries have a mass ratio $\ll 0.1$ are not considered here because theoretically they usually do not occur in galaxy mergers. However, OJ 287 is a special case of a binary in a galaxy center with a mass ratio value of about 0.005, and

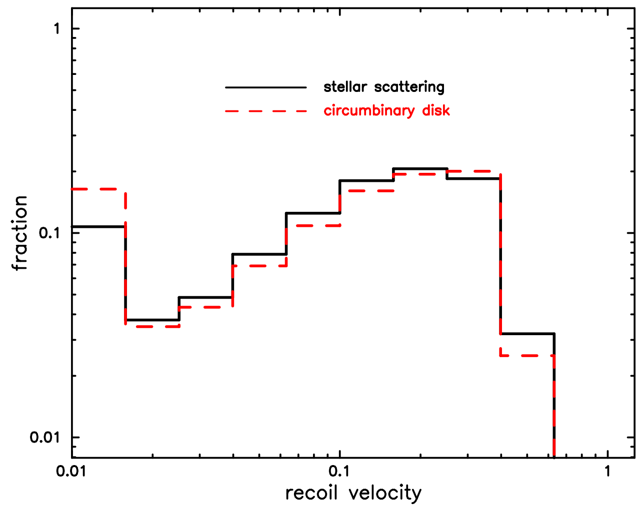

Fig. 4 The distributions of recoil velocity normalized to the bulge velocity dispersion in the host halo using the pure stellar scattering model (*solid line*) and circumbinary interaction model (*dashed line*). All values for the recoil velocity are below the escape velocity.

an accretion disk around the primary MBH. For OJ 287, the assumption we made in this article that the accretion rate of the secondary MBH is larger than the primary MBH is applied to MBH binaries with a mass ratio > 0.1. While the mass ratio of OJ 287 is quite small ($\ll 0.1$), it may not be a normal situation in galaxy mergers.

A recoil velocity will be gained as the final coalescence of the binary occurs due to asymmetry in the spins and masses. The final recoil velocity of unequal-mass systems will decide whether the final MBH could be ejected out of the galaxy center. In this study, we assume the gas material exerts a torque tending to align the spins as the binary evolves in a circumdisk. A minimum recoil velocity of the binary will be gained according to equations (10) and (11) in Rezzolla (2009). For simplicity, we also assume the spins of the MBHs are aligned with the orbital angular momentum in the pure stellar scattering model.

In Figure 4 we compare the recoil velocity of MBH binaries from the pure stellar scattering and the circumbinary disk scenarios. Figure 4 gives the normalized distribution of final MBH recoil velocities. The solid line is the distribution under the pure stellar scattering model. The dashed line gives the result from the circumbinary disk model. In general there are less MBHs with high velocities under the circumbinary disk scenario due to a decrease of the asymmetry in the masses of the binaries. None of the final MBHs has a high enough velocity to escape the halo potential in the simulation because we assumed the minimum recoil velocity for each coalescence and the effect of the eccentricity is ignored. The mass ratio distributions of MBH binaries and recoil velocities of the final MBH are essentially important for the detections of gravitational waves in the future (Gong et al. 2011).

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