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GRAVITATIONAL WAVES FROM MERGING INTERMEDIATE-MASS BLACK HOLES

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ABSTRACT

The discovery of an intermediate-mass black hole (IMBH) supports a runaway path of supermassive black hole (SMBH) formation in galactic nuclei. No concrete model to explain all the steps of this bottom-up scenario for SMBHs is yet known, but here we propose to use gravitational radiation to probe the merging history of IMBHs. Collisions of black holes of mass 10^3–10^6 $M_\odot$ will produce gravitational radiation of 10^{-1} to 10^2 Hz in their final merging phase. We assume that a thousand 10^3 $M_\odot$ IMBHs form a 10^6 $M_\odot$ black hole in each galaxy via two different merging histories—hierarchical growth and monopolistic growth—using a theoretical model of quasar formation having a peak at $z \simeq 2.5$. We find that there would be 22–67 IMBH merging events per year in the universe and that the event numbers of the two models apparently differ in the frequency of gravitational radiation. Most of the bursts by these events will be detectable by currently proposed space gravitational wave antennas, such as *LISA* or DECIGO. We conclude that the statistics of the signals would provide both a galaxy distribution and a formation model of SMBHs.

Subject headings: black hole physics — gravitational waves

1. INTRODUCTION

The discovery of an intermediate-mass black hole (IMBH; $\sim 10^3$ $M_\odot$) in the starburst galaxy M82 (Matsumoto et al. 2001; Matsushita et al. 2000) opens new possibilities for modeling supermassive black holes (SMBH) in the center of galaxies.

Ebisuzaki et al. (2001) proposed new possible scenario based on IMBHs. This SMBH formation scenario consists of three steps: (1) formation of IMBHs by runaway mergers of massive stars in dense star clusters, (2) accumulation of IMBHs at the center region of a galaxy due to sinkages of clusters by dynamical friction, and (3) mergings of IMBHs by multibody interactions and gravitational radiation. Successive mergings of IMBHs are likely to form a SMBH with a mass greater than 10^6 $M_\odot$. Numerical simulations support step 1 (Marchant & Shapiro 1980; Portegies Zwart et al. 1999, 2004; Portegies Zwart & McMillan 2002; Miller & Hamilton 2002; Holger & Makino 2003), and step 2 is confirmed by a realistic mass-loss model (T. Matsubayashi & T. Ebisuzaki 2004, in preparation), but the third step has not yet been investigated in detail. The recent discovery of a SMBH binary system (Sudou et al. 2003) also supports this formation scenario.

Today we know observationally that the population of quasars evolves on a cosmological timescale. At $z \simeq 2.5$, the comoving quasar number density was at maximum (McLure & Dunlop 2001; Rees 1990). It has been widely accepted that quasars are fueled by the accretion of gas onto SMBHs in the nuclei of host galaxies. Some observed images of quasars show that quasars exist in the spheroids of bulge and elliptical galaxies (Bahcall et al. 1997; McLure et al. 1999).

The growing massive black holes (BHs) produce lower frequency gravitational radiation than stellar mass BHs or other compact objects. As has already been reported by many authors, we can model the radiation process both in binaries of massive BHs (e.g., Thorne & Braginsky 1976; Carr 1980; Begelman et al. 1980; Fukushige et al. 1992; Haehnelt 1994) and in stellar objects orbiting around or falling into a massive BH (e.g., Shibata 1994; Hils & Bender 1995). These are plausible sources for space satellite laser interferometers such as *LISA* (*Laser Interferometer Space Antenna*; ESA 2000), which is now scheduled to be launched in 2011. We also note the recent proposal by Seto et al. (2001) of another space antenna for gravitational wave detection named DECIGO (Decihertz Interferometer Gravitational Wave Observatory).[3] *LISA* will target 10^{-4} to 10^{-1} Hz, while DECIGO will target 10^{-3} to 10 Hz, as we plot in Figure 1.

After the discovery of IMBHs, several authors pointed out the possibility of detecting gravitational waves from IMBHs (Flanagan & Hughes 1998; Ebisuzaki et al. 2001; Miller & Hamilton 2002; Miller 2002). Miller (2002) estimated the signal-to-noise ratio (S/N) and event rate in detail for systems with two black holes with total mass of 50–300 $M_\odot$. He concluded that the gravitational waves from such systems have $S/N \geq 10$ and an event rate of ~ 0.02 yr^{-1}, and systems with an IMBH and a stellar mass BH have an event rate of ~ 40 yr^{-1}. (Note that Will [2004], using updated estimates for the *LISA* noise curve and a correction to Miller's estimation for non–equal-mass binaries, has recently reported that the detection rates are expected to be much smaller [1/700].) Both *LISA* (or an extension of *LISA*) and LIGO II will be able to detect sources both in amplitude and event rate, although several uncertain processes still exist.

In this paper we discuss another aspect of the gravitational radiation from merger of IMBHs, based on the scenario by Ebisuzaki et al. (2001). We estimate the gravitational radiation

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[3] DECIGO project was proposed by Seto et al. (2001) as a direct way to measure the acceleration of the universe using observational statics of gravitational radiation from binary neutron stars. They argue that the optimal frequency is about ~ 0.1 Hz, which is between the target ranges of ground-based laser interferometers (such as LIGO, GEO, TAMA, LCGT) and that of *LISA*. They proposed a new satellite-type laser interferometer with one-tenth of the arm length of *LISA* and named it DECIGO.

amplitude and the event rate and argue their astrophysical importance to the *LISA* and DECIGO projects. According to the runaway formation scenario of SMBHs, we expect very many mergings of IMBHs, and these would be a source of gravitational radiation. We also propose to use the statistics of the events to probe the formation process of SMBHs.

The organization of the paper is as follows. In § 2 we present the basic equations of gravitational radiation from IMBH binaries. In § 3 we estimate the event rate of IMBH mergers under the simplest assumptions about galaxy distribution and the formation process of SMBHs. A summary and a discussion are presented in § 4. Throughout the paper, we use c and G for the light speed and the gravitational constant, respectively.

2. GRAVITATIONAL RADIATION FROM IMBHS

Based on the runaway SMBH formation scenario (Ebisuzaki et al. 2001), we begin by estimating typical observational quantities due to a merger of two IMBHs. Such a merger is normally considered to be divided into three phases: the inspiral phase, the coalescing phase, and the ringdown phase. The latter two need general relativistic treatments, and we call them together the merging phase.

Inspiral phase.—Suppose that two BHs with mass M_1 and $M_2 (M_1 \geqq M_2)$ form a binary with circular orbit of radius a.[4] The quadrupole formula of the gravitational radiation gives the time to coalesce $t_{\rm insp}$ as

$$t_{\rm insp} = \frac{5}{256} a^3 \left(\frac{a}{c}\right)\left(\frac{c^2}{GM_1}\right)\left(\frac{c^2}{GM_2}\right)\left(\frac{c^2}{GM_T}\right)$$
$$\approx 1.23 \times 10^{-2} \left(\frac{a}{R_{\rm grav}}\right)^4 \left(\frac{10^3\ M_\odot}{M_1}\right)$$
$$\times \left(\frac{10^3\ M_\odot}{M_2}\right)\left(\frac{M_T}{2\times 10^3\ M_\odot}\right)^3 \text{ s}, \qquad (1)$$

where we use $R_{\rm grav} = 2GM_T/c^2$ and $M_T = M_1 + M_2$. For $a = 10R_{\rm grav}$, the inspiral time, $t_{\rm insp}$, is about 2.1 minutes if $M_1 = M_2 = 10^3\ M_\odot$ and about 3.4 hr if $M_1 = M_2 = 10^5\ M_\odot$.

The typical frequency of a gravitational wave, $f_{\rm insp}$, in this inspiral phase is

$$f_{\rm insp} = \frac{1}{\pi}\sqrt{\frac{GM_T}{a^3}}$$
$$\approx 11.4 \left(\frac{a}{R_{\rm grav}}\right)^{-3/2} \left(\frac{2\times 10^3\ M_\odot}{M_T}\right) \text{ Hz}, \qquad (2)$$

and the amplitude of gravitational wave, its angle, and its polarization averaged expression (Douglas & Braginsky 1979) are

$$h_{\rm insp} = \sqrt{\frac{32}{5}} \pi^{2/3} G^{5/3} c^{-4} M_1 M_2 M_T^{-1/3} f^{2/3} R^{-1},$$
$$\approx 1.49 \times 10^{-21} \left(\frac{M_1}{10^3\ M_\odot}\right)\left(\frac{M_2}{10^3\ M_\odot}\right)$$
$$\times \left(\frac{M_T}{2\times 10^3\ M_\odot}\right)^{-1/3} \left(\frac{f}{1\ \text{Hz}}\right)^{2/3} \left(\frac{R}{4\ \text{Gpc}}\right)^{-1}. \qquad (3)$$

We plot ($f_{\rm insp}$, $h_{\rm insp}$) in Figure 1. The data are evaluated at the distance $R = 4$ Gpc, which we estimate assuming that quasars peak at redshift $z = 2.5$ (see § 3.1). Figure 1*a* is for equal-mass binaries, and Figure 1*b* is for cases with one BH fixed to be $10^3\ M_\odot$. These two cases correspond to our hierarchical growth model and monopolistic growth model, respectively (we describe them in § 3). The plots are for $a = 50R_{\rm grav}$, $10R_{\rm grav}$, and $5R_{\rm grav}$, respectively, for each case, and arrows indicate the time evolution. We see that the characteristic frequencies of the two cases have quite different evolutions.

We note again that the above formulae are based on a circular orbit of the binary. Such a circular orbit is plausible in the final phase of inspirals due to gravitational radiation (Peters & Mathews 1963); we also note, however, that the effect of spins and the eccentricity of the orbit are quite important in the evolution of binaries of different masses.

Merging phase.—The merging phase requires a direct numerical integration of the Einstein equation. However, several numerical experiments show that the results of numerical simulations (e.g., the amount of the produced gravitational radiation and the waveform) of coalescing binary BHs show quite good agreement with the results from perturbational treatments of the Einstein equation (e.g., Anninos et al. 1995; Baker et al. 2002).

The dominant quasi-normal frequency of a merged BH, $f_{\rm QNM}$, is estimated from the perturbation of black hole geometry and is given as

$$f_{\rm QNM} \approx \frac{lc^3}{\sqrt{27}GM_T} \sim 39.1 \left(\frac{2\times 10^3\ M_\odot}{M_T}\right) \text{ Hz}, \qquad (4)$$

where we evaluate the spherical harmonic index as $l = 2$.

Following Davis et al. (1971) and Thorne & Braginsky (1976), the dimensionless amplitude of gravitational wave, $h_{\rm coal}$, is estimated from the energy balance equation,

$$\epsilon \frac{M_2}{M_1} M_2 c^2 = \left(\frac{c^3 h_{\rm coal}^2}{8\pi G \tau^2}\right)(4\pi R^2)\tau(1+z), \qquad (5)$$

where τ is the redshifted burst timescale, $\tau \sim \sqrt{27}(1+z) GM_T/c^3$, and ϵ is the efficiency. Recent numerical simulations of binary BHs show that ϵ is about 1% (e.g., Alcubierre et al. 2001). We obtain

$$h_{\rm coal} \approx 5.45 \times 10^{-21} \left(\frac{\epsilon}{0.01}\right)^{1/2} \left(\frac{4\ \text{Gpc}}{R}\right)\left(\frac{\mu}{\sqrt{2}\times 10^3\ M_\odot}\right), \qquad (6)$$

where μ is the reduced mass, $\mu = (M_T/M_1)^{-1} M_2$.

In Figure 1 we also plot ($f_{\rm QNM}$, $h_{\rm coal}$). Data are evaluated again at $R = 4$ Gpc, $\epsilon = 10^{-2}$. This figure indicates that gravitational radiation from merging IMBHs with masses of 10^3–$10^6\ M_\odot$ exists in the frequency range between those of the *LISA* and LIGO/LCGT projects. If we were to have a detector in this range, such as the DECIGO, it would contribute greatly to probing the formation process of SMBHs.

3. EVENT RATE OF IMBH MERGERS

The event rate of IMBH mergers depends both on a distribution model of galaxies and on a formation model of SMBHs. We apply the two simplest assumptions for them.

[4] The initial orbit of a binary is not necessarily circular. However, we assume that the orbit becomes circular immediately as a result of the loss of eccentricity due to gravitational radiation (Peters & Mathews 1963; Peters 1964). This assumption simplifies the situation as the first step for the estimation.

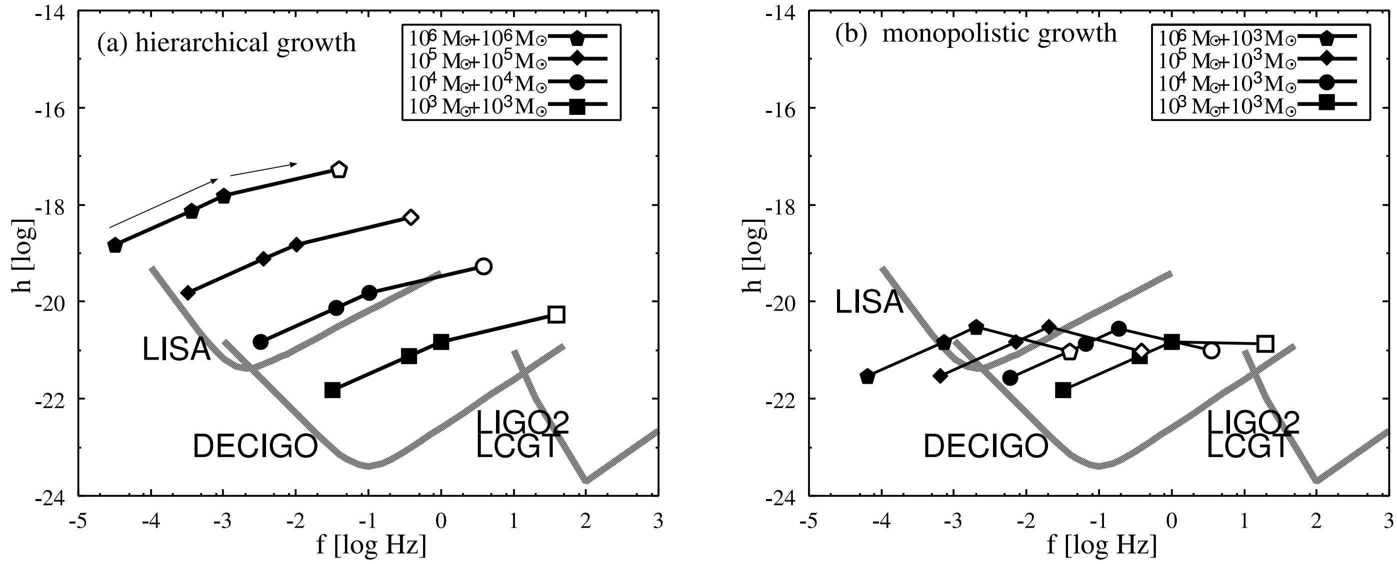

Fig. 1.—Expected gravitational radiation amplitude from merging IMBHs of (*a*) the hierarchical growth model and (*b*) the monopolistic growth model. We plot both the inspiral phase ($f_{\rm insp}$, $h_{\rm insp}$; eqs. [2] and [3]) and the ringdown phase ($f_{\rm QNM}$, $h_{\rm coal}$; eqs. [4] and [6]) for various mass combinations. The open and filled circles and squares in the inspiral phase are of $a = 50R_{\rm grav}$, $10R_{\rm grav}$, and $5R_{\rm grav}$. The final burst frequency, $f_{\rm QNM}$, depends on the efficiency, ϵ, which we fix at $\epsilon \simeq 10^{-2}$ for the plots. The lines represent the sensitivities of future detectors (*LISA*, DECIGO, LIGO 2, and LCGT), taken from Fig. 1 in Seto et al. (2001). The data are evaluated at the distance $R = 4$ Gpc.

3.1. *Galaxy Distribution*

The merger event rate, ν, can be written as

$$\nu = \int_0^{c/H_0} 4\pi R^2 N n_m(R) dR \quad {\rm yr}^{-1}, \tag{7}$$

where $n_m(R)$ is the density distribution of mergers and N is the number of mergers that a central SMBH of a galaxy experienced. We assume that all elliptical galaxies within $z = 2.5$ have the same evolution scenario and consider two distribution models of galaxies that were applied to SMBH mergers by Fukushige et al. (1992). The first model is that all galaxies were born and grow at $z = 2.5$, i.e.,

$$n_m(R) = \delta(R - R_{2.5}) c n_{\rm gl}, \tag{8}$$

where $R_{2.5}$ is the distance to the redshift $z = 2.5$ and $n_{\rm gl}$ is the number density of the galaxies. We call equation (8) the "thin-shell" (TH) model. The second model is that each galaxy appears at a constant rate between $0 \leqq z \leqq 2.5$, i.e.,

$$n_m(R) = R_{2.5}^{-1} c n_{\rm gl} \quad (0 < R \leqq R_{2.5}). \tag{9}$$

We call equation (9) the "homogeneous " (HM) model. These two assumptions are consistent with the observation that the distribution of quasars peaks at $z \simeq 2.5$ (McLure & Dunlop 2001; Rees 1990).

If we apply these accumulating models to the entire universe, and if we assume that every galaxy has SMBHs and that each galaxy experiences $N = 10^3$ IMBH megers, we can apply the merger event rate, from equations (7)–(9):

$$\nu \begin{pmatrix} \text{TH model} \\ \text{HM model} \end{pmatrix} \approx \begin{pmatrix} 67 \\ 22 \end{pmatrix} \left(\frac{n_{\rm gl}}{10^{-3}\ {\rm Mpc}^{-3}} \right) \times \left(\frac{N}{10^3} \right) \left(\frac{R_{2.5}}{4\ {\rm Gpc}} \right)^2 {\rm yr}^{-1}. \tag{10}$$

We estimate the distance, $R_{2.5} \propto H_0^{-1}$, to be 4 Gpc[5] and the number density, $n_{\rm gl}$, to be 10^{-3} Mpc^{-3}, using the CfA survey data (Huchra et al. 1990; Huchra & Corwin 1995) in the same manner as Fukushige et al. (1992). The number of BH merger events, 22–67, may be large enough to distinguish the accumulating models of IMBHs, which we discuss next.

3.2. *SMBH Formation Model*

It is natural to extend the event rate estimation to include the dependency of the mass-accumulating models. Suppose that we consider the process by which a thousand IMBHs with $\langle m \rangle = 10^3\ M_\odot$ merge and grow into a single SMBH with mass $M_c = 10^6\ M_\odot$. The actual growth behavior should be investigated by numerical simulations, but here we simply consider two extreme merging models: (I) the hierarchical growth model and (II) the monopolistic (or runaway) growth model.

In the hierarchical growth model two nearby equal-mass BHs merge simultaneously, and then the process repeats. In this model the number of BHs goes from 500 with $2 \times 10^3\ M_\odot$, to 250 with $4 \times 10^3\ M_\odot$, and so on until finally there is a single $10^6\ M_\odot$ BH. Conversely, in what we call the monopolistic growth model, a single BH expands through continual mergers with surrounding BH companions.

In the hierarchical model, the two merging BH masses are the same, $M_1 = M_2 = \frac{1}{2} M_T$, while in the monopolistic model the merging BH mass, M_2, is constant, $\langle m \rangle \simeq 10^3\ M_\odot$, and the most massive BH mass represents M_T at the later phase. Thus, the number of mergers, N (which is a function of the model), M_1, and M_2, are given only as a function of M_T. For the mass range $M_T \sim M_T + \Delta M_T$, N is given by

$$N({\rm model}, M_T \sim M_T + \Delta M_T) = \int_{M_T}^{M_T + \Delta M_T} \frac{dN}{dM_T}\, dM_T, \tag{11a}$$

[5] Note that the distance R_z is 4.00, 5.07, and 6.00 Gpc for $z = 2.5$, 5, and 10, respectively, where we assume a flat FRW universe with $\Omega_m = 0.32$, $\Omega_\Lambda = 0.68$, and $H_0 = 72$ km s^{-1} Mpc^{-1}.

TABLE 1
Models in This Paper

SMBH Formation Model	Galaxy Distribution	
	Thin Shell (eq. 8)	Homogeneous (eq. [9])
Hierachical growth (eq. [11b])	Ia	Ib
Monopolistic growth (eq. [11c])	IIa	IIb

where

$$dN(\text{hier.},\ M_T) = \frac{M_c}{M_T^2}\, dM_T, \tag{11b}$$

$$dN(\text{mono.},\ M_T) = \frac{dM_T}{\langle m \rangle}, \tag{11c}$$

for the hierarchical and the monopolistic models, respectively. Consequently, the merger event rate becomes

$$\begin{bmatrix} \nu_{\rm Ia}(M_T) \\ \nu_{\rm Ib}(M_T) \end{bmatrix} \approx \begin{pmatrix} 67 \\ 22 \end{pmatrix} \left(\frac{n_{\rm gl}}{10^{-3}\ {\rm Mpc}^{-3}}\right) \left(\frac{R_{2.5}}{4\ {\rm Gpc}}\right)^2 \times \alpha \left(\frac{10^3\ M_\odot}{M_T}\right) \left(\frac{M_c}{10^6\ M_\odot}\right)\ {\rm yr}^{-1}, \tag{12a}$$

$$\begin{bmatrix} \nu_{\rm IIa}(M_T) \\ \nu_{\rm IIb}(M_T) \end{bmatrix} \approx \begin{pmatrix} 67 \\ 22 \end{pmatrix} \times 10^{-3} \left(\frac{n_{\rm gl}}{10^{-3}\ {\rm Mpc}^{-3}}\right) \left(\frac{R_{2.5}}{4\ {\rm Gpc}}\right)^2 \times \alpha \left(\frac{M_T}{10^3\ M_\odot}\right) \left(\frac{10^3\ M_\odot}{\langle m \rangle}\right)\ {\rm yr}^{-1}, \tag{12b}$$

where $\alpha \equiv \Delta M_T / M_T$ is the rate of the mass increase and the subscripts indicate the models listed in Table 1. We note that the mass dependency can be converted into dependency on the frequency of gravitational bursts, f, using equation (4):

$$\frac{dM_T}{df} = -\frac{M_T}{f}. \tag{13}$$

From equations (4), (12) and (13), the merger event rate for the frequency range $f - f + \Delta f$ is

$$\begin{bmatrix} \nu_{\rm Ia}(f) \\ \nu_{\rm Ib}(f) \end{bmatrix} \approx \begin{pmatrix} 8.6 \\ 2.9 \end{pmatrix} \times 10^{-1} \left(\frac{n_{\rm gl}}{10^{-3}\ {\rm Mpc}^{-3}}\right) \left(\frac{R_{2.5}}{4\ {\rm Gpc}}\right)^2 \times \alpha \left(\frac{f}{1\ {\rm Hz}}\right) \left(\frac{M_c}{10^6\ M_\odot}\right)\ {\rm yr}^{-1}, \tag{14a}$$

$$\begin{bmatrix} \nu_{\rm IIa}(f) \\ \nu_{\rm IIb}(f) \end{bmatrix} \approx \begin{pmatrix} 5.2 \\ 1.7 \end{pmatrix} \left(\frac{n_{\rm gl}}{10^{-3}\ {\rm Mpc}^{-3}}\right) \left(\frac{R_{2.5}}{4\ {\rm Gpc}}\right)^2 \times \alpha \left(\frac{1\ {\rm Hz}}{f}\right) \left(\frac{10^3\ M_\odot}{\langle m \rangle}\right)\ {\rm yr}^{-1}. \tag{14b}$$

We plot these in Figure 2 as a function of the merged BH mass, M_T, and the ringdown frequency $f_{\rm QNM}$. In this figure we fix the increasing-mass rate, α, at unity. If a SMBH expands hierarchically, then the bursts of gravitational radiation appear in the higher frequency region. In the monopolistic model, the bursts

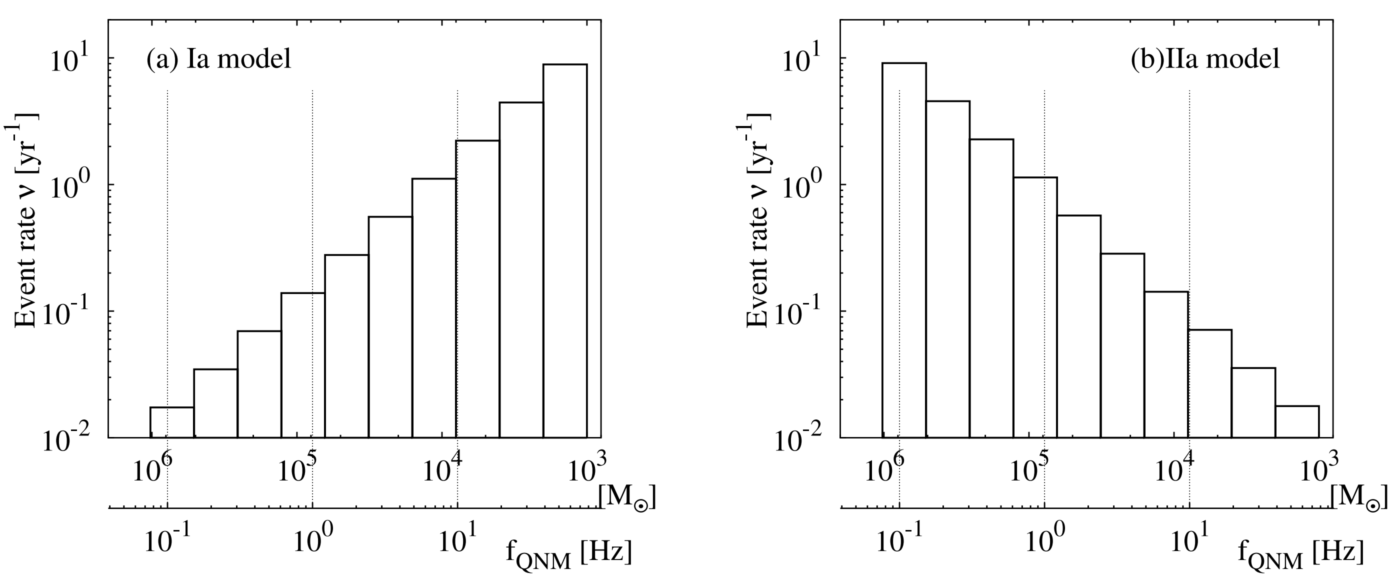

Fig. 2.—Event numbers of mergers starting from 1000 IMBHs with masses of $10^3\ M_\odot$. The vertical axis is the event rate $\nu({\rm yr}^{-1})$ from eqs. (12), and (14). The horizontal axis is for the mass of the postmerger BH, M_T, which is also interpreted in the final gravitational radiation frequency $f_{\rm QNM}$. Panels (*a*) and (*b*) are for the hierarchical growth model and for the monopolistic growth model, respectively. Both plots are for a homogeneous distribution model in which we just multiply by 3 each event rate for the thin-shell galaxy distribution model. If a SMBH expands hierarchically, then the bursts of gravitational radiation appear in the higher frequency region. In the monopolistic model, the bursts appear in lower frequency region. We fix the increasing-mass rate, α, at unity for the plots.

appear in the lower frequency region. Therefore, we conclude that using the observational statistics of burst events detected by future space satellite gravitational wave laser-interferometers, we will be able to distinguish several growth models of IMBHs to a SMBH.

4. CONCLUDING REMARKS

The discovery of an IMBH supports the runaway path scenario SMBH formation. In the merging processes of IMBHs, we expect gravitational radiation signals from both their inspiral and merger (burst) phases. In this paper we discus the event rate and detectability of the gravitational radiation from SMBH-IMBH and IMBH-IMBH binaries, applying simple toy models.

The event rate depends on the number of IMBHs and the galaxy distribution models, but it may be roughly 22–67 events per year if we assume that all galaxies experience 1000 IMBH mergers. This number is quite attractive, both for the gravitational radiation observation and theoretically, for probing the SMBH formation scenario. We have demonstrated that two extreme merging IMBH models (hierarchical and monopolistic growth models) show quite different event numbers in the final burst frequency of the gravitational radiation. Therefore, it would be possible to determine the growth model from observations of the bursts of gravitational radiations

By taking account of realistic simulations, Portegies Zwart et al. (1999, 2004) showed the formation of massive black holes through runaway collision in dense young star clusters. Since the same is true for the formation of supermassive black hole through IMBH merger events at the center of galaxies, we expect the following processes: In the early stage of mergers, IMBHs gradually sink toward the galactic center owing to dynamical friction, and a few percent of the IMBHs merge hierarchically because of gravitational radiation. The merged IMBHs then become seed BHs for the rest and continue to swallow other IMBHs monopolistically. Therefore, the actual mergers can be modeled by applying our hierarchical growth model and monopolistic growth model in this order.

As seen in Figures 1*a* and 1*b*, the amplitude of gravitational radiation from the inspiral and the final mergers of the different mass binaries ($M_2 \ll M_1$) is smaller than that of the equal-mass binaries ($M_2 = M_1$). For the hierarchical growth model, signals from equal-mass binaries with the masses $M_1 = M_2 > 10^4\ M_\odot$ will be detectable by *LISA* (and by DECIGO), while for the monopolistic growth model, the signals will be detectable by DECIGO (but not by *LISA*). We therefore conclude that the frequency and sensitivity levels of DECIGO are quite important for probing the merger models of SMBHs, especially for binaries of different masses (the later stage of a SMBH formation).

Gravitational radiation from IMBHs would be observed mostly in the frequency range 10^{-1} to 102 Hz, which is exactly the target range of *LISA* and DECIGO. *LISA* is supposed to operate for at least 2–3 yr (and perhaps up to 10 yr) after its launch, so we expect that *LISA* and DECIGO will establish the actual merging history from the statistics of gravitational radiation signals.

This work can be extended in two steps. The first is to investigate the SMBH formation scenario using realistic large-scale numerical simulations. Both analytical and *N*-body studies of the dynamics and mergers of BHs will provide more realistic models of the SMBH scenario. Then we will come back to the present analysis of the statistics of the gravitational radiation signals, and we plan to present more realistic predictions.

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