Rapidly spinning massive black holes in active galactic nuclei: evidence from the black hole mass function

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ABSTRACT
The comparison of the black hole mass function (BHMF) of active galactic nuclei (AGN) relics with the measured mass function of the massive black holes in galaxies provides strong evidence for the growth of massive black holes being dominated by mass accretion. We derive the Eddington ratio distributions as functions of black hole mass and redshift from a large AGN sample with measured Eddington ratios given by Kollmeier et al. We find that, even at the low-mass end, most black holes are accreting at Eddington ratio \( \lambda \approx 0.2 \), which implies that the objects accreting at extremely high rates should be rare or such phases are very short. Using the derived Eddington ratios, we explore the cosmological evolution of massive black holes with an AGN bolometric luminosity function (LF). It is found that the resulted BHMF of AGN relics is unable to match the measured local BHMF of galaxies for any value of (constant) radiative efficiency \( \eta_{\text{rad}} \). Motivated by Volonteri, Sikora & Lasota’s study on the spin evolution of massive black holes, we assume the radiative efficiency to be dependent on black hole mass, i.e. \( \eta_{\text{rad}} \) is low for \( M_{\text{bh}} < 10^8 M_\odot \) and it increases with the black hole mass for \( M_{\text{bh}} \geq 10^8 M_\odot \). We find that the BHMF of AGN relics can roughly reproduce the local BHMF of galaxies if \( \eta_{\text{rad}} \approx 0.08 \) for \( M_{\text{bh}} < 10^8 M_\odot \) and it increases to \( \gtrsim 0.18 \) for \( M_{\text{bh}} \gtrsim 10^9 M_\odot \), which implies that most massive black holes \((\gtrsim 10^9 M_\odot)\) are spinning very rapidly.

Key words: accretion, accretion discs – black hole physics – galaxies: evolution – quasars: general.

1 INTRODUCTION
It is believed that quasars are powered by accretion on to massive black holes, and the growth of the massive black holes could be governed by mass accretion in quasars. The massive black holes [active galactic nuclei (AGN) relics] should be present in the centres of galaxies. Thus, the luminosity functions (LFs) of AGN provide important clues on the growth of massive black holes. It is indeed found that most nearby galaxies contain massive black holes at their centres, and a tight correlation is revealed between central massive black hole mass and the velocity dispersion of the galaxy (Ferrarese & Merritt 2000; Gebhardt et al. 2000). The black hole mass is also found to be tightly correlated with the luminosity of the spheroid component of its host galaxy (e.g. Magorrian et al. 1998; Marconi & Hunt 2003). These correlations of the black hole mass with velocity dispersion/host galaxy luminosity were used to derive the mass functions of the central massive black holes in galaxies (e.g. Yu & Tremaine 2002; Marconi et al. 2004; Tamura, Ohta & Ueda 2006; Graham et al. 2007). On the other hand, the black hole mass function (BHMF) of AGN relics can also be calculated by integrating the continuity equation of massive black hole number density on the assumption of the growth of massive black holes being dominated by mass accretion, in which the activity of massive black holes is described by a LF of AGN (e.g. Cavaliere, Morrison & Wood 1971; Soltan 1982; Chokshi & Turner 1992; Small & Blandford 1992; Marconi et al. 2004; Shankar et al. 2004; Tamura, Ohta & Ueda 2006). Such calculations on the cosmological evolution of massive black holes were usually carried out by adopting two free parameters: the radiative efficiency \( \eta_{\text{rad}} \) and the Eddington ratio \( \lambda \) for AGN. The derived BHMF of AGN relics in this way is required to match that estimated either from velocity dispersion or the luminosity of the spheroid of its host galaxy, which always leads to \( \lambda \sim 1 \), i.e. almost all AGN are required to be accreting close to the Eddington limit (e.g. Yu & Tremaine 2002; Marconi et al. 2004; Shankar et al. 2004; Tamura et al. 2006).

In the last decade, several approaches for measuring the masses of the central black holes in AGN have been developed, in which the reverberation mapping may be the most effective one (Peterson 1993; Kaspi et al. 2000). Using the tight correlation between the size of the broad-line region and the optical luminosity established with the reverberation mapping method for a sample of AGN, the
black hole masses of AGN can be easily estimated from their optical luminosity and width of broad emission line. The Eddington ratios for thousands of AGN were estimated with the analyses of the Sloan Digital Sky Survey (SDSS) by McLure & Dunlop (2004), which indicate that the mean Eddington ratio \( L_{\text{bol}} / L_{\text{bol}}^{\ast} \approx 0.1 \) at \( z \approx 0.2 \) to \( z \approx 0.4 \) at \( z \approx 2 \). Warner, Hamann & Dietrich (2004) also derived the Eddington ratio distribution for a sample of \( \approx 500 \) AGN with redshifts \( 0 \leq z \leq 5 \). As pointed by Kollmeier et al. (2006), both these derived Eddington ratios are heavily weighted towards high-luminosity objects due to the limited sensitivity of SDSS. Kollmeier et al. (2006) estimated the Eddington ratios of AGN discovered in the AGN and Galaxy Evolution Survey (AGES), which is more sensitive than the SDSS (Kochanek et al. 2004). The derived Eddington ratio distribution at fixed luminosity is well described by a single lognormal distribution peaked at \( \sim 0.25 \) independent of redshift and luminosity (see Kollmeier et al. 2006, for the details).

In this work, the Eddington ratio distribution at fixed luminosity given by Kollmeier et al. (2006) is converted to that at fixed black hole mass by using an AGN LF. We integrate the continuity equation for black hole number density adopting the derived Eddington ratio distributions of AGN to calculate the BHMF of AGN relics at different redshifts \( z \), which is different from a free parameter \( \lambda \) adopted in most of the previous works. The resultant BHMF of AGN relics is constrained by those from the galaxy LFs (Marconi et al. 2004; Tamura et al. 2006). The conventional cosmological parameters \( \Omega_M = 0.3, \Omega_\Lambda = 0.7 \) and \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) have been adopted in this work.

### 2 THE EDDINGTON RATIO DISTRIBUTION OF ACTIVE GALACTIC NUCLEI

The Eddington ratio distribution of AGN for given bolometric luminosity can be approximated as a lognormal distribution:

\[
\xi(l) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[\frac{-(l-\mu)^2}{2\sigma^2}\right],
\]

where \( l = \log \lambda, \lambda = L_{\text{bol}} / L_{\text{Edd}}, \mu \simeq \log 0.25 \) and \( \sigma \simeq 0.3 \) (see Kollmeier et al. 2006, for the details). We can derive the BHMF of AGN from the bolometric LF \( \Phi(z, L_{\text{bol}}) \):

\[
N_{AGN}(z, M_{bh}) = \int \Phi(z, L_{\text{bol}}) \frac{d \log L_{\text{bol}}}{d \log M_{bh}} \xi(l) dl,
\]

where \( L_{\text{bol}} = I + I_{\text{Edd}}, L_{\text{Edd}} = 1.251 \times 10^{39} \, M_{bh} \, \text{erg s}^{-1} \) and \( M_{bh} \) is in units of solar mass. Using the bolometric LF \( \Phi(z, L_{\text{bol}}) \) of AGN, the Eddington ratio distribution for given black hole mass \( M_{bh} \) can be calculated with

\[
\chi(z, M_{bh}, l) = \frac{\Phi(z, L_{\text{bol}}) \xi(l)}{N_{AGN}(z, M_{bh})},
\]

where \( L_{\text{bol}} = 10^5 L_{\text{Edd}} \), and the BHMF of AGN, \( N_{AGN}(z, M_{bh}) \), is available with equation (2). The mean Eddington ratio of AGN with \( M_{bh} \) at \( z \) is

\[
\bar{\lambda}(z, M_{bh}) = \int \lambda \chi(z, M_{bh}, l) dl.
\]

In this work, we adopt the luminosity-dependent density evolution (LDDE) bolometric LF calculated from the rest-frame optical, soft and hard X-ray, and near- and mid-infrared (mid-IR) bands in the redshift interval \( z = 0 \) to \( z = 0.6 \) by Hopkins, Richards & Hernquist (2007)

\[
\Phi(L_{\text{bol}}, z) = \Phi(L_{\text{bol}}, 0) e_d(L_{\text{bol}}, z) = \frac{\phi_e}{(L_{\text{bol}}/L_e)^{\gamma_1} + (L_{\text{bol}}/L_e)^{\gamma_2}} e_d(L_{\text{bol}}, z).
\]

The density function \( e_d \) is given by

\[
e_d(L_{\text{bol}}, z) = \begin{cases} 
(1 + z)^{\gamma_1}, & z \leq z_c, \\
(1 + z_c)^{\gamma_1} [(1 + z)/(1 + z_c)^{\gamma_2}]^{\gamma_2}, & z > z_c.
\end{cases}
\]

with

\[
z_c(L_{\text{bol}}) = \begin{cases} 
z_{c,0} & (L_{\text{bol}} \leq L_c), \\
z_{c,0} & (L_{\text{bol}} > L_c).
\end{cases}
\]

and

\[
p1(L_{\text{bol}}) = p1_{46} + \beta_1 \left[ \log \left( L_{\text{bol}}/10^{46} \, \text{erg s}^{-1} \right) \right],
\]

\[
p2(L_{\text{bol}}) = p2_{46} + \beta_2 \left[ \log \left( L_{\text{bol}}/10^{46} \, \text{erg s}^{-1} \right) \right].
\]

All the parameters of the LF are as follows. \( \phi_e = -6.20 \pm 0.15 \, \text{Mpc}^{-3}, \log L_{\ast} (\text{erg s}^{-1}) = 45.99 \pm 0.10, \gamma_1 = 0.933 \pm 0.045, \gamma_2 = 2.20 \pm 0.14, \log L_{\ast} (\text{erg s}^{-1}) = 46.72 \pm 0.05, z_{c,0} = 1.852 \pm 0.025, \alpha = 0.274 \pm 0.025, p1_{46} = 5.95 \pm 0.23, p2_{46} = -1.65 \pm 0.21, \beta_1 = 0.29 \pm 0.34 \) and \( \beta_2 = -0.62 \pm 0.17 \) (see table 4 in Hopkins et al. 2007).

In Fig. 1, we plot the Eddington ratio distributions \( \chi(z, M_{bh}, l) \) for fixed black hole mass derived from that for fixed luminosity given by Kollmeier et al. (2006). We find that the derived Eddington ratio distributions are close to the lognormal distribution, while their peaks vary with black hole mass and redshift. We plot the mean Eddington ratios as functions of black hole mass in Fig. 2. It is found that the mean Eddington ratios \( \bar{\lambda}(z, M_{bh}) \) are in the range of \( \sim 0.1 \) to \( 0.3 \) as functions of black hole mass \( M_{bh} \) and redshift \( z \).

### 3 THE EVOLUTION OF MASSIVE BLACK HOLES

The evolution of massive black hole number density is described by (Small & Blandford 1992)

\[
\frac{\partial N(M_{bh}, t)}{\partial t} + \frac{\partial}{\partial M_{bh}} [N(M_{bh}, t) < M(M_{bh}, t) >] = S(M_{bh}, t),
\]

where \( N(M_{bh}, t) \) is the mass function of the massive black holes including both active and inactive black holes, \( < M(M_{bh}, t) > \) is the mean mass accretion rate for the black holes with \( M_{bh} \) and \( S(M_{bh}, t) \) describes the effect of black hole mergers on the BHMF. The total black hole mass density will not be altered by mergers.
is still quite uncertain, which is not included in the hard X-ray LF. The contribution of Compton-thick AGN to the black hole evolution was taken into account by multiplying a correction factor of 1.6 independent of the luminosity (e.g. see Marconi et al. 2004; Tamura et al. 2006).

The hard X-ray (>20 keV) and the mid-IR (5–50 μm) bands are optimal for the detection of AGN with column densities \( \lesssim 10^{24} \text{cm}^{-2} \) (e.g. Treister & Urry 2005). The observations with the International Gamma-Ray Astrophysics Laboratory and the Swift Burst Alert Telescope indicate that the fraction of an absorbed AGN decreases with the 20–100 keV luminosity (Markwardt et al. 2005; Bassani et al. 2006) (but also see Wang & Jiang 2006), which is confirmed by the mid-IR Spitzer observations of 25 luminous and distant quasars (Maiolino et al. 2007). Maiolino et al. (2007) suggested that the fraction of the obscured AGN to the total can be well fitted with

\[
f_{\text{obs}} = \frac{1}{1 + L_{\text{opt}}},
\]

where

\[
L_{\text{opt}} = \frac{\lambda L_{\lambda}(5100 \, \text{Å})(\text{erg s}^{-1})}{10^{45.63}}.
\]

Muller & Hasinger (2007) found that the fraction of type II AGN detected in the hard X-ray band can be described by this function (equation 14) quite well (see fig. 3 in their paper). Hopkins et al. (2007) suggested that the fraction of Compton-thick to the total also decreases with luminosity and it is less than \( \sim 30 \) per cent based on a variety of very hard X-ray/soft gamma-ray observations on AGN (see their paper for the detailed discussion). Motivated by the results of these works, besides the luminosity-independent correction for Compton-thick AGN, we tentatively employ a similar luminosity-dependent correction as that given by Maiolino et al. (2007). We assume the number ratio of Compton-thick to Compton-thin AGN to be

\[
f_{\text{CT}} = \frac{0.6}{1 + L_{\text{opt}}^{0.414}},
\]

where \( L_{\text{bol}} = L_{\text{bol}}/10^{46.6} \), as \( L_{\text{bol}} \gtrsim 9\lambda L_{\lambda}(5100 \, \text{Å}) \) is adopted (e.g. Kaspi et al. 2000). We change the numerator in equation (14) to 0.6 here, so that \( f_{\text{CT}} \) reduces to \( \sim 0.6 \) for low-luminosity AGN, which is the same as that in Marconi et al. (2004), while \( f_{\text{CT}} \to 0 \) for the luminous AGN.

In most of the previous works, both the radiative efficiency of \( \eta_{\text{rad}} \) and Eddington ratio \( \lambda \) are free parameters, and the comparisons between the BHMF of AGN relics and the measured local BHMF of galaxies always require: \( \eta_{\text{rad}} \sim 0.1 \) and \( \lambda \sim 1 \) (e.g. Yu & Tremaine 2002; Marconi et al. 2004; Tamura et al. 2006). As we have derived the mean Eddington ratio distributions as functions of black hole mass and redshift in the last section, there is only one free parameter \( \eta_{\text{rad}} \) in our calculations for the cosmological evolution of massive black holes. The local BHMFs estimated by using the correlation of the black hole mass with host galaxy luminosity are adopted in this work (see Marconi et al. 2004; Tamura et al. 2006, for the details). The continuity equation (13) for black hole number density is integrated from \( z = z_{\text{max}} \) by using equations (2)–(4) and assuming the duty cycle is 0.5 at \( z_{\text{max}} \). The final results are insensitive to the initial conditions at \( z_{\text{max}} \). In all our calculations, \( z_{\text{max}} = 4 \) is adopted because the Eddington ratio distributions are calculated from a sample of AGN with \( z < 4 \) (Kollmeier et al. 2006). The resulted BHMFs of AGN relics at low redshifts are insensitive to the value of \( z_{\text{max}} \) because the fraction of local black hole mass accreted at high redshifts can be neglected. We plot our results with different values of \( \eta_{\text{rad}} \) in the upper panel of Fig. 3, which indicates

![Figure 2. The mean Eddington ratios as functions of black hole mass \( M_{\text{bh}} \) for the AGN at different redshifts: \( z = 0 \) (black), 1 (red), 2 (green), 3 (blue) and 4 (yellow).](https://academic.oup.com/mnras/article-abstract/390/2/561/1029311)
that the measured local BHMF cannot be fitted with any values of $\eta_{\text{rad}}$. This is due to the mean Eddington ratios derived in this work being $\sim 0.1 - 0.3$, which deviates significantly from $\lambda \sim 1$ suggested in most of the previous works (e.g. Yu & Tremaine 2002; Marconi et al. 2004). In our calculations, we only consider the uncertainty of the number density in the bolometric LF given by Hopkins et al. (2007).

The radiative efficiency of black hole accretion is closely related to the black hole spin. The massive black holes will be spun up through accretion, as the black holes acquire mass and angular momentum simultaneously through accretion. The spins of the massive black holes may also be affected by mergers of black holes. A rapidly rotating new black hole will be present after the merger of two black holes, only if the binary’s larger member already spins quickly, and the merger with the smaller hole, or if the binary’s mass ratio approaches unity (Hughes & Blandford 2003). The comoving space density for the heavier black holes is much lower than that for smaller black holes (see e.g. the BHMF in Marconi et al. 2004), which means that the probability of the mergers of two black holes with similar masses is lower for heavy black holes. This implies that the spins of heavy black holes are mainly regulated by an accretion rather than the mergers, and the spin parameters can reach $\sim 1$ after their masses are doubled through accretion. For smaller black holes in disc galaxies, a small number of minor mergers might have happened, which are believed to be responsible for rebuilding their host galaxy discs, and small minor accretion episodes on to black holes are triggered by these minor mergers (e.g. Volonteri, Sikora & Lasota 2007; King, Pringle & Hofmann 2008). This is also supported by the observations that single accretion events last $\sim 10^3$ yr in Seyfert galaxies and their total active lifetime is $10^8$–$10^9$ yr (Kharb et al. 2006; Ho, Filippenko & Sargent 1997; Volonteri, Sikora & Lasota 2007). Volonteri et al. (2007) studied on how the accretion from a warped disc influences the evolution of black hole spins and concluded that within the cosmological framework, one indeed expects most supermassive black holes in elliptical galaxies to have on average higher spin than black holes in spiral galaxies. The random small accretion episodes (e.g. tidally disrupted stars, accretion of molecular clouds) might have played a more important role on the spin evolution of small black holes in spiral galaxies, which lead to relatively low-average spins for these black holes (Volonteri et al. 2007; King et al. 2008). Motivated by their results on the cosmological spin evolution of black holes, we tentatively adopt a $M_{bh}$-dependent radiative efficiency, in which $\eta_{\text{rad}}$ remains constant for $M_{bh} < 10^8$ and increases as a power law with black hole mass for $M_{bh} \geq 10^8$:

$$\eta_{\text{rad}} = \begin{cases} \eta_{\text{rad,0}} & \text{if } M_{bh} < 10^8 M_\odot; \\ \eta_{\text{rad,0}} \left( \frac{M_{bh}}{10^8 M_\odot} \right)^q & \text{if } M_{bh} \geq 10^8 M_\odot, \end{cases}$$

in our calculations. We find that the measured local BHMF can be roughly reproduced by the BHMF of AGN relics provided $\eta_{\text{rad,0}} = 0.08$ and $q = 0.36$ are adopted (see the lower panel in Fig. 3).

Tamura et al. (2006) tried to derive the BHMFs with redshifts up to $z \sim 1$ from the spheroid LF of early-type galaxies using the correlation between the spheroid luminosity and black hole mass (see their paper for the details), which provides further constraints on the model calculations for the cosmological evolution of massive black holes. The model calculations performed with this $M_{bh}$-dependent radiative efficiency (equation 16) are compared with the spheroid BHMFs derived by Tamura et al. (2006) in Fig. 4. We find that the calculated BHMFs of AGN relics can roughly reproduce the spheroid BHMFs at different redshifts either for luminosity-dependent or luminosity-independent corrections for the Compton-thick AGN.

### 4 DISCUSSION

As in the most previous works, we implicitly assume that the black hole growth is dominated by mass accretion in bright AGN, while some inactive black holes may still be accreting gases, though their mass accretion rates are very low. If the duration of the accretion in these objects is as long as the Hubble time-scale, they can accrete sufficient mass comparable with that accumulated in bright AGN phases, as the AGN phase is much shorter than the Hubble time-scale. It is believed that the advection-dominated accretion flows (ADAFs) are present in those objects, which are very hot and radiate mostly in hard X-ray bands (Narayan & Yi 1994). They are very difficult to be detected due to low luminosity, unless those in the nearby Universe. Cao (2005) suggested that the accretion of such low-luminosity objects can be constrained by the hard X-ray background, though the emission from most of these individuals cannot be detected by any facilities now. It was found that less than $\sim 5$ per cent of the local black hole mass density was accreted during the ADAF phases, which will be even lower if the Compton-thick AGN are included (see Cao 2007, for the details). Hopkins, Narayan & Hernquist (2006) considered the distribution of local supermassive black hole Eddington ratios and accretion rates, accounting for the dependence of radiative efficiency and bolometric corrections on the accretion rate. They also found that black hole mass growth was dominated by the AGN phases, and not by the radiatively...
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Figure 4. The BHMFs at different redshifts of $z = 0$, 0.25, 0.45, 0.65, 0.85 and 1.05 transformed from the COMBO-17 LFs are indicated with shaded areas (taken from Tamura et al. 2006). The BHMFs of AGN relics at different redshifts calculated from the AGN LF are plotted by using $M_{\text{bh}}$-dependent radiation efficiency $\eta_{\text{rad}}(M_{\text{bh}})$ (see the text for the details). The blue lines are calculated with a correction factor of 1.6 independent of luminosity for Compton-thick AGN, while the red lines represent the cases with a luminosity-dependent correction for the Compton-thick AGN.

The BHMFs at different redshifts of $z = 0$, 0.25, 0.45, 0.65, 0.85 and 1.05 transformed from the COMBO-17 LFs are indicated with shaded areas (taken from Tamura et al. 2006). The BHMFs of AGN relics at different redshifts calculated from the AGN LF are plotted by using $M_{\text{bh}}$-dependent radiation efficiency $\eta_{\text{rad}}(M_{\text{bh}})$ (see the text for the details). The blue lines are calculated with a correction factor of 1.6 independent of luminosity for Compton-thick AGN, while the red lines represent the cases with a luminosity-dependent correction for the Compton-thick AGN.

The main difference of this work from the previous works is that the Eddington ratio distributions are derived from an AGN sample with measured Eddington ratios (Kollmeier et al. 2006). The Eddington ratio distributions for fixed black hole mass derived in our work approximate to the lognormal distribution (see Fig. 1), and the mean Eddington ratios are in the range of $\sim 0.1$–0.3 varying with black hole mass and redshift (see Fig. 2). For most cases, the mean Eddington ratios peak at $\sim 10^{8} M_{\odot}$, and then decline with increasing black hole mass. Even at the low-mass end, most black holes are accreting at $\lambda \sim 0.2$, which implies that the objects accreting at extremely high rates should be rare or such phases are very short. It was suggested that the radiative efficiency $\eta_{\text{rad}}$ declines for a slim accretion disc provided the mass accretion rate is sufficiently high due to the photon trapping effect (e.g. Begelman 1978; Abramowicz et al. 1988; Wang et al. 1999). Watarai et al.’s (2000) calculations on the slim discs showed that the radiative efficiency will not deviate significantly from that for standard thin discs if $L_{\text{rad}}/L_{\text{Edd}} \lesssim 2$, which implies that the present adopted radiative efficiency independent of Eddington ratio $\lambda$ is indeed a good assumption.

There is only one free parameter $\eta_{\text{rad}}$ in our calculations for the cosmological evolution of massive black holes. We find that the resulted BHMF of AGN relics is unable to reproduce the measured local BHMF for any value of $\eta_{\text{rad}}$ adopted, provided the radiative efficiency $\eta_{\text{rad}}$ is independent of black hole mass, as treated in the previous works (e.g. Yu & Tremaine 2002; Marconi et al. 2004; Tamura et al. 2006). The mean Eddington ratios adopted in our calculations are derived from an AGN sample, which are in the range of $\sim 0.1$–0.3. Thus, it is not surprising that the local BHMFs cannot be reproduced by our calculations with any constant radiative efficiency because the Eddington ratio $\lambda \sim 1$ is usually required in order to let the resulted BHMF match the local one in those works. In this work, we use two different corrections (either luminosity independent or luminosity dependent) for the Compton-thick AGN (see Section 3 for the details), and find that the final results are quite similar (see Figs 3 and 4). We also use the hard X-ray LF derived from an AGN sample at high redshifts by Silverman et al. (2008) instead of the bolometric LF of Hopkins et al. (2007) in the calculations. It is found that the main results of this work change very little and the main conclusion is not altered.

Volonteri et al. (2007) studied on how the accretion from a warped disc influences the evolution of black hole spins and concluded that within the cosmological framework one indeed expects most supermassive black holes in elliptical galaxies to have on average higher spin than black holes in spiral galaxies, where random, small accretion episodes (e.g. tidally disrupted stars, accretion of molecular clouds) might have played a more important role. Thus, we tentatively adopt a $M_{\text{bh}}$-dependent radiative efficiency (see equation 16), in which $\eta_{\text{rad}}$ remains constant for $M_{\text{bh}} \lesssim 10^{8}$ and increases with black hole mass for $M_{\text{bh}} > 10^{8}$. This $M_{\text{bh}}$-dependent radiative efficiency is qualitatively consistent with the results of Volonteri et al. (2007). It is found that the measured BHMFs can be fairly well reproduced by our model calculations with this $M_{\text{bh}}$-dependent radiative efficiency (see Figs 3 and 4), which require $\eta_{\text{rad}} \gtrsim 0.18$ for $M_{\text{bh}} \gtrsim 10^{8} M_{\odot}$. This provides evidence for most massive black holes being spinning very rapidly. It is interesting to find that $a \gtrsim 0.9$ is also required by the fitting of the residual hard X-ray background with the emission from the ADAFs in the low-luminosity objects (Cao 2007). Our calculations can be improved if the mean spin parameter $a$ as a function of black hole mass is available from the work within the cosmological framework, which is beyond the scope of this work.

In our present calculations of the black hole evolution, the black hole mergers have been neglected. Shankar et al. (2007) assessed the importance of black hole mergers on the evolution of the BHMF. They found that the impact of black hole mergers on the cosmological evolution of BHMF may probably be small compared with the black hole accretion processes, while its impact on the black hole spin evolution may be important (e.g. Wilson & Colbert 1995; Hughes & Blandford 2003; Volonteri et al. 2005, 2007). The effect of black hole mergers increases the number density of very massive black holes (Shankar et al. 2007), which implies that the radiative efficiencies for very massive active black holes should be higher than the present values if black hole mergers are included in our calculations. This strengthens our conclusion that most massive black holes are spinning very rapidly.

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