EPISODIC ACTIVITIES OF SUPERMASSIVE BLACK HOLES AT REDSHIFT $z \leq 2$: DRIVEN BY MERGERS?

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ABSTRACT

It has been suggested for quite a long time that galaxy mergers trigger activities of supermassive black holes (SMBHs) on the grounds of imaging observations of individual galaxies. To quantitatively examine this hypothesis, we calculate quasar luminosity functions (LFs) by manipulating the observed galaxy LFs provided that the mass ratio ($q$) of the secondary galaxy to the newly formed one changes with cosmic time. The results show that the fraction of major mergers decreases from $f_{\text{maj}} \sim 0.2$ at $z \sim 2$ to $f_{\text{maj}} \rightarrow 0$ at $z \sim 0$. As a consequence, the newly formed SMBHs from major mergers at $z \sim 2$ may acquire a maximal spin due to the orbital angular momentum of the merging holes. Subsequently, random accretion led by minor mergers rapidly drives the SMBHs to spin down. Such an evolutionary trend of the SMBH spins is consistent with the fact that radiative efficiency of accreting SMBHs strongly declines with cosmic time, reported by Wang et al. This suggests that minor mergers are important in triggering activities of SMBHs at low redshift, while major mergers may dominate at high redshift.

Key words: galaxies: evolution – galaxies: high-redshift – quasars: general

1. INTRODUCTION

In the hierarchical model of galaxy formation, quasar activities are related to the mergers of galaxies (e.g., Toomre 1977; Hernquist 1989; Barnes & Hernquist 1992; Hopkins et al. 2008). During the merging processes, tidal torque drives gas inflows into the inner region of galaxies, forming starbursts and igniting the central supermassive black holes (SMBHs; e.g., Hernquist 1989; Barnes & Hernquist 1996; Springel et al. 2005). Once quasar activities are triggered, the mutual interaction between the SMBHs and galaxies is unavoidable accompanied by feedback of active galactic nuclei (AGNs; e.g., outflows or radiation; see Di Matteo et al. 2005; Croton et al. 2006; Bower et al. 2006). This is believed to regulate coevolution of SMBHs and their host spheroids, inferred from the well-established correlation between SMBH mass and spheroid mass or dispersion velocity (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Marconi & Hunt 2003; Häring & Rix 2004); however, the details remain open.

Based on the long-standing “merger hypothesis” (Toomre 1977), quasar luminosity functions (LFs) have been extensively modeled within the framework of hierarchical structure formation (Roos 1985; Carlberg 1990; Haehnelt & Rees 1993; Haiman & Loeb 1998; Wyithe & Loeb 2002, 2003; Volonteri et al. 2003; Hopkins et al. 2008; Shen 2009). A brief summary of hierarchical models from the published literature is given in Table 1. We note that most models employ major mergers. In these models, the scaling relations between black hole mass and dark matter halo mass are generally employed to combine the mergers of galaxies with dark matter halos. The dark matter halos follow the extended Press–Schechter (EPS) theory (e.g., Lacey & Cole 1993). After a merger event, a quasar is ignited and shines at the Eddington luminosity with a universal light curve. The rapid decreases as a main feature of quasar LFs can be well produced by the decrease in the merger rates and the availability of cold gas to fuel the SMBHs after the peak activities of SMBHs. Although these models quantitatively describe the shape of quasar LFs, it is still insufficient to understand the cosmological evolution of quasars in light of merger hypothesis.

There is increasing evidence showing that major mergers cannot constitute the only triggering mechanism of quasar activities from observations based on the studies of absorption properties of AGNs (e.g., Hasinger 2008) or the galaxy morphologies (e.g., Georgakakis et al. 2009; Rechard et al. 2009), as well as from theoretical work by modeling LFs of low-level AGNs (e.g., Hopkins & Hernquist 2006; Marulli et al. 2007). It is evident that minor mergers between galaxies and smaller satellites occur much more frequently (Barnes & Hernquist 1992; Mihos & Hernquist 1994). Many previous works have investigated the role of minor mergers in triggering quasar activities (Gaskell 1985; Hernquist 1989; Hernquist & Mihos 1995; De Robertis et al. 1998; Taniguchi & Wada 1996; Taniguchi 1999; Corbin 2000; Chatzichristou 2002; Kendall et al. 2003; Hopkins & Hernquist 2009a). Assuming that growth of SMBH occurs via episodic accretion in light of Soltan’s argument (Soltan 1982), Wang et al. (2009, hereafter W09) derived an $\eta$-equation to describe cosmological evolution of radiative efficiency of SMBHs. It is found that the radiative efficiency does exhibit a strong cosmological evolution: it decreases from $\eta \sim 0.3$ at $z \sim 2$ to $\eta \sim 0.03$ at $z \sim 0$. This can be interpreted by the mounting importance of minor mergers toward low redshifts. At high redshift, major mergers produce fast rotating SMBHs due to conservation of (orbital) angular momentum of the merging holes. Subsequently random accretion, which may be related to minor mergers (Kendall et al. 2003; King & Pringle 2007), acts to spin them down efficiently.

In this paper, we extend previous model (Wyithe & Loeb 2002) and construct quasar LFs from the observed galaxy LFs and theoretical merger rates. Our goal is to investigate the redshift-dependent merger history and the resulting spin evolution of SMBHs. We describe our model in Section 2. In Section 3, we present comparisons of the modeled quasar LFs with the observational data, followed by discussions on the merger history and accretion history, and the spin evolution...
of SMBHs. The conclusions are drawn in Section 4. We use cosmological constants $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, the Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $\sigma_8 = 0.87$ throughout the paper.

2. MERGERS AND BLACK HOLE ACTIVITIES

2.1. Merger Rates of Galaxies

It is generally assumed that galaxies reside in the central region of dark matter halos, and consequently galaxy mergers follow dark matter halo mergers. In our calculations, this is implemented through the relationship between the masses of central SMBHs in galaxies and their host dark matter halos. First, we present merger rates of dark matter halos based on the EPS theory in this section. The probability for a halo of mass $M_1$ at time $t$ merging with another halo of mass $\Delta M$ is given by (Lacey & Cole 1993)

$$ \mathcal{R} = \kappa \frac{1}{\pi} \frac{1}{t} \frac{(d \ln \delta_c)}{d \ln M_2} \frac{d \ln \sigma_2}{d \ln M_2} \frac{\delta_c}{\sigma_2^2} \left( 1 - \frac{\sigma_2^2}{\sigma_1^2} \right)^{-\frac{1}{2}} \times \exp \left[ - \frac{\delta_c^2}{2} \left( \frac{1}{\sigma_1^2} - \frac{1}{\sigma_2^2} \right) \right], \tag{1} $$

where $M_2 = M_1 + \Delta M$ is the mass of newly formed halo, $\sigma_1 = \sigma(M_1)$, and $\sigma_2 = \sigma(M_2)$. The expression of $\sigma$ is given by

$$ \sigma^2(M) = \int_0^M \frac{dk}{2\pi} k^2 P(k) \left[ \frac{3j(kR)}{kR} \right]^2, \tag{2} $$

where $j(x) = (\sin x - x \cos x)/x^2$, $\rho_0 = 3H_0^2\Omega_m/8\pi G$, and $M = 4\pi \rho_0 R^3/3$ is the mass within a comoving sphere of radius $R$, $G$ is the gravity constant, $H$ is the Hubble constant, and $\Omega_m$ is the fraction of baryons. The primordial power-law spectrum is

$$ P(k) = p_0 k T^2(k), \tag{3} $$

where the transfer function is $T(k) = (1 + \sum_{i=1}^{4} c_i q_i^{-1/4}(c_5 q_i^{-1}) \ln(1 + c_5 q_i))$, $c_1 = 3.89$, $c_2 = 259.21$, $c_3 = 162.77$, $c_4 = 2027.17$, $c_5 = 2.34$, $p_0$ is determined by observations of $\sigma_8$ at 8 $h^{-1}$ Mpc and $q = k/(Q_m h^2 Mpc^{-1})$, where $h$ is the Hubble constant in a unit of 100 km s$^{-1}$ Mpc$^{-1}$. $\delta_c(t)$ is expressed by

$$ \delta_c(t) = \delta_{c,0} \left( \frac{\ln t}{\tau} \right)^{2/3} = 1.69 \left( \frac{\ln t}{\tau} \right)^{2/3}, \tag{4} $$

where $\tau_0$ is a referenced epoch.

2.2. Quasar Luminosity Functions

In modeling quasar LFs, we extend the method of Wyithe & Loeb (2002) by employing the realistic galaxy LFs instead of the halo mass function and considering the redshift-dependent merger history. To derive quasar LFs from known galaxy LFs through mergers, we assume that (1) each galaxy hosts an SMBH; (2) all mergers trigger SMBH activities; and (3) a merger simultaneously triggers an SMBH activity. We neglect the time delay between a galaxy merger and igniting of the central SMBH.

We use the scaling relation between the black hole mass and the dispersion velocity $M_\bullet \propto \sigma^3$ (Tremaine et al. 2002) to connect SMBHs with dark matter halos. The dispersion velocity correlates with the Keplerian velocity of the dark matter halo via $v_c \propto \sigma^\beta$ with $\beta \approx 0.84$ (Ferrarese 2002), where $v_c$ is determined by $M_H$ (Barkana & Loeb 2001):

$$ v_c = 159.4 M_H^{1/3} \left( \frac{\Omega_m}{\Omega_m + \Lambda} \right)^{1/6} \left( 1 + z \right)^{1/2} \text{km s}^{-1}. \tag{5} $$

where $M_{H,12} = M_H/10^{12} M_\odot$ is the dark matter halo mass, $\Delta_c = 18\pi^2 + 82d - 39d^2$ is the critical density relative to the critical density at redshift $z$, $d = \Omega_{m,z} - 1$ and $\Omega_{m,z} = [\Omega_m(1+z)^3]/[\Omega_m(1+z)^3 + \Omega_\Lambda]$. The ratio of SMBH mass to halo mass is then computed as (Wyithe & Loeb 2002)

$$ \epsilon = \frac{M_\bullet}{M_H} = \epsilon_0 M_{H,12}^{\gamma/3 - 1} \left( \frac{\Omega_m}{\Omega_m + \Lambda} \right)^{1/6} h^{-1}(1+z)^{\gamma/2}, \tag{6} $$

where $\gamma = 4/\beta = 4.76$, and $\epsilon_0$ is a free parameter. We note that $\epsilon$ is weakly dependent on $M_H$, but sensitive to redshift. The nonlinear relation between SMBH mass and halo mass with $\gamma > 3$ is due to the significant baryon accretion during
SMBH activities visible to observers (Yu & Tremaine 2002). It is worth pointing out that the potential evolution of \( y \) is poorly understood (e.g., Shields et al. 2003; Jahnke et al. 2009; Shields et al. 2006; Alexander et al. 2008; Coppin et al. 2008). In our model, we take \( y = 4.76 \) and neglect the effects of its evolution. The modeled quasar LFs are found to be insensitive to \( y \).

Once a quasar is triggered, it is assumed to shine with a universal \( B \)-band light curve as (see also Haiman & Loeb 1998)

\[
L_B(t) = M_B f(t) = \epsilon M_B f(t), \quad (M_{\text{H}} > M_{\text{H, min}}),
\]

where \( f(t) \) is a function of time, and \( M_{\text{H, min}} \) is the minimum mass of the halo, inside which an SMBH can form. Here we simply use a step function for \( f(t) \) (Wyithe & Loeb 2002),

\[
f(t) = \frac{\lambda L_{\text{Edd}}}{C_B M_*} \Theta \left( \frac{M_{\text{H}}}{M_*} t_{\text{dc,0}} - t \right),
\]

where \( L_{\text{Edd}} = 3.18 \times 10^{38} (M_*/M_\odot) \) is the Eddington luminosity, \( \lambda \) is the Eddington ratio, \( M_{\text{H}} \) is the mass of the secondary halo, \( \Theta(t) \) is the Heaviside step function, \( C_B \) is the bolometric correction factor defined as the bolometric luminosity \( L_{\text{bol}} = C_B L_B \) (Marconi et al. 2004). This light curve takes into account that the gas deposited from the satellite galaxy runs out in a time proportional to \( \Delta M_{\text{H}}/M_{\text{H}} \) (Wyithe & Loeb 2002). It turns out that spectral energy distributions (SEDs) of AGNs have no appreciable evolution with cosmic time (e.g., Shen et al. 2008). This would guarantee that Eddington ratio \( (\lambda) \) may also be independent of redshift, according to its correlation with the SEDs (Wang et al. 2004). A similar conclusion has been drawn through an analysis of a large quasar sample from the Sloan Digital Sky Survey (SDSS; Shen et al. 2008) and the AGN and Galaxy Evolution Survey (AGES; Kollmeier et al. 2006), respectively. Therefore, we assume that the triggered SMBHs shine at a fixed Eddington ratio. The value of \( \lambda \) can be obtained from fittings of quasar LFs.

With these assumptions, the modeled quasar LFs can be written as (Wyithe & Loeb 2002)

\[
\Psi(L_B, z) = \int_{z}^{\infty} d z' \int_{M_{\text{min}}}^{M_*} d M_* \int_{0}^{q M_*} d \delta L_B - M_* f(t_z - t') \frac{d N_{\text{merg}}}{d M_* dt'} \frac{d t'}{d M_*} d M_*.
\]

The upper limit forces the secondary galaxy to always be smaller than the primary one. We treat \( q \) as a function of redshift and constrain it from the fittings of quasar LFs.

Integrating over \( M_* \), we can find

\[
\Psi(L_B, z) = \int_{z}^{\infty} d z' \frac{L_B}{M_* f(t_z - t')} \int_{0}^{q M_*} \frac{d N_{\text{merg}}}{d M_* dt'} \frac{d t'}{d M_*} d M_*.
\]

Quasars in the cosmic time range \((t_z - t_Q, t_z)\) with a lifetime \( t_Q = (\Delta M_{\text{H}}/M_{\text{H}})H_{\text{dc,0}} \) contribute to the LFs at cosmic time \( t_z \). Since the lifetime is much smaller than the cosmic time \( t_z \sim H(z)^{-1} \) at the redshift \( z < 2 \), we can then integrate over \( z' \) by replacing \( d t' \) with \((\Delta M_{\text{H}}/M_{\text{H}})H_{\text{dc,0}} \). We employ the galaxy LFs, defined as \( \Phi(L', z) \), to trace the SMBH mass function \( d n_*/d M_* \), and use the ratio \( (M_*/M_{\text{H}}) \) to calculate the merger rate of SMBHs from that of dark matter halos,

\[
\frac{d N_{\text{merg}}}{d M_* dt'} = \frac{3}{\gamma e} \frac{d^2 N_{\text{merg}}}{d M_* dt'} = \frac{3}{\gamma e} \frac{\dot{\mathcal{R}}}{M_*}.
\]

where \( M_{\text{H}} = M_{\text{H}} - \Delta M_{\text{H}} \). Finally, we get the quasar LFs

\[
\Psi(L_B, z) = \int_{t_{\text{dc,0}}}^{t_z} \frac{d L'}{d L_B} \frac{d^2 N_{\text{merg}}}{d M_* dt'} \frac{\dot{\mathcal{R}}(L', z)}{M_{\text{H}}} - d M_{\text{H}}.
\]

where \( \dot{\mathcal{R}}(L'/d L_B) \) comes from the different luminosity bands used in the galaxy and quasar LFs, and \( L' \) is the luminosity of galaxies hosted in the halos with a mass \( M_{\text{H}} - \Delta M_{\text{H}} \). We calculate \( L' \) using the relation between the R-magnitude of normal galaxies and the mass of black holes from McLure & Dunlop (2002; see the Appendix). Note that the low limit in Equation (13) is set so that the secondary galaxy should be massive enough to provide significant gas for the mass assembly of the newly formed black hole.

With the merger rates, we have a duty cycle time \( \delta \) of the quasars during a Hubble time \( H_z^{-1} \).

\[
t_{\text{dc}}(L_B, z) = \int_{0.05 M_{\text{H}}}^{0.5 M_{\text{H}}} \frac{\Delta M_{\text{H}}}{H_z^{-1} \dot{\mathcal{R}} d M_{\text{H}}},
\]

where \( H_z \) is the Hubble constant at redshift \( z \). We also define a fraction of major mergers to the total as

\[
f_{\text{maj}}(z, M_{\text{H}}) = \frac{\dot{N}_{\text{maj}}(z, M_{\text{H}})}{\dot{N}_{\text{tot}}(z, M_{\text{H}})},
\]

where

\[
\dot{N}_{\text{maj}}(z, M_{\text{H}}) = \int_{0.25 M_{\text{H}}}^{0.5 M_{\text{H}}} \dot{\mathcal{R}}(z) d M_{\text{H}},
\]

and

\[
\dot{N}_{\text{tot}}(z, M_{\text{H}}) = \int_{0.05 M_{\text{H}}}^{0.5 M_{\text{H}}} \dot{\mathcal{R}}(z) d M_{\text{H}}.
\]

According to the definition of a major merger, when \( q(z) \leq 0.25 \), we have \( f_{\text{maj}} = 0 \). We stress here that the parameter \( f_{\text{maj}}(z) \) conveniently traces the gradual evolution from major to minor mergers, showing a merger history.

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5 Basically, the gas from the satellite galaxy is

\[
\Delta M_{\text{gas}} = \frac{\Delta M_{\text{gas}}}{M_{\text{H}}} = \frac{\Delta M_{\text{H}}}{M_{\text{H}}} \approx \frac{\Delta M_{\text{H}}}{M_{\text{H}}} M_*. \]

where the ratios \( \epsilon = M_*/M_{\text{H}} \) and \( \Delta M_{\text{gas}}/\Delta M_{\text{H}} \) are assumed as constants in a zeroth-order approximation. As accretion of the SMBH is limited at the Eddington rate, the gas will run out via accretion in a time proportional to \((\Delta M_{\text{H}}/M_{\text{H}}) \).

6 Note that here “duty cycle time” refers to the active time of the quasars in a timescale \( H_z^{-1} \).
As a summary, Table 2 gives a list of the free parameters used in our model. The parameter $q$ determines both the shape and the number density of quasars. The amplitude of quasar LFs is linearly proportional to $q_{\lambda,0}$, which is easily justified from Equation (13). The other parameters ($\epsilon_0$ and $\lambda$) can be independently quantified by theoretical or observational arguments. Fitting quasar LFs would provide more precise values of these parameters deliberately.

### 3. COMPARISON WITH OBSERVATIONS

#### 3.1. Modeling Quasar LFs

We use two sets of galaxy LFs well determined by the Hubble Space Telescope and the Great Observatories Origins Deep Survey (Dahlen et al. 2005), and VIMOS-VLT Deep Survey (Ilbert et al. 2005), respectively. Since both sets of galaxy LFs are only available for $z \lesssim 2.0$, the modeled quasar LFs are then also limited. Galaxy LFs are generally described by

$$\Phi(L, z) = \Phi_s \left( \frac{L}{L_*} \right)^\alpha \exp \left( - \frac{L}{L_*} \right),$$  \hspace{1cm} (18)

where $\Phi_s$ is a constant, $\alpha$ is an index, and $L_*$ is the cutoff luminosity of galaxies. We have to keep in mind that the galaxy LFs are based on photometric redshifts. We use quasar LFs determined by the combined data of the Two-Degree Field survey and the SDSS, which to date are the best constrained LFs with unprecedented precision (10,637 quasars) and the dynamic range ($g$-band flux limit of 21.85; Croom et al. 2009).

Quasar LFs are characterized by double power laws with a break luminosity (e.g., Hopkins et al. 2007). In our model, the break luminosity is mainly determined by the cutoff luminosity of galaxies ($L_*$). The indices of the double power laws of quasar LFs are jointly determined by $\alpha$ and the merger rates. In modeling quasar LFs, the free parameters ($\lambda$, $\epsilon_0$, and $q_{\lambda,0}$) degenerate weakly. However, their typical values can be quantified directly from observations. We fix $\lambda \sim 15$ (Shen et al. 2008), $q_{\lambda,0} \sim 3.0 \times 10^5$ yr (Martini & Weinberg 2001), and $\epsilon_0 \sim 10^{-5}$ (Ferrarese 2002). We calculate a grid of quasar LFs in a range of $\lambda$, $q_{\lambda,0}$ and $\epsilon_0$ around their typical values and then obtain the fitting values accordingly.

The best fittings with minimal $\chi^2$ are given in Table 2 and shown in Figure 1. We find that the global features of quasar LFs can be well produced by Equation (13). The results modeled by galaxy LFs from Ilbert et al. (2005) and Dahlen et al. (2005) are in reasonable agreement. To match the observational data, we find that $q$ must be a function of redshift for both sets of galaxy LFs. We get a dependence of the mass ratios $q$ with respect to redshift as shown in Figure 2(a). It is found that $q$ exhibits a rapid decline with redshift. A more explicit parameter $f_{\text{maj}}$
clearly shows significant evolution with redshift in Figure 2(b): it decreases from $f_{\text{maj}} \sim 0.2$ at $z \sim 2$ to $f_{\text{maj}} \rightarrow 0$ at $z \sim 0$. This suggests a merger history with a trend from major to minor since $z \sim 2$. Major merger rates measured from the Hubble Ultra Deep Field get a peak at $z \sim 1–2$ (Ryan et al. 2008), further supporting the evolution of $f_{\text{maj}}$ obtained here.

The duty cycle time is obtained from Equation (14), and the results are illustrated in Figure 3(a). We find that $t_{dc}$ is strongly dependent on redshift, but insensitive to the quasar luminosity, namely, the SMBH mass. The typical duty cycle time is $\gtrsim 10^7$ years, indicating that the SMBHs are undergoing many episodes (Martini 2004; Wang et al. 2006, 2008, 2009). The lifetime of quasars is longer at higher redshift. This should be due to the increase of merger rates and the mounting importance of major mergers with increasing redshift. Major mergers provide more abundant gas, and thus drive SMBH activities to live longer than minor mergers. We also calculate the luminosity-averaged duty cycle time in Figure 3(b), and simply fit its relation to redshift as

$$\bar{t}_{dc}(z) = 2 \times 10^6 (1 + z)^{2.5} \text{yr.}$$

The evolution of the duty cycle time should be independently examined by future observational data, for example from the clustering measurements of quasars (for a review see Martini 2004). In addition, a more realistic model of the quasar lifetime and light curve (Hopkins et al. 2005; Hopkins & Hernquist 2009b) is worth considering in a future paper.

For the bin of $0.4 \leq z \leq 0.68$, we find the modeled LFs under and overestimate the observed number of quasars at faint and bright tails, respectively. Bonoli et al. (2009) also find similar behaviors from semi-analytically modeling quasar LFs coupled with numerical simulations. The overestimate for the bright tail is because most of the galaxies are gas-poor (dry mergers, see Lin et al. 2008) and some fraction of (low-level) quasar activities may be stochastical accretion-driven (Hopkins & Hernquist 2006). This naturally drives an underestimate of quasars for the faint tail regarding passive evolution of galaxies after $z \sim 1$ (Faber et al. 2007).

### 3.2. Mergers and Accretion History

Major mergers are undoubtedly taking place in very luminous submillimeter galaxies at $z \sim 2–3$ (Tacconi et al. 2006, 2008). Detailed studies from Spectroscopic Imaging survey in the near-infrared with SINFONI (SINS) of high-redshift galaxies ($z \sim 1–3$) show that about one-third of the galaxies are rotation-dominated rings/disks undergoing star formations, another one-third are compact and velocity-dispersion-dominated objects, and the remaining are clearly interacting/merging systems (Genzel et al. 2008; Förster Schreiber et al. 2009). It appears that rapid and continuous gas accretion via “cold flows” and/or minor mergers are playing an important role in driving star formation and the assembly of star-forming galaxies (Genzel et al. 2008; Förster Schreiber et al. 2009). Based on morphologies of X-ray-selected AGNs with redshifts $0.5 \leq z \leq 1.3$, Georgakakis et al. (2009) suggested that AGNs in disk galaxies are likely fueled by minor mergers. More interestingly, Robaina et al. (2009) reported that only less than 10% of star formation in massive galaxies for $z \sim 0.6$ is triggered by major interaction. These pieces of independent evidence are consistent with the change of the major merger fraction as shown in Figure 2(b).
The importance of minor mergers in triggering SMBH activities has been realized by many authors (e.g., De Robertis et al. 1998; Hernquist & Mihos 1995; Taniguchi 1999; Kendall et al. 2003; Hopkins & Hernquist 2009a). The dynamical studies of minor mergers find that the merging satellites retain memory of the initial random orientations when arriving at the nucleus of the primary galaxy (Kendall et al. 2003). We therefore may infer that during a succession of minor mergers, gas fueling to the central SMBH will carry on in a manner with stochastical orientations relative to the host galactic plane. This affords a natural explanation of random accretion proposed by King & Pringle (2006, 2007), as one fueling scenario to AGNs. There are several independent indications for minor mergers as a triggering mechanism of random accretion.

First, radio jets in a sample of nearby Seyfert galaxies (z ≤ 0.03) have a random orientation with respect to their host galactic plane (Kinney et al. 2000). Presumably, the jet direction aligns with the axis of the accretion disk; therefore, the fueling gas to the SMBHs could not be supplied from their host galaxies directly (see a brief review of fueling mechanisms of SMBHs in Taniguchi 1999), but probably from minor mergers (King & Pringle 2007).

Second, AGN types are independent of orientations of their host galaxies (Keel 1980; Dahari & De Robertis 1988; Munoz Marin et al. 2007). Additionally, the orientations of extended [O III] emission in some nearby Seyfert galaxies have no correlation with the major axis of the host galaxies (Schmitt et al. 2003). This suggests that the dusty torus axis is not aligned with the host galaxy rotation axis.

Third, W09 derived an η-equation to describe cosmological evolution of radiative efficiency of accretion into SMBHs, based on the argument that the SMBH growth is dominated by baryon accretion (Soltan 1982). Applying the equation into existing survey data of quasars and galaxies, they report that the radiative efficiency strongly evolves with redshift, with values of η ∼ 0.3 at z ∼ 2 and η ∼ 0.03 at z ∼ 0. As described below, episodic random accretion definitely leads to a decrease in spin for SMBHs. Presumably, with the link between radiative efficiency and SMBH spin (Thorne 1974), this trend clearly supports the cosmological evolution of mergers from major at high-z to minor at low-z found from our model of quasars LF.

With the above comprehensive indications and the results obtained in our model of quasar LFs, it quite appears that minor mergers may mainly be driving SMBH activities after z ∼ 2.0, and random accretion driven by minor mergers supplies shining power of the quasars.

### 3.3. Spin Evolution

During the active phases of a quasar, the SMBH accretes a significant amount of gas to build up its mass (the Soltan’s argument; see also Yu & Tremaine 2002; Volonteri et al. 2003). The previous studies using hierarchical merger tree found that mass accretion also plays a dominant role in determining spin evolution of black holes compared with coalescence (Volonteri et al. 2005; Berti & Volonteri 2008). However, the detailed spin distribution of black holes depends on the specific accretion scenarios: prolonged or random accretion. In prolonged accretion, the material keeps constant sign of angular momentum. In this case, an initially non-rotating black hole that accretes about one-third of its mass will end up very fast spinning (Thorne 1974). By contrast, random accretion rapidly spins down black holes (Berti & Volonteri 2008). On the other hand, in a major coalescence some orbital angular momentum of a black hole may be converted to the spin of the newly formed black hole. This most likely yields a rapidly rotating black hole.

As mentioned above, random accretion can be naturally interpreted through stochastically oriented minor mergers (Kendall et al. 2003). We have shown that minor mergers become important in driving SMBH activities toward low redshifts. Then we can estimate spin evolution of SMBHs due to random accretion induced by minor mergers. For an approximation, we apply the equation a = a0(M∗0/M0)η (Equation (26) in Hughes & Blandford 2003, for random captures of minor black holes originally). Here a = Jc/GM2 is the spin parameter of a black hole with a mass M, and angular momentum J, c is the speed of light, a0 and M0 are the initial spin and mass of the hole, respectively. Under the assumption that each merger triggers a quasar activity, the number of merger events can be estimated through the ratio of the duty cycle time to the average lifetime of a single activity

\[ n = \frac{t_{dc}}{\Delta t_Q}, \]  

where \( t_{dc} \) is the average lifetime of a single activity, \( t_{dc} \) is given by Equation (19). The lifetime of a single activity can be inferred from the proximity effect, \( \Delta t_Q \sim 1 \) Myr (Kirkman & Tytler 2008). For z ∼ 2, we apply \( t_{dc} \sim 3 \times 10^7 \) yr and then obtain the order-of-magnitude estimate n ∼ 10. To satisfy the ratio of SMBH mass and halo mass in Equation (6), the mass growth of SMBHs due to accretion during each merger is (see also Volonteri et al. 2003)

\[ \Delta m = \frac{γ v^6}{3} \Delta M_H = \frac{γ}{3} \langle ξ \rangle M_*, \]  

where \( \langle ξ \rangle \) is the average mass ratio of two merging galaxies/halos. The total mass growth during a Hubble time is thus

\[ \frac{\Delta M_*}{M_*} = \frac{n \Delta m}{M_*} = \frac{γ}{3} n \langle ξ \rangle \sim 2, \]  

where \( γ = 4.76 \) and we set \( \langle ξ \rangle \) ∼ 0.1 for minor mergers. Consequently, the spin of the black hole drops off by a factor of 32–4 from z ∼ 2 to z ∼ 0. This is generally consistent with the results found by Berti & Volonteri (2008) that random accretion predicts the spin distribution with \( a \lesssim 0.1 \).

We may suggest a picture that at high redshift z ∼ 2, the newly formed SMBHs from major mergers acquire a rapid spin due to the orbital angular momentum of the merging holes, and subsequently random accretion driven by minor mergers may rapidly spin them down. It is interesting to note that King et al. (2008) proposed a scenario that self-gravity of a accretion disk can give rise to a long series of episodic activities during a major merger event. We neglect this effect in our model. A future work combining spin evolution with semi-analytical theory will provide new insights into the coevolution among SMBHs, galaxies and dark matter halos.

### 4. CONCLUSIONS

With the assumption that black holes are triggered through galaxy mergers, we successfully reproduce the observed quasar LFs by manipulating the galaxy LFs and merger rates from semi-analytic theory from z ∼ 0 to z ∼ 2.0. This supports that mergers are driving black hole activities with many episodes. We find that minor mergers become important in triggering quasar activities toward low redshifts. As a natural consequence of minor mergers, the random accretion may drive growth and
spin evolution of SMBHs at low redshift. The estimated spin declines rapidly with decreasing redshift in agreement with the evolutionary trend of radiative efficiency for SMBHs.

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APPENDIX

INFLUENCES OF $M_\bullet-L_{\text{bul}}$ RELATIONSHIP ON QUASAR LFs

The relationship between SMBH mass and bulge luminosity ($M_\bullet-L_{\text{bul}}$) is an important ingredient in modeling quasar LFs from the galaxy LFs. Many previous works have focused on this relationship (see Table 3 for a brief summary). Unfortunately, not all of them reach the consistent conclusions. At first glance, the quiescent galaxies have a steeper slope of $M_\bullet-L_{\text{bul}}$ than the AGNs. This may be due to neglecting the effect of radiation pressure, which causes underestimations of black hole mass in AGNs as proposed by Marconi et al. (2008; see, however, Netzer 2009). Meanwhile, Graham (2007) recently made an attempt to compensate for the analysis techniques employed by previous groups (McLure & Dunlop 2002; Marconi & Hunt 2003; Erwin et al. 2004). They took into account a number of issues, e.g., the removal of a dependency on the Hubble constant and a correction for the dust attenuation in bulges and disk galaxies. After careful revisions and adjustments, they found the differences among previous groups could be eliminated and they reproduced a somewhat shallower slope. However, they did not exclude the potential sample bias, which might lead to a similar relation as McLure & Dunlop (2002; see Equation (A7) in Graham 2007).

To sum up, there appear to be many unclear aspects in the $M_\bullet-L_{\text{bul}}$ relationship that deserve further examinations with improved observational data. We adopt McLure & Dunlop’s relation in the present work. To show the influences of $M_\bullet-L_{\text{bul}}$ relationship on the quasar LFs, we simply perform an approximate estimate. For $\Delta M_\text{HI}/M_\text{HI} \ll 1$, we have the merger rate (Lacey & Cole 1993)

$$\dot{R} \propto \left( \frac{\Delta M_\text{HI}}{M_\text{HI}} \right)^{-3/2}. \quad (A1)$$

Using the $M_\bullet-L_{\text{bul}}$ relation and the mass ratio between the black hole and the dark matter halo, we have

$$M_\text{HI} = M_\bullet/\epsilon \propto 10^{bM_\bullet}/\epsilon, \quad (A2)$$

and the galaxy LFs in $R$ band

$$\Phi(R) \propto 10^{0.4(1+\alpha)(M_\bullet-M_\text{bul})} \exp\left[-10^{0.4(M_\bullet-M_\text{bul})}\right], \quad (A3)$$

where $M_\text{bul}^* = 10^{z+eM_\text{bul}}$. Combining the above equations into Equation (13) and performing some mathematical expansions for $\Delta M_\text{HI}/M_\text{HI} \ll 1$, we have the quasar LFs approximately as

$$\Psi \propto \int_0^\infty \left( \frac{\Delta M_\text{HI}}{M_\text{HI}} \right)^{-1/2} \left( \frac{M_\text{bul}^*/M_\text{HI}}{1-\Delta M_\text{HI}/M_\text{HI}} \right)^{0.4(1+\alpha)/b} \exp\left[-\left( \frac{M_\text{bul}^*/M_\text{HI}}{1-\Delta M_\text{HI}/M_\text{HI}} \right)^{0.4/b}\right] d\Delta M_\text{HI} \propto \left( \frac{M_\text{bul}^*/M_\text{HI}}{M_\text{HI}} \right)^{0.4(1+\alpha)/b} \exp\left[-\left( \frac{M_\text{bul}^*/M_\text{HI}}{M_\text{HI}} \right)^{0.4/b}\right] \propto \left( \frac{L^*}{L} \right)^{0.4(1+\alpha)/b} \exp\left[-\left( \frac{L^*}{L} \right)^{0.4/b}\right]. \quad (A4)$$

We can find that the break luminosity $L^*$ of the quasar LFs is dependent on the cutoff luminosity $M_\text{bul}^*$ of the galaxy LFs, and the slope $0.4(1+\alpha)/b$ is relative to the slope of the $M_\bullet-L_{\text{bul}}$ relation.

| Table 3 |
| Relationship: $\log (M_\bullet/M_\odot) = a + b M_\text{bul}$, from Published Literature |

| Reference | Sample$^a$ | Band$^b$ | $a$ | $b$ | Scatter | Note |
|-----------|------------|---------|-----|-----|---------|------|
| MD02      | 72S+18E    | R       | -2.96 ± 0.48 | -0.50 ± 0.02 | 0.39 | ... |
| BFFF03    | 20E        | R       | -3.00 ± 1.35 | -0.50 ± 0.06 | 0.39 | ... |
| MH03      | 12E+10S    | B       | -2.54 ± 1.10 | -0.50 ± 0.05 | 0.48 | ... |
| EGCO4$^c$ | 8E+5S      | R       | +1.70        | -0.25         | 0.35 | ... |
| G07       | 12E+10S    | R       | +1.40 ± 0.33 | -0.38 ± 0.04 | 0.33 | Sample bias? |
| L07       | 100E+55S+64B | V   | -3.70 ± 0.77 | -0.55 ± 0.03 | ... | ... |
| K08       | 45S        | R       | -2.87 ± 0.04 | -0.50         | 0.41 | Fix $\beta$ |
| BPPV09    | 19E        | V       | -1.67 ± 1.58 | -0.47 ± 0.08 | 0.64 | Fitting routine? |
| BPPV09    | 26A        | V       | +1.22 ± 0.75 | -0.32 ± 0.04 | 0.44 | Fitting routine? |

Notes.

$^a$ “E” is for elliptical galaxies, “S” is for either S0 galaxies or Spiral galaxies, “A” is for AGNs, and “B” is for bright cluster galaxies.

$^b$ $B - R = 1.52$ and $V - R = 0.61$ from Fukugita et al. (1995) are used to convert $B$- and $V$-band magnitude to $R$-band magnitude. The standard relation $\log L_V/L_R = 0.4(\log M_V + 4.83)$ is employed to calculate $M_V$ from $L_V$ (Bentz et al. 2009) and $M_{R,\odot} = 5.47$ is used (Cox 2000).

$^c$ We artificially extract the data from Figure (1.3) in EGCO4.

References. MD02: McLure & Dunlop 2002; BFFF03: Bettoni et al. 2003; MH03: Marconi & Hunt 2003; EGCO4: Erwin et al. 2004; G07: Graham 2007; L07: Lauer et al. 2007; K08: Kim et al. 2008; BPPV09: Bentz et al. 2009.
