ABSTRACT

Episodic activity of quasars is driving growth of supermassive black holes (SMBHs) via accretion of baryon gas. In this Letter, we develop a method to analyze the duty cycle of quasars up to the redshift \( z \sim 6 \) universe from luminosity functions (LFs). We find that the duty cycle below redshift \( z \sim 2 \) follows the cosmic history of star formation rate (SFR) density. Beyond \( z \sim 2 \), the evolutionary trends of the duty cycle are opposite to that of the cosmic SFR density history, implying the role of feedback from black hole activity. With the duty cycle, we get the net lifetime of quasars \( (z\leq5) \) about \( \sim10^6 \) yr. Based on the local SMBHs, the mean mass of SMBHs is obtained at any redshifts and their seeds are of \( 10^7 M_\odot \) at the reionization epoch \( (z_{\text{re}}) \) of the universe through the conservation of black hole number density in a comoving frame. We find that primordial black holes \( (\sim10^3 M_\odot) \) are able to grow up to the seeds via a moderate super-Eddington accretion of \( \sim30 \) times the critical rate from \( z = 24 \) to \( z_{\text{re}} \). Highly super-Eddington accretion onto the primordial black holes is not necessary.

Subject headings: black hole physics — galaxies: active — galaxies: evolution — galaxies: nuclei — quasars: general

1. INTRODUCTION

Accretion of gas onto SMBHs is powering the huge energy output from quasars, but SMBH formation and quasar lifetime remain open in this well-established paradigm. The elegant idea, comparing the total accreted mass density during the active phases with the local mass density of SMBHs in normal galaxies (Sołtan 1982, hereafter the Sołtan argument), has been examined in detail from the quasar LF (Chokshi & Turner 1992; Yu & Tremaine 2002) and X-ray background (Marconi et al. 2004). This generally convinces us that accretion during their episodic activities is the main source of mass growth. However, the SMBH growth at different redshifts remains open.

In the present Letter, we make an attempt to develop an efficient way to estimate the duty cycle for high redshifts, offering a new clue to understand SMBH growth at different redshifts. We use the cosmological parameters \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_r = 0.3 \), and \( \Omega_\Lambda = 0.7 \) throughout this Letter.

2. DUTY CYCLE OF QUASARS

The SMBH mass function at redshift \( z \) in active and dormant galaxies is \( N(M_\bullet, z) \); the duty cycle is defined as the fraction of active black holes to the total,

\[
\delta(M_\bullet, z) = \frac{\Psi(M_\bullet, z)}{N(M_\bullet, z)},
\]

where \( M_\bullet \) is black hole mass and \( \Psi(M_\bullet, z) \) is the mass function of black holes in quasars at redshift \( z \). The averaged duty cycle is \( \bar{\delta}(z) = \frac{\bar{N}_\text{re}(z)}{N_\text{all}(z)} \) in term of the number density, where \( \bar{N}_\text{re}(z) = \int_{M_\text{crit}}^{M_\text{max}} \Psi(M_\bullet, z) dM_\bullet \), \( N_\text{all}(z) = \int_{M_\text{crit}}^{M_\text{max}} N(M_\bullet, z) dM_\bullet \), and \( M_\text{crit} \) is the lower mass limit of SMBHs in the sample. Meanwhile, the mass-weighted duty cycle is given by \( \bar{\delta}_M(z) = \frac{\bar{\rho}_\bullet(z)}{\bar{\rho}_\bullet^\text{all}(z)} \), where \( \bar{\rho}_\bullet(z) = \int_{M_\text{crit}}^{M_\text{max}} \rho_\bullet(M_\bullet, z) dM_\bullet \) and \( \bar{\rho}_\bullet^\text{all}(z) = \int_{M_\text{crit}}^{M_\text{max}} \frac{\Psi(M_\bullet, z) M_\bullet}{N(M_\bullet, z)} dM_\bullet \). It has been shown that \( \bar{\delta}(z) = \delta(z) \), in Wang et al. (2006c), namely,

\[
\delta(z) = \frac{\rho_\bullet^*(z)}{\rho_\bullet^\text{all}(z)}. \tag{2}
\]

Equation (2) assumes that the mean masses of active and inactive black holes are equal, and then converts the number density to mass density ratio (Wang et al. 2006c). It should be noted that \( \delta(z) \) represents the duty cycle of the major population of SMBHs at a given redshift.

We get the mass density of black holes from the quasar LF if we assume a constant \( \bar{m} \) of quasars as in the literature (e.g., Marconi et al. 2004; but see evidence for this in Kollmeier et al. 2006). The dimensionless accretion rate is defined as \( \bar{\dot{m}} = M/M_{\text{crit}} \), where \( M \) is the accretion rate of black holes, \( M_{\text{crit}} = L_{\text{Edd}}/c^2 \) the critical rate, \( L_{\text{Edd}} = M_{\text{Edd}} c^7 H_{\text{Salp}} \) the Eddington luminosity, \( H_{\text{Salp}} = \sigma_T c/4\pi G m_p = 0.45 \) Gyr the Salpeter time, \( \sigma_T \) the Thomson scattering section, \( c \) the light speed, \( G \) the gravity constant, and \( m_p \) the proton mass. With the help of \( L_{\text{bol}} = \eta M c^2 = \eta m_p c^2 H_{\text{Salp}} \), where \( \eta \) is the radiative efficiency, and the quasar LF, we have the black hole mass density in active galaxies at redshift \( z \)

\[
\rho_\bullet^*(z) = \frac{1}{\eta \bar{m} c^2} \bar{U}(z) H_{\text{Salp}}, \tag{3}
\]

where \( \bar{m} \) is the mean dimensionless accretion rate, and the luminosity density is given by

\[
\bar{U}(z) = \int_{L_{\text{bol}}} L_{\text{bol}} \Phi(L_{\text{bol}}, z) dL_{\text{bol}}, \tag{4}
\]

where \( \Phi(L_{\text{bol}}, z) \) is the bolometric LF, \( L_{\text{bol}} \) the bolometric luminosity, and \( L_{\text{bol}}^\text{crit} \) its corresponding limit. If the mass density of seed black holes of quasars is \( \rho_\bullet^* \) at their birth epoch \( (z_{\text{max}}) \),

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the mass density of all (active and inactive) black holes is given by

\[ \rho_{bh}^e(z) = \rho_{bh}^s + \int_z^{z_{max}} \frac{1 - \eta}{\eta} \frac{dU(z)}{dz} \frac{dt}{dz} dz \]

\[ = \rho_{bh}^s + \frac{1 - \eta}{\eta} U(z) e^{-3} \]

where \( U(z) = \int_z^{z_{max}} \dot{U}(dtdz/dz) dz \). The dependence of \( \eta \) on \( z \) can be neglected in equation (5) as shown by Wang et al. (2006a) from Sloan Digital Sky Survey (SDSS) data. We almost know nothing about \( \rho_{bh}^s \) at \( z_{max} \) except for some limited information on the reionization of the universe (Madau et al. 2004). Inserting equations (3) and (5) into equation (2), we have

\[ \dot{\delta}(z) = \frac{\dot{U}(z) \eta_{Sfr}}{\langle \dot{m} \rangle [U_z + (1 - \eta)U(z)]} \approx \frac{\dot{U}(z) \eta_{Sfr}}{\langle \dot{m} \rangle (1 - \eta)U(z)} \]

(6)

where \( U_z = \eta \eta_{Sfr} e^{-3} \) is the energy density of the seed black holes and the approximation is valid for \( \rho_{bh}^s \rho_{bh}^e(z) \ll 1 \).

Information on \( \rho_{bh}^s \) can be estimated from the reionization of the universe. WMAP (Wilkinson Microwave Anisotropy Probe) detected a large optical depth to Thomson scattering, \( \tau = 0.17 \pm 0.04 \), and suggests that the reionization happened at much higher redshift \( z_{re} = 17 \pm 3 \) (Spergel et al. 2003). Madau et al. (2004) suggest that the reionization may be powered by miniquasars, which have a mass density of accreting black holes at least \( 2 \times 10^3 M_\odot \cdot \text{Mpc}^{-3} \), which roughly agrees with that extrapolated by the luminosity function used below. We take \( \rho_{bh}^s = 2 \times 10^3 M_\odot \cdot \text{Mpc}^{-3} \) and \( \eta = 0.1 \) in this Letter.

We would like to point out the following: (1) The approximation is accurate enough within a certain redshift \( z \), when \( \rho_{bh}^s \) can be neglected and baryon accretion dominates. It breaks when \( \delta > 1 \). (2) The advantage of equation (6) is that \( \delta \) is not sensitive to \( \eta \). (3) Here \( \delta \) is insensitive, if the specific LF is applied, to the bolometric correction factor since it will be canceled on both sides of the numerator and the denominator. (4) Here \( \langle \dot{m} \rangle \) is an observable in principle and seems to be a constant at least between \( z = 0.3 \) and 4 (Kollmeier et al. 2006; but see Netzer et al. 2007 for a small high-redshift sample). Although the cosmological evolution of \( m \) is poorly understood (Netzer & Trakhtenbrot 2007), the influence of \( \langle \dot{m} \rangle \) is clear in equation (6). These make equation (6) robust to calculating \( \delta \) for high-redshift SMBHs and accurate enough for low-redshift ones.

In this Letter, we use the bolometric LF given by Hopkins et al. (2007). It is combined through bolometric luminosity correction from a large set of LFs in optical, soft, and hard X-rays and near- and middle-IR bands, and also covers the fraction of obscured quasars (see also Maiolino et al. 2007; Müller & Hasinger 2007 for the fraction of type II quasars). We use the LDDE LF given by equations (11)–(16) in Hopkins et al. (2007), the parameters of which are listed in Table 4 of that paper, and extrapolate LFs beyond \( z = 6.0 \). We assume \( z_{max} = z_{re} \) and find that the final results are not sensitive to \( z_{max} \).

Figure 1a shows \( \dot{U}(z) \). There is a break at \( z \sim 2 \) (also small effects on the duty cycle), which is caused by the LF. \( \dot{U} \) dramatically drops toward low redshifts and gradually decreases toward high redshifts. The function \( U(z) \) is not plotted here, but its trends are equivalent to that of the cumulative mass density of black holes, whose behaviors can be seen from

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{(a) Luminosity density vs. redshift based on bolometric luminosity function (Hopkins et al. 2007). (b) Duty cycle vs. redshift. We calculate cases of \( \langle \dot{m} \rangle = 10, 5, 2.5, 1 \), corresponding to quasars radiating at \( L_{bol} = 0.5L_{Edd} \), \( 0.25L_{Edd} \), and \( 0.1L_{Edd} \), respectively. The error bars are taken from the averaged value of LF \( \Delta \delta = \Delta \Phi/\Phi = 0.2 \). The cosmic history of SFR density is inserted as open circles taken from Reddy et al. (2008), but scaled by a factor of \( 10^3 M_\odot \cdot \text{yr}^{-1} \cdot \text{Mpc}^{-3} \).}
\end{figure}
gradually decreases from high to low redshifts while $\dot{\rho}_{\text{SFR}}$ slowly increases. During this epoch there is enough gas for both star formation and accretion onto SMBHs. We note that the strong feedback of black hole activities (Schawinski et al. 2006; Wang et al. 2007) is driving to blow away fueling gas so as to switch off quasars (Di Matteo et al. 2005). It has been found by Peng et al. (2006) and McLure et al. (2006) that quasars at $z \sim 2$ have stellar mass less than expected from the local Magorrian relation. This also is indicated by the broken relation between star formation and AGN activity at high luminosities (Maiolino et al. 2007), suggesting the SMBHs are growing faster than star formation at high redshifts in the presence of strong feedback of black hole activity. On the other hand, one can check whether the star formation still obeys the Kennicutt-Schmidt law as in Seyfert galaxies (Wang et al. 2007). It is expected that further evidence for the evolution of the feedback can be found by searching statistics at high redshifts. Future high spatial resolution observations with ALMA (Atacama Large Millimeter Array) will directly uncover the detailed nature of the feedback. 

3. ACCRETION AND GROWTH

3.1. Lifetime of Quasars

The net lifetime of quasars (i.e., the total over the Hubble time) is given by

$$t_{\text{qso}} = \int_0^{z_{\text{max}}} \delta(z) \frac{dt}{dz} dz,$$

where $t$ is the cosmic time. Figure 2a shows the net lifetimes for quasars with different accretion rates. For the rate $\dot{m} = 2.5$, we find that the typical value is $\lesssim 10^8$ yr for $z \lesssim 5$. Marconi et al. (2004) obtained a lifetime of a few $10^8$ yr, based on $\dot{m} = 10$, which agrees with our results for the same $\dot{m}$. If a single episodic lifetime is measured from the transverse proximity effect (Gonçalves et al. 2008), the cycles of episodic activities can be estimated. The cutoff around $z \sim 15$ in Figure 2a is caused by setting the birth of quasars at this epoch.

3.2. Growth of Seed Black Holes from Primordial Ones

Neglecting mergers, we have the conserved number density in the comoving frame as

$$\frac{\rho_0^s(z)}{\langle M_s(z) \rangle} = \frac{\rho_s^z}{\langle M_s^z \rangle} = \frac{\rho_s^0}{\langle M_s^0 \rangle},$$

where $\rho_s^0$ and $\langle M_s^0 \rangle$ are the SMBH mass density and mean mass in the local universe. This is justified by the results from detailed numerical simulations, which show that the mass contributed from major mergers is only roughly a few percent after the $z = 10$ epoch (Volonteri et al. 2003). The mass density of the local SMBHs is given by $\rho_0^s = 4.2 \times 10^{-2} M_\odot \text{Mpc}^{-3}$ (Shankar et al. 2004; Marconi et al. 2004; but see Graham & Driver 2007). We convert the function of dispersion velocity $\langle \sigma(z) \rangle$ of early-type galaxies (Sheth et al. 2003) into the mass function of the SMBHs, $\phi(M_s) = \rho_0^s \langle M_s \rangle d\langle M_s \rangle$, where $\langle M_s \rangle / M_\odot = 10^{8.13} (\sigma/200)^{4.02}$ is used (Tremaine et al. 2002). The mean mass of local SMBHs is given by $\langle M_s^0 \rangle = \int \rho_s^0 \phi(M_s^0) d\langle M_s^0 \rangle / \phi(M_s^0) dM_s^0 = 8.9 \times 10^7 M_\odot$. We thus have the mean mass of black holes at $z$

$$\langle M_s(z) \rangle = \left[ \frac{\rho_0^s(z)}{\rho_s^0} \right] \langle M_s^0 \rangle.$$

Figure 2b shows $\langle M_s(z) \rangle$ as a function of redshifts. If future observations could provide the mean mass of SMBHs $\langle [M_s^0(z)] \rangle$ for a complete sample at a given redshift, it becomes feasible to determine whether the nonbaryon accretion onto the black holes is necessary by a simple comparison of $\langle M_s^0(z) \rangle$ and $\langle M_s(z) \rangle$.

From equation (8), we have the mean mass of seed black holes

$$\langle M_s^z \rangle = \left( \frac{\rho_s^0}{\rho_s^z} \right) \langle M_s^0 \rangle \approx 2.0 \times 10^5 M_\odot,$$

where we use $\rho_s^z$ limited by WMAP. It should be noted that the real $\langle M_s \rangle$ could be smaller than that given by equation (10) if stars partially ionize the universe. The value of $\langle M_s \rangle$ agrees well with the black hole mass of the miniquasar model in Madau et al. (2004). How to form such a massive seed black hole at $z = 24$ remains an open question. The primordial black holes can be generally produced by the collapse of Population III stars (Madau & Rees 2001), gravitational collapse of relativistic star clusters (Khalopov et al. 2005; Volonteri 2006) with typical masses of $10^4$–$10^5 M_\odot$, $10^5$–$10^6 M_\odot$, and $10^6$–$10^7 M_\odot$, respectively. For a growing primordial black hole with a typical mass of $\langle M_s^z \rangle = 10^3 M_\odot$, the necessary accretion rate is

$$\dot{m}_c = \left[ \frac{t_{\text{Salp}}}{(1 - \eta) \Delta t} \right] \ln \left( \frac{\langle M_s^0 \rangle}{\langle M_s^z \rangle} \right) \approx 30$$

in the Salpeter growth, where $\Delta t (\approx 0.09 \text{ Gyr})$ is the interval.
between \( z = 24 \) and 17. This is only moderately super-Eddington and is realistic in the high-redshift universe. The photon trapping effects make the accretion have low radiative efficiency, but disks of the black holes radiate at a level of \( L_{\text{edd}} \) (Wang et al. 1999; Wang & Zhou 1999; Ohsuga et al. 2005).

We note that this conclusion is inconsistent with that in Volonteri & Rees (2005, hereafter VR05). VR05 suggested that a highly super-Eddington accretion onto primordial black holes occurs between \( z = 23 \) and 24 and forms seed black holes of \( 10^5 M_\odot \) in term of Bondi accretion (see their Fig. 1), and subsequently the seeds gradually grow up to be a \( 10^9 M_\odot \) SMBH until \( z = 6 \). Using the Bondi rate, we obtain \( \dot{m} = m_0 m_{\odot}^2 / [1 - m_0^2 (t / \tau_0)] \), where \( m_0^* \) is the initial mass of a primordial black hole in units of solar mass, \( m_0 = GM_\odot c \sigma_{T} n_0 / c_s^2 \), and \( \tau_0 = c / 4 \pi G M_\odot n_0 M_\odot = 13.9 T_{3/2} n_4 \) Gyr, here \( n_4 = n_0 / 10^4 \) cm\(^{-3}\), the number density of ambient medium, \( c_s = (kT m_p)^{1/2} \) the sound speed of the medium, \( T_{3/2} = 78000 \) K the temperature of the medium, and \( k \) Boltzmann’s constant. The rate \( \dot{m} \) goes to \( 10^4 \) to \( 10^5 \), or even infinity for a critical time of \( t_c = \tau_0 / m_0^* \), before the Bondi radius is larger than the typical dimension of the primordial clouds (VR05). The classical Bondi accretion is valid provided the lifetime of quasars can be obtained from the quasar luminosity function. The mean mass of the seed black holes is up to \( 2 \times 10^5 M_\odot \) at \( z \sim 17 \), which is able to grow from the primordial \( (\sim 10^3 M_\odot) \) at \( z = 24 \) via moderate super-Eddington accretion. Deeper surveys are expected to improve the LFs for more sophisticated investigations of the growth of black holes in the high-redshift universe.

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4. DISCUSSION AND CONCLUSION

We develop a convenient way to calculate the duty cycle based on LF, which applies to any redshift. We find that the trends of the duty cycle and the cosmic history of the SFR density are opposite when \( z > 2 \). This could be explained by AGN feedback to star formation. With the duty cycle, the net lifetime of quasars can be obtained from the quasar luminosity function. The mean mass of the seed black holes is up to \( 2 \times 10^5 M_\odot \) at \( z \sim 17 \), which is able to grow from the primordial \( (\sim 10^3 M_\odot) \) at \( z = 24 \) via moderate super-Eddington accretion. Deeper surveys are expected to improve the LFs for more sophisticated investigations of the growth of black holes in the high-redshift universe.

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