COSMOLOGICAL EVOLUTION OF THE DUTY CYCLE OF QUASARS

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ABSTRACT

Quasars are powered by accretion onto supermassive black holes, but the problem of the duty cycle related to the episodic activity of the black holes remains one of the major questions of the cosmological evolution of quasars. In this Letter, we obtain quasar duty cycles based on analyses of a large sample composed of 10,979 quasars with redshifts \( z \leq 2.1 \) from the Sloan Digital Sky Survey (SDSS) Data Release 3 (DR3). We estimate the masses of the quasar black holes and obtain their mass function (MF) in the present sample. We then get the duty cycle \( \delta(z) = 10^{-3} \sim 1 \) based on Soltan’s argument, implying that black holes are undergoing multiple episodic activity. We find that the duty cycle has a strong evolution. By comparison, we show that the evolution of the duty cycle follows the history of the cosmic star formation rate (SFR) density in the universe, providing intriguing evidence of a natural connection between star formation and the triggering of black hole activity. Feedback on star formation from black hole activity is briefly discussed.

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

Online material: color figure

1. INTRODUCTION

Supermassive black holes are relics of quasars in the universe (Soltan 1982; Rees 1984, 1990). The evolution of quasars is led by the on and off switching of accretion onto the black holes. During their entire evolution, how many black holes are triggered and how many times? What is the triggering mechanism and why do quasars switch off?

The duty cycle, defined as the fraction of active black holes to their total number, is key to tackling the above questions (Richstone et al. 1998; Martini 2004). A popular method for getting the duty cycle invokes the continuity equation and the MF of quasar black holes. With the assumption that quasar black holes have the same Eddington ratio, their MF can be obtained from the luminosity function, and then the duty cycle can be found from the continuity equation (Small & Blandford 1992; Marconi et al. 2004). This is a convenient way to discuss the evolution of black holes, but the degeneracy of the Eddington ratio and the duty cycle still holds. Actually, not only are the Eddington ratios not constant for different quasars at different epochs, but they appear to be quite scattered (Vestergaard 2004). The duty cycle is poorly understood as a statistical parameter tracing the evolution of quasar populations.

In recent years, much progress has been made in estimating black hole masses both in nearby galaxies and in distant quasars. The empirical relation of reverberation mapping allows us to conveniently obtain the black hole masses from a large sample and to directly get their MF. Thus, it becomes realistic to get new clues to understanding the evolution of quasars. Fortunately, by invoking the MF, we can decouple the degeneracy of the duty cycle from the Eddington ratio in order to get the duty cycle.

In this Letter, we use the available SDSS data to directly get the MF of the black holes so as to discuss the duty cycle based on the MF and we find that there is a strong cosmological evolution. Our calculations assume a cosmology with the Hubble constant \( H_0 = 70 \text{ Mpc}^{-1} \text{ km s}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \).

2. BLACK HOLE EVOLUTION

Active black hole evolution can be described by the MF \( \Phi(M_*, z) \), which is defined as \( \Phi(M_*, z) = d^3N/dM_* dV \), where \( M_* \) is the black hole mass, and \( dN \) is the number of quasars within the comoving volume element \( dV \) and mass interval \( dM_* \). The number density of quasar black holes is then given by \( N_{\text{qso}}(z) = \int M^* \Phi(M_*, z) dM_* \) at redshift \( z \), where \( M_* \) is the flux-limited black hole mass in a survey. If \( N(M_*, z) \) is the MF of all black holes, including the active and inactive ones, the total number density of black holes is \( N_{\text{tot}}(z) = \int M^* N(M_*, z) dM_* \) at redshift \( z \). The relation between \( N(M_*, z) \) and \( \Phi(M_*, z) \) can be written as (Small & Blandford 1992; Marconi et al. 2004)

\[
\Phi(M_*, z) = \delta(M_*, z) N(M_*, z),
\]

where the duty cycle \( \delta(M_*, z) \) is a function of black hole mass and redshift. Integrating equation (1) over all black hole masses, we have a mean duty cycle in terms of their number density of

\[
\bar{\delta}(z) = \frac{\int M_* \Phi(M_*, z) dM_*}{\int M_* N(M_*, z) dM_*} = \frac{N_{\text{qso}}(z)}{N_{\text{tot}}(z)}. \quad (2)
\]

This duty cycle represents the relative number of the active black holes to the total. Multiplying by \( M_* \) and integrating equation (1) over all black hole masses, we have an averaged duty cycle weighted by the masses of the black holes of

\[
\bar{\delta}(z) = \frac{\int M_* \Phi(M_*, z) M_* dM_*}{\int M_* N(M_*, z) M_* dM_*} = \frac{\langle M_*(z) \rangle_{\text{qso}}}{\langle M_*(z) \rangle_{\text{tot}}} \bar{\delta}(z), \quad (3)
\]

where \( \langle M_*(z) \rangle_{\text{qso}} = \int M_* \Phi(M_*, z) M_* dM_* / N_{\text{qso}} \) is the averaged mass of the quasar black holes at redshift \( z \) and \( \langle M_*(z) \rangle_{\text{tot}} = \int M_* N(M_*, z) M_* dM_* / N_{\text{tot}} \) for all of the active and inactive black holes.
holes. We show below that \( \langle M_\odot(z) \rangle_{\text{iso}} = \langle M_\odot(z) \rangle_{\text{all}} \) for \( M_\odot > M_{\odot}^* \). So we have \( \delta(z) = \tilde{\delta}(z) \).

The averaged mass of all black holes is \( \langle M_\odot(t) \rangle_{\text{all}} = \langle M_\odot^\prime(t) \rangle_{\text{all}} + \int_{t_{\text{start}}}^{t_{\text{end}}} \langle M_\odot^\prime(t) \rangle_{\text{all}} dt \), where \( M_{\odot}^* \) is the mean mass of seed black holes and \( \langle M_\odot^\prime(t) \rangle_{\text{all}} \) is the averaged accretion rate of all black holes larger than \( M_{\odot}^* \). Considering that \( \langle M_\odot^\prime(t) \rangle_{\text{all}} = \delta(t) / \langle M_\odot^\prime(t) \rangle_{\text{iso}} \) (see eq. [9] in Small & Blandford 1992 and the first equation in the sentence that includes eq. [14] in Marconi et al. 2004), we have \( \langle M_\odot(t) \rangle_{\text{all}} = \langle M_\odot^\prime(t) \rangle_{\text{iso}} + \int_{t_{\text{start}}}^{t_{\text{end}}} \delta(t) / \langle M_\odot^\prime(t) \rangle_{\text{iso}} dt \). On the other hand, the duty cycle can be written as \( \delta(t) = \Delta t_{\text{act}} / \Delta t \) for a single episodic phase within a time interval \( \Delta t \), where \( \Delta t = \Delta t_{\text{act}} + \Delta t_{\text{dec}} \), \( \Delta t_{\text{act}} \) and \( \Delta t_{\text{dec}} \) are the active and dormant times, respectively. Then, for the \( i \)th episodic phase within \( \Delta t_{\text{act}} \), the accreted mass is given by \( \langle M_\odot^\prime(t) \rangle_{\text{iso}} \delta_i(t) / \Delta t_{\text{act}} \). The mean mass of quasar black holes then reduces \( \langle M_\odot(t) \rangle_{\text{iso}} = \langle M_\odot^\prime(t) \rangle_{\text{iso}} + \sum_i \langle M_\odot^\prime(t) \rangle_{\text{iso}} \delta_i(t) / \Delta t_{\text{act}} = \langle M_\odot^\prime(t) \rangle_{\text{iso}} \delta(t) / \Delta t_{\text{act}} \) after multiple episodic phases. We then have \( \langle M_\odot(t) \rangle_{\text{iso}} = \langle M_\odot(t) \rangle_{\text{iso}} \). This relation can be understood more easily if we consider the multiple episodic growth of black holes. We thus have the duty cycle of the black holes in the coarse form of \( \delta(z) = \tilde{\delta}(z) = \delta(z) \).

The total mass density of the black holes at redshift \( z \) due to accretion is then given by

\[
\rho_{\text{acc}}(z) = \int_0^z \frac{dt}{dz} \int_{L(t)}^{L(z)} \frac{1 - \eta}{L_{\text{bol}} \eta} \frac{1}{c^2} \Psi(L, z) dL,
\]

where \( L_{\text{bol}}(z) \) is the luminosity limit due to survey sensitivity, \( \Psi(L, z) \) is the luminosity function, the bolometric luminosity is given by \( L_{\text{bol}} = C_{\text{bol}} L_{\text{bol}} \) (with \( C_{\text{bol}} \) being the correction factor relating the \( B \)-band luminosity \( L_B \) to \( L_{\text{bol}} \)), \( \eta \) is the radiative efficiency, and \( c \) is the light speed. This density includes all the black holes that were brighter than \( L_{\text{bol}}(z) \). The mass density of the active black holes at \( z \) with \( L > L_{\text{bol}} \) is given by

\[
\rho_{\text{iso}}(z) = \int_0^z \Phi(M_\odot, z) M_\odot dM_\odot,
\]

where \( M_{\odot}^\prime \) is the limiting black hole mass due to the luminosity limit. We apply Soltan’s argument to the present sample at any redshift \( z \),

\[
\rho_{\text{int}}(z) = \int_0^z N(M_\odot, z) dM_\odot = \rho_{\text{acc}}(z).
\]

Although we do not know the distribution \( \mathcal{N}(M_\odot, z) \), we do know the mass density of all of the black holes from Soltan’s argument. Finally, we have duty cycle

\[
\tilde{\delta}(z) = \frac{\rho_{\text{iso}}(z)}{\rho_{\text{acc}}(z)}.
\]

If we know \( \Psi(L, z) \) and \( \Phi(M_\odot, z) \), we can easily get the duty cycle of quasars at redshift \( z \). We have to stress that equation (7) does not need an initial condition or the assumption of a constant Eddington ratio, which must be specified for in the alternative approach to solving the continuity equation (e.g., \( \delta = 1 \) at \( z = 3 \) in Marconi et al. 2004).

3. SAMPLE AND BLACK HOLE MASS FUNCTION

3.1. Spectrum Analysis

The largest quasar sample, given by Richards et al. (2006) from the SDSS DR3, consists of 15,343 quasars from \( z = 0 \) to \( 5 \), which is complete and homogeneous for an apparent magnitude \( i = 15–19 \). We only use those quasars (11,954) with \( z \leq 2.1 \) in the present Letter. We subtract the continuum and iron emission (based on the iron template derived from I Zw 1 spectra, which was kindly provided by R. J. McLure 2006, private communication). We then fit \( H\beta \) and \( Mg \) lines. For those with \( z \leq 0.7 \), four components are used to model the spectra: broad and narrow \( H\beta \) plus narrow \([O III]\) 4959 Å and \([O III]\) 5007 Å. For others, we use one broad and one narrow component to model the \( Mg \) line. Some objects are removed from the sample for one of three reasons; they have (1) too poor spectra to fit due to low signal-to-noise ratio; (2) only narrow lines (\( <2000 \) km s\(^{-1}\)), or (3) serious absorption at the \( Mg \) line. Finally, we have 10,979 quasars available for estimating black hole masses with \( z \leq 2.1 \). The removed quasars reduce the completeness of the sample given in Table 1. The last bin (z>5) is poor because the quality of quasar spectra is not good enough to measure the width of \( Mg \) line. A future paper will give a detailed description of the estimation of black hole masses and related issues (Y.-M. Chen et al. 2006, in preparation).

3.2. Black Hole Mass Function

We apply the latest version of the empirical relation of reverberation mapping (Kaspi et al. 2005; Vestergaard & Peterson 2006) to our calculation of the black hole mass in each quasar. For low-redshift quasars with \( z \leq 0.7 \), we use the FWHM of \( H\beta \), whereas we use \( Mg \) for those with \( 0.7 < z \leq 2.1 \) (McLure & Dunlop 2004). The scatter of the recalibrated relation for the black hole masses is less than 0.4 dex, which is much improved. Figure 1a shows the mass distribution of the present sample. We fit the mass distribution of the black holes via the least-squares method in a form of three power laws,

\[
\mathcal{F}(m_*) = f_1 m_*^{-a_1} \left( 1 + \frac{m_*}{m_{11}} \right)^{-a_1} \left( 1 + \frac{m_*}{m_{22}} \right)^{-a_2},
\]

where \( m_* \) is the mass of the black holes in units of solar mass. This expression has the limits \( \mathcal{F}(m_*) \propto m_*^a \) for \( m_* \ll m_{11} \), \( \mathcal{F}(m_*) \propto m_*^{-a_2} \) for \( m_{11} \ll m_* \ll m_{22} \), and \( \mathcal{F}(m_*) \propto m_*^{-a_3} \) for \( m_{22} \ll m_* \). We obtain \( f_1 = (2.70 \pm 0.35) \times 10^{-25} \), \( m_{11} = (4.14 \pm 0.56) \times 10^7 \), \( m_{22} = (2.50 \pm 0.22) \times 10^9 \), \( a_1 = 3.56 \pm 0.28 \), \( a_2 = 2.87 \pm 0.25 \), and \( a_3 = 2.71 \pm 0.07 \). A significant break appears at \( M_* = 2.5 \times 10^8 M_\odot \), and then a steeper mass spectrum \( \mathcal{F}(m_*) \propto m_*^{2.65} \) follows the break mass, which
is consistent with the maximum mass from the SDSS DR1 (McLure & Dunlop 2004).

We get the MF by dividing our sample into 10 redshift bins with an interval $dz = 0.21$ and then into 20 black hole mass bins in each redshift bin. Figure 1b shows the MF. We find that the function can be well fit by double power laws in the following form:

$$\Phi(M_\bullet, z) = \Phi^*_\chi \left[ \left( \frac{M_\bullet}{M^*_{\text{acc}}} \right)^{-2q} + \left( \frac{M_\bullet}{M^*_{\text{dep}}} \right)^{-2q-1} \right],$$  \quad (9)

where $\beta_1$, $\beta_2$, $\Phi^*$, and $M^*_\bullet$ are constants. The peak mass is given by $M^*_\text{peak} = \left( \frac{1}{\beta_1} + \frac{1}{\beta_2} \right)^{1/(\beta_1 + \beta_2)} M^*_{\text{dep}}$. We get the four parameters from the least-squares fit. The black hole mass function at each redshift $M_\bullet$ is caused by the survey flux limit. We have to point out that the MF shows an increasing peak mass toward high redshifts. The mass break at the low-mass side is not real. It is implied that there is evidence of intrinsic star formation–episodic activity. The value of $\bar{z}$ agrees with $\bar{z} = 0.15$ by Gammie et al. (2004), based on Sołtan’s argument, the X-ray background, and numerical simulations, respectively. Numerical calculations indicate that black holes are rotating with their maximum spin all the time during their evolution if accretion is included (Volonteri et al. 2005), and this is supported by studies of SDSS quasars (Wang et al. 2006); then $\eta \approx 0.3$ without significant evolution. We thus calculate the duty cycle for two different radiative efficiencies, $\eta = 0.1$ and 0.3.

Results are shown in Figure 2. First, quasars have a duty cycle of $\delta(z) = 10^{-3} \sim 1$ as shown in Figure 2a, indicating that black holes are undergoing active and dormant phases, namely, episodic activity. The value of $\delta(z) \rightarrow 1$ at $z \sim 2$ agrees with the assumption of $\delta = 1$ at $z = 3$ in Marconi et al. (2004). Second, the duty cycle is rapidly evolving from $z \sim 2$ to the local universe. We find $\delta(z) \propto z^\gamma$, where $\gamma \sim 2.5$ until $z = 1.5$, above which it tends to flatten. Third, as shown in Figures 2a and 2b, the duty cycle connects quite naturally with the history of the SFR density. The SFR density is taken from Pérez-González et al. (2005). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 1.—(a) Mass distribution of the black holes in our sample. The red line is the least-squares fit. The black hole mass function $\Phi(M_\bullet, z)$ at each redshift bin is shown in (b). The lines represent the best fits given in Table 1.

Fig. 2.—(a) Duty cycle of quasars as a function of redshift in our sample and (b) the history of the SFR density. The SFR density is taken from Pérez-González et al. (2005). [See the electronic edition of the Journal for a color version of this figure.]

4. RESULTS

The $B$-band luminosity is converted from the absolute magnitude $M_B(z = 2)$ via the relation of $M_B = M(z = 2) + 0.804$ (Richards et al. 2006). It has been found that the factor $C_\beta$ is not a function of redshift (Steffen et al. 2006). A more elaborate treatment gives $C_\beta = 6.7$ for quasars (Marconi et al. 2004). We use $C_\beta = 6.5$ throughout the redshift range in this Letter. The luminosity function is taken from Richards et al. (2006). We take $M^*_\bullet$ from the minimum mass of the black holes in each redshift bin to calculate their mass density, $\rho_{\text{acc}}$ (eq. [5]). This corresponds to the survey limit and is consistent with the accretion density $\rho_{\text{acc}}$ (eq. [4]). The radiative efficiency $\eta \geq 0.1$ was reached by Yu & Tremaine (2002), $\eta \geq 0.15$ by Elvis et al. (2002), and $\eta = 0.15$ by Gammie et al. (2004), based on the assumption of at $z = 2$. Then $\eta \approx 0.3$ without significant evolution.

Results are shown in Figure 2. First, quasars have a duty cycle of $\delta(z) = 10^{-3} \sim 1$ as shown in Figure 2a, indicating that black holes are undergoing active and dormant phases, namely, episodic activity. The value of $\delta(z) \rightarrow 1$ at $z \sim 2$ agrees with the assumption of $\delta = 1$ at $z = 3$ in Marconi et al. (2004). Second, the duty cycle is rapidly evolving from $z \sim 2$ to the local universe. We find $\delta(z) \propto z^\gamma$, where $\gamma \sim 2.5$ until $z = 1.5$, above which it tends to flatten. Third, as shown in Figures 2a and 2b, the duty cycle connects quite naturally with the history of the SFR density as a consequence of the coevolution of galaxies and black holes. Massive, gas-rich mergers account not only for most of the star formation at $z \approx 2–3$ but are probably also responsible for triggering major episodes of black hole activity (Di Matteo et al. 2005). Figures 2a and 2b show that the duty cycle follows the star formation history, implying that there is evidence of intrinsic star formation—
triggered black hole activity. The higher the SFR density, the higher the triggering frequencies of the black hole activity. Finally, we define $R = \Delta t_{\text{act}}/\Delta t_{\text{dor}}$ and then have $R = \delta(z)/[1 - \delta(z)]$. The episodic activity of the black holes can be described by this parameter. When $\delta(z) \to 1$, black holes have $R \gg 1$; namely, the dormant black holes are frequently triggered at $z \sim 2$ by star formation. At that time, quasars look like long-lived phenomena because of $R \approx 1$.

5. DISCUSSION AND SUMMARY

The evolution of quasars is jointly controlled by the triggering mechanism and accretion. The duty cycle is a key parameter for unveiling the evolution of quasars. The results of the present Letter show a very strong cosmological evolution of a quasar's duty cycle. The triggering history represented by $\delta(z)$ is quite similar to the evolution of cosmic SFR density. This indicates that star formation may be the direct mechanism for triggering the activity of black holes.

The duty cycle can be roughly justified from the galaxy luminosity function. According to the luminosity function of galaxies at $1.8 \leq z \leq 2.0$ (Dahlen et al. 2005), the galaxy number density is $n_g \approx 826 \text{ Gpc}^{-3}$ for galaxies brighter than the $R$-band magnitude $M_g = -24$. This corresponds to the number density of galaxies with black hole mass larger than $10^9 M_\odot$ converted from $\log (M_{BH}/M_\odot) = -0.5M_g - 3$ (McLure & Dunlop 2001). The number density of quasars brighter than $M_i = -28$ (corresponding to a black hole with mass $>10^9 M_\odot$ if it is accreting at the Eddington limit) is $n_q \approx 175 \text{ Gpc}^{-3}$ based on the quasar luminosity function (Richards et al. 2006). We thus estimate a duty cycle of $\sim0.18$, which is roughly consistent with the present results (see Fig. 2a).

The SFR density rises with redshift out to $z = 1.5$ and appears to be roughly flat between $z \approx 1.5$ and $z \approx 3.0$. This tendency could be explained by the strong feedback from the activity of black holes to their host galaxies (Silk 2005; Di Matteo et al. 2005; Croton et al. 2006). With a balance between star formation and feedback in $z \sim 1.5-3.0$, the violent star formation is then suppressed. However, the SFR density is going to decrease with time due to a shortage of gas, and the black hole duty cycle follows this trend. To further confirm this, future work will focus on the dependence of the duty cycle on the black hole masses. It could show the feedback dependence on the black hole growth itself. Additionally, the total accretion time (net lifetime) of black holes will then be obtained.

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