EPISODIC RANDOM ACCRETION AND THE COSMOLOGICAL EVOLUTION OF SUPERMASSIVE BLACK HOLE SPINS

JIAN-MIN WANG1,2, CHEN HU3, YAN-RONG LI1, YAN-MEI CHEN1, ANDREW R. KING3, ALESSANDRO MARCONI4, LUIS C. HO5, CHANG-SHOU YAN1, RÜDIGER STAUBERT6, AND SHU ZHANG1

1 Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing 100049, China
2 Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China
3 Theoretical Astrophysics Group, University of Leicester, Leicester LE1 7RH, UK
4 Department of Astronomy and Space Science, University of Florence, Largo Enrico Fermi 2, 50125 Firenze, Italy
5 The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA
6 IAAT, Abt. Astronomie, Universität Tübingen, Sand 1, 72076 Tübingen, Germany

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ABSTRACT

The growth of supermassive black holes (BHs) located at the centers of their host galaxies comes mainly from the accretion of gas, but how to fuel them remains an outstanding unsolved problem in quasar evolution. This issue can be elucidated by quantifying the radiative efficiency parameter ($\eta$) as a function of redshift, which also provides constraints on the average spin of the BHs and its possible evolution with time. We derive a formalism to link $\eta$ with the luminosity density, BH mass density, and duty cycle of quasars, quantities we can estimate from existing quasar data. We find that $\eta$ has a strong cosmological evolution: at $z \approx 2$, $\eta \approx 0.3$, and by $z \approx 0$ it has decreased by an order of magnitude, to $\eta \approx 0.03$. We interpret this trend as evolution in BH spin, and we appeal to episodic, random accretion as the mechanism for reducing the spin. The observation that the fraction of radio-loud quasars decreases with increasing redshift is inconsistent with the popular notion that BH spin is a critical factor for generating strong radio jets. In agreement with previous studies, we show that the derived history of BH accretion closely follows the cosmic history of star formation, consistent with other evidence that BHs and their host galaxies co-evolve.

Key words: black hole physics – galaxies: evolution – quasars: general

1. INTRODUCTION

The empirical correlation between black hole (BH) mass and bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998; Marconi & Hunt 2003) and stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002) have stimulated the notion that BHs evolve jointly with their host galaxies, mediated perhaps through feedback from active galactic nuclei (AGNs; e.g., Di Matteo et al. 2005). Many issues affect our detailed understanding of the relationship between BHs and their hosts, including (1) the evolution of BH mass, accretion rate, and spin; (2) the assembly and evolution of galaxies; and (3) the mutual interaction between BHs and galaxies. A simple comparison of the mass density of BHs in local galaxies with the integrated energy density of quasars (Soltan 1982) leads to the conclusion that radiatively efficient accretion, with an average efficiency of $\eta \approx 0.1$, is the main driver of BH growth (Small & Blandford 1992; Chokshi & Turner 1992; Yu & Tremaine 2002; Marconi et al. 2004). If the angular momentum of the accreting material is aligned with the spin of the BH and remains constant, we expect the BH to spin up to its maximum rate after accreting one-third of its mass, and attain $\eta \approx 0.4$ (Thorne 1974), in apparent conflict with the efficiency deduced from Soltan’s argument. This inconsistency can be plausibly resolved if BHs are fed by episodic, random accretion (King & Pringle 2006), which has a tendency to spin down the BH over time (King et al. 2008; Volonteri et al. 2007; Berti & Volonteri 2008). If this, indeed, is the main mechanism for BH growth, we predict that the radiative efficiency of quasars should decrease from high to low redshift. The main goal of this Letter is to test this prediction observationally. By comparing the cosmic history of BH accretion with the better-established cosmic history of the star formation rate, we can further constrain the purported joint evolution of central BHs and their host galaxies (e.g., Silk & Rees 1998; Croton et al. 2006; Wang et al. 2007).

In this Letter, we set up a formalism to describe the dependence of $\eta$ on the luminosity density, growth rate, and duty cycle of quasars. We apply it to survey data and show that $\eta$ evolves strongly with redshift, which we interpret as a signature of BH spin-down as a consequence of episodic, random accretion. Our calculations assume a standard cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. THE $\eta$-EQUATION

Following Soltan’s argument, we assume that the growth of BHs comes mainly from accretion during their active galactic nucleus (AGN) phases. From its definition (Marconi et al. 2004), the radiative efficiency is

$$\eta = \frac{\Delta \epsilon}{\Delta \epsilon + \Delta \rho_{\cdot} c^2},$$

(1)

where $\Delta \epsilon$ and $\Delta \rho_{\cdot}$ are the cumulative increases of the energy and the mass density of BHs from $z + \Delta z$ to $z$, and $c$ is the speed of light. We can define the duty cycle as the ratio of the number density of quasars ($N_Q$) to that of active and inactive galaxies ($N_G$),

$$\delta (z) = \frac{N_Q(z)}{N_Q(z) + N_G(z)} \approx \frac{\rho_{\cdot}^{\text{qso}} (z)}{\rho_{\cdot}^{\text{acc}} (z)},$$

(2)

which can be equivalently expressed as (Wang et al. 2006, 2008)

$$\delta (z) = \frac{\rho_{\cdot}^{\text{qso}} (z)}{\rho_{\cdot}^{\text{acc}} (z)},$$

(3)

where $\rho_{\cdot}^{\text{qso}} (z)$ is the mass density of quasar BHs and $\rho_{\cdot}^{\text{acc}} (z)$ is the mass density of all gas accreted onto BHs until $z$. The
mass density of quasar BHs can be obtained from \( \rho_{\text{qso}}(z) = \int_{M_{\bullet}} M_{\bullet} \Phi(z, M_{\bullet}) dM_{\bullet} \), where \( \Phi(z, M_{\bullet}) \) is the mass function of BHs with the break given by \( M_{\bullet}^* \). Since quasars can increase their masses only via accretion (i.e., \( \Delta \rho_{\bullet} = \Delta \rho_{\text{acc}} \)), we have, using the equivalent formulation of the duty cycle, the cumulative increase of the mass density

\[
\Delta \rho_{\bullet} = \Delta (\delta^{-1} \rho_{\text{qso}}^0).
\]  

Equation (4) is striking in that it describes \( \eta \) in terms of \( \rho_{\text{qso}}^0 / \delta \), which combines the growth and the episodic cycles of BHs with the evolution of their host galaxies. This equation has the advantage of only depending on observables: (1) \( \rho_{\text{qso}}^0(z) \), which can be reasonably estimated from empirical relations calibrated against reverberation mapping; (2) \( \delta(z) \), which in principle can be estimated from deep galaxy surveys; and (3) \( \dot{U}(z) \), which can be directly obtained from quasar LFs. Furthermore, the equation directly gives \( \eta \) at any redshift, whereas the usual Sołtan’s argument requires a comparison of the accreted mass density of BHs with the local mass density of BHs to get the averaged radiative efficiency over time (Soltan 1982; Yu & Tremaine 2002; Marconi et al. 2004). These features allow us to deduce the radiative efficiency as a function of redshift from observables.

3. EVOLUTION OF THE RADIATIVE EFFICIENCY

Equation (6) can be applied to existing survey data. We use the duty cycle expressed by \( \eta_{\text{QG}}(z) \) and \( \eta_c(z) \), where \( \eta_{\text{QG}}(z) = \int_{z_0}^z \Psi_Q(z, L_{\text{bol}}) L_{\text{bol}} dL_{\text{bol}} \) and \( \eta_c(z) = \int_{M_\bullet} M_\bullet \Psi_c(z, M_\bullet) dM_\bullet \) are the number densities of quasars and galaxies from their LFs \( \Psi_Q \) and \( \Psi_c \), respectively. It should be noted that \( \Psi_c \) is wavelength-dependent (Wolf et al. 2003), being less sensitive to stellar population changes at longer wavelengths (Ilbert et al. 2005). We calculate \( \eta_c(z) \) from the rest-frame R-band LFs of galaxies up to \( z \approx 2 \) derived from the deep Hubble Space Telescope study of Dahlen et al. (2005) and the VIMOS-VLT Deep Survey (VVDS) of Ilbert et al. (2005). Both samples have similar selection criteria and photometric redshift estimates from \( z \approx 0 \) to \( z \approx 2 \). \( \eta_{\text{QG}}(z) \) is calculated from Bongiorno et al. (2007), who supplement the Sloan Digital Sky Survey (SDSS) quasar sample of Richards et al. (2006) with VVDS data for low-luminosity AGNs. We calculate \( \rho_{\text{qso}}^0 \) with BH masses estimated from the “virial” method, as given in Vestergaard et al. (2008), but use the corrected value for \( z = 0.49 \) and the new value for \( z = 0.17 \) in Kelly et al. (2009). The samples of quasars and galaxies used in these LFs overlap in at least some survey fields, minimizing potential observational biases. We relate the lower limits of the galaxy LF (\( M_{\bullet}^* \)) and the BH mass function (\( M_{\bullet}^* \)) through the BH–bulge mass relation of McLure & Dunlop (2002), which we assume to be invariant with redshift (compared to Ho 2007). The completeness of the BH mass function depends on both the flux limit of SDSS and the widths of the broad emission lines. The adopted BH mass function of Vestergaard et al. (2008), complete only for \( M_\bullet > 10^8 M_\odot \), yields \( M_{\bullet}^* = -22.4 \) mag, which corresponds to \( L_Q^* = 10^{45.5} \) erg s\(^{-1}\) if bright quasars have an average Eddington ratio of \( \sim 0.2 \) (Shen et al. 2008).

Figure 1 shows the results for \( \dot{U}(z) \), \( \rho_{\text{qso}}^0(z) \), and \( \delta(z) \). Panel (b) gives the best fit for \( \rho_{\text{qso}}^0(z) \). Since the duty cycle \( \delta(z) \) depends on \( M_{\bullet}^* \), we plot the results for three choices of \( M_{\bullet}^* \) (the dependence on \( L_Q^* \) is absorbed into \( M_{\bullet}^* \)). We fit the variation of \( \delta \) with \( z \) using a polynomial \( \log \delta = \sum_{i=0}^3 a_i z^i \); the coefficients \( a_i \) are given in Table 1. We find that \( \delta(z) \) is very similar for the samples of Dahlen et al. (2005) and Ilbert et al. (2005), indicating the robustness of the present results. The large uncertainties in the photometric redshifts for low-\( z \) galaxies preclude us from deriving \( \delta \) directly for \( z < 0.3 \); in this regime, \( \delta \) is extrapolated from the analytical fits at higher redshift. We hope to remedy this situation with future surveys.
orbital momentum in major BH coalescences (i.e., BH binaries spin angular momentum of BHs may originate mainly from the is mainly contributed by AGNs at $z \approx 0$): (1) major and minor BH coalescences and (2) accretion of gas. While major coalescences offer strong evolution in $\eta$, the universe agrees with the results from the continuity equation of the BH number density (Merloni & Heinz 2008). The high values of $\eta$ at large $z$ are consistent with the estimate from the cosmic X-ray background (Elvis et al. 2002), which is mainly contributed by AGNs at $z \approx 1$--2. At this epoch, the spin angular momentum of BHs may originate mainly from the orbital momentum in major BH coalescences (i.e., BH binaries with mass ratio $\sim$1; those with mass ratio $<1$ are referred to as minor coalescences; Hughes & Blandford 2003). The strong evolution in $\eta$ provides important constraints on the accretion history of BHs. There are two ways for BHs to grow (Berti & Volonteri 2008): (1) major and minor BH coalescences and (2) accretion of gas. While major coalescences do contribute some angular momentum to BHs (Hughes & Blandford 2003), accretion is the main contributor to their masses (King et al. 2008). An initially nonrotating BH rotates very fast after accreting about one-third of its mass with the same sign of angular momentum (Thorne 1974), and its radiative efficiency approaches the maximum value of $\eta_{\text{max}} = 0.42$. However, the net angular momentum contributed to accreting BHs depends on whether the accretion is prograde or retrograde, as described below.

4. BH GROWTH BY RANDOM ACCRETION

Supposing that accretion occurs randomly and episodically in quasars, then, at episode $i$ with angular momentum $\Delta L_i$ and mass $\Delta m_i$, we have (as in a random walk), after $n$ episodes, the net angular momentum $\Delta L_{\text{total}} = \sum_{i=1}^{n} \Delta L_i$, and $\Delta L_{\text{total}} = \sum_{i=1}^{n} \Delta L_i = n \Delta L^2$, whereas the growth in mass $\Delta M_{\bullet} = \sum_{i=1}^{n} \Delta m_i = n \Delta m$. The specific angular momentum of an accreting BH,

$$a \propto \sqrt{n \Delta L} / n \Delta m \propto n^{-1/2},$$

decreases with the number of accretion events. Consistent with the numerical simulations of King et al. (2008), we expect $a$ to decrease with decreasing $z$. The evolution of $\eta$ offers strong observational support for this picture. The episode number $n$ can be estimated by

$$n = \frac{\Delta M_{\bullet}}{\Delta m} = \delta(z) t_c(z) / \Delta t_0,$$

where $\Delta t_0$ is the episode lifetime and $t_c(z)$ is the age of the universe at redshift $z$. For $z \approx 2$, we have $\delta \approx 10^{-1.5}$ (Figure 1(c)), $t_c = 2.0$ Gyr, and $\Delta t_0 = 1.0$ Myr as estimated from the proximity effect of $z \approx 2$ quasars (Kirkman & Tytler 2008), and hence $n \approx 10^2$. The parameter $a$ decreases by a factor of $\sim$10 from $z \approx 2$ to $z \approx 0$. On the other hand, random accretion may occur through disks whose masses are limited by self-gravity (King et al. 2008) to $\Delta M_{\text{BH}} \approx (H/R) M_\bullet$, where $H$ is the height of the disk at radius $R$. We have

$$n = f \left( \frac{H}{R} \right)^{-1} \approx 10^2,$$

where $H/R \approx 10^{-2}$ and $f = \Delta M_{\bullet}/M_\bullet \approx 1$ is the factor by which the BH mass has been increased due to accretion. The rough consistency between these two estimates of $n$ suggests that the random accretion events originate from a self-gravitating disk. Additionally, the gas accreted onto BHs is only a tiny fraction of the gas content of the entire galaxy ($\sim 10^{-3}$), so the net angular momentum from accretion should be independent of the total angular momentum. The evolution of the radiative efficiency found here does not favor accretion with consistently prograde angular momentum, as would occur if the typical accretion event has much larger aligned angular momentum than the BH. Rather, this study strongly favors a picture in which most of the mass in BHs was gained through random accretion.

Accretion rates of $\sim 10$--100 $M_\odot$ yr$^{-1}$ are needed to generate the prodigious luminosities seen in quasars. Such large amounts of fuel cannot be sustained by internal sources (e.g., stellar mass loss); they almost certainly require external triggers, in the form of major gas-rich galaxy mergers and interactions. How do major mergers lead to episodic, random accretion? Numerical simulations and direct observations (see Schweizer 1998 for a review) show that gas-rich mergers drive large quantities of gas to the circunuclear region of the merger remnant, where a large

Table 1

| $a_i$ | $M^*_R = -22.3$ | $M^*_R = -22.4$ | $M^*_R = -22.5$ |
|------|----------------|----------------|----------------|
| $a_0$ | $-4.10$ | $-4.01$ | $-3.92$ |
| $a_1$ | 3.34 | 3.32 | 3.29 |
| $a_2$ | $-1.60$ | $-1.59$ | $-1.57$ |
| $a_3$ | 0.26 | 0.26 | 0.25 |

Our main results are summarized in Figure 2(a). We find (1) $\eta \approx 0.3$ at $z \approx 2$, and (2) a strong cosmological evolution, with $\eta$ decreasing to $\sim$0.03 by $z \approx 0$. The evolution of $\eta$ as described below.

![Figure 2](image_url)

Figure 2. (a) Radiative efficiency as a function of redshift, showing strong cosmological evolution. (b) The derived cosmic history of BH accretion is compared with the star formation rate density ($\rho_{\text{SFR}}$, gray points from Hopkins & Beacom 2007), scaled by a factor of $10^{-3.7}$. The BH accretion history closely follows the star formation history.
portion of the fuel gets consumed in a starburst. The mechanisms by which gas gets further funneled to smaller scales relevant for feeding AGNs are unclear (see Wada 2004 for a review). But two things are certain: the gas in the circumnuclear region is clumpy, and in order for the gas to accrete, it must get rid of most of its angular momentum. This can be accomplished by clump–clump collisions, especially in a turbulent environment. Such a process is inherently random, and the material that manages to fall in carries little or no memory of its original angular momentum. Thus, despite the fact that the original source of gas derives from a major merger, the final, individual accretion events are essentially random, small fragments.

5. SUMMARY AND CONCLUDING REMARKS

We derive a simple formalism to link the radiative efficiency parameter $\eta$ with the luminosity density, BH mass density, and duty cycle of quasars. Applying this formalism to existing survey data of quasars and galaxies, we show that $\eta$ evolves strongly with redshift, with values of $\sim 0.3$ at $z \approx 2$ and $\sim 0.03$ at $z \approx 0$. A straightforward interpretation of this trend is that the BHs in the quasar population begin with high spins at early $z$ and episodic, and that this mode of accretion naturally reduces the BHs in the quasar population.

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