EVIDENCE FOR RAPIDLY SPINNING BLACK HOLES IN QUASARS

JIAN-MIN WANG,1 YAN-MEI CHEN,1,2 LUIS C. HO,3 AND ROSS J. McLURE4

Received 2006 February 4; accepted 2006 April 3; published 2006 April 25

ABSTRACT

It has long been believed that accretion onto supermassive black holes powers quasars, but there are still relatively few observational constraints on the spins of the black holes. We address this problem by estimating the average radiative efficiencies of a large sample of quasars selected from the Sloan Digital Sky Survey, by combining their luminosity function and their black hole mass function. Over the redshift interval 0.4 < z < 2.1, we find that quasars have average radiative efficiencies of ~30%–35%, strongly suggesting that their black holes are rotating very rapidly, with specific angular momentum $a \approx 1$, a value that remains roughly constant with redshift. The average radiative efficiency could be reduced by a factor of ~2, depending on the adopted zero point for the black hole mass scale. The inferred large spins and their lack of significant evolution are in agreement with the predictions of recent semianalytical models of hierarchical galaxy formation if black holes gain most of their mass through accretion. 

Subject headings: black hole physics — quasars: general

1. INTRODUCTION

Supermassive black holes are generally believed to be the power sources of quasars and other active galactic nuclei (Rees 1984), and in recent years there has been tremendous progress not only in measuring their masses but also in linking them to the global properties of their host galaxies (see reviews in Ho [2004]). Apart from mass, the other fundamental property of astrophysical black holes is the spin. However, to date there exist relatively few observational constraints. A handful of Seyfert galaxies, the most notable being MCG —6-30-15 (Wilms et al. 2001; Fabian et al. 2002), show a relativistically broadened, highly redshifted iron Kα line that can most plausibly be interpreted as arising from a compact region around a rapidly rotating black hole.

The quasi-periodic variability detected in Sgr A*, both in the near-infrared and in X-rays, can also be interpreted as evidence for a large spin for the Galactic center black hole (Genzel et al. 2003; Aschenbach et al. 2004). Spectral fitting of the broadband X-ray spectrum of active galaxies has achieved particular success by invoking ionized reflection disc models with inner disk radii sufficiently compact to suggest maximally rotating black holes (Crummy et al. 2006). Last, mild evidence for rotating black holes has come from integral constraints derived for global populations of active galaxies. Yu & Tremaine (2002), applying Sołtan’s (1982) argument to a sample of z = 0–5 quasars, concluded that their high average radiative efficiency ($\tilde{\eta} \approx 0.1$) implies that their black holes are spinning. Elvis et al. (2002) applied a similar calculation to the cosmic X-ray background and concluded that $\tilde{\eta} \approx 0.15$.

Theoretical considerations do not provide a clear prediction of the observational expectation. While gas accretion inevitably increases the spin of a black hole, as do mergers of comparable-mass black holes under most circumstances (Volonteri et al. 2005), minor mergers tend to have the opposite effect (Hughes & Blandford 2003; Gammie et al. 2004; Volonteri et al. 2005). Thus, the spin of the black hole of any given galaxy at any particular time depends on its specific merger history up to that point.

In this Letter, we attempt to constrain the spins of supermassive black holes by estimating the average radiative efficiency of a large sample of quasars with redshifts z = 0.4–2.1. The underlying assumption of our method is that black holes attain most of their mass through accretion. We find that quasars radiate with a high efficiency ($\tilde{\eta} \approx 0.3–0.35$), from which we infer that their black holes are rapidly rotating. Throughout, we adopt the following cosmological parameters: $H_0 = 70$ Mpc$^{-1}$ km s$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. ACCRETION GROWTH EQUATION AND RADIATIVE EFFICIENCY

If quasar light derives from accretion of matter onto a black hole, then the radiative efficiency is $\tilde{\eta} \equiv \Delta e/\Delta m \gamma^2$, where the black hole mass density increase $\Delta M_*$ in a redshift interval $\Delta z$ at $z$ results in an increase of the radiative energy density $\Delta e$. In practice, $\Delta e$ can be derived from the quasar luminosity function and $\Delta M_*$ can be obtained from the mass distribution function. Thus we can estimate the radiative efficiency at any redshift and, hence, place a strong constraint on the average spin of black holes, since $\eta$ varies as a function of spin ($\sim 0.06$ and $0.42$ for a nonrotating and a maximally rotating black hole, respectively). If black hole masses are known for a quasar sample, we can define their mass distribution function as

$$\Phi(M_*, z) = \frac{d^2N}{dM_* dV},$$

where $M_*$ is the black hole mass and $dN$ is the number of quasars within the comoving volume element $dV$ and mass interval $dM_*$. Then the integrated mass density of black holes with $M_* \geq M_*$ at a redshift $z$ is given by

$$\rho_*(z) = \int_z^\infty \int_{M_*}^{\infty} M_* \Phi(M_*, z) dM_*,$$

where $M_*$ is a lower limit set by the flux limit of the survey.

1 Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, 100049 Beijing, China.
2 Graduate School, Chinese Academy of Sciences, 19A Yuquan Road, 100049 Beijing, China.
3 Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101.
4 Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK.
Accretion of matter onto a black hole generates radiation and increases the mass of the hole. The relationship between the radiated energy and the accumulated mass density in black holes can be expressed by the accretion growth equation as

$$\rho_*(z) = \int_z^{\infty} \frac{dt}{dz} \int_{z_{\text{min}}(z)}^{\infty} (1 - \eta) L_{\text{bol}} \frac{L}{c^2} \Psi(L, z) dL,$$

(3)

where $L_{\text{bol}}(z)$ is the minimum luminosity of the survey at redshift $z$, $c$ is the speed of light, $L_{\text{bol}}$ is the bolometric luminosity, $\Psi(L, z)$ is the luminosity function of the quasar sample, $L$ is the specific luminosity, and the radiative efficiency $\eta$ varies with redshift. Equation (3) involves a relation between the bolometric and specific luminosities. We convert the B-band luminosity $L_B$ into the bolometric luminosity via $L_B \approx L_{\text{bol}}$, where $C_B \approx 6.5$ is the B-band bolometric correction factor for quasars brighter than $L_{\text{bol}} \approx 10^{11.5} L_{\odot}$ (Marconi et al. 2004); we adopt $C_B = 6.5$. Since the spectral energy distributions of quasars show little evidence for redshift evolution (Steffen et al. 2006), we assume that $C_B$ does not vary with redshift. With $\Phi(M_*, z)$ and $\Psi(L, z)$, the average radiative efficiency $\tilde{\eta}(z)$ at each redshift bin follows from the differential version of equation (3):

$$\tilde{\eta}(z) = \frac{\Delta \epsilon}{\Delta \rho_*} e^{-z},$$

(4)

where

$$\Delta \epsilon = \int_z^{\infty} L_{\text{bol}} \Psi(L, z) dL,$$

(5)

$$\Delta \rho_* = \int_{M_*}^\infty M \Phi(M_*, z) dM_*.$$

(6)

Assuming that the innermost stable circular orbit is the inner radius of the accretion disk, the inferred radiative efficiency yields an estimate of the black hole spin.

Equation (4) constrains the radiative efficiency at any redshift, provided the black hole mass function is known. It should be stressed that both sides of equation (3) only include the active black holes (i.e., quasars), and thus the radiative efficiency from equation (4) does not rely on the lifetime of quasars. This method is also independent of obscured sources, which is an important complicating factor when estimating the radiative efficiency using Soltan’s method (Elvis et al. 2002; Yu & Tremaine 2002).

### 3. APPLICATION TO SDSS QUASARS

#### 3.1. Estimation of Black Hole Masses

The large database provided by the Sloan Digital Sky Survey (SDSS; York et al. 2000) affords us an excellent opportunity to examine this problem. Reverberation mapping of local active galaxies has resulted in empirical scaling relations based on quasar luminosity and broad emission line width (Kaspi et al. 2000; McLure & Jarvis 2002; Vestergaard 2002) that enable “virial” black hole masses to be obtained, and hence the distribution function for the black hole masses of a sample of quasars can be estimated independently from their luminosity function. Because the profile of the C iv line is complex and may be strongly affected by outflows (Baskin & Laor 2005), we only consider objects with broad Hβ and Mg ii lines detected in SDSS. This limits the maximum redshift of the present sample to $z \leq 2.1$. For quasars with $z \leq 0.7$, we obtain the virial black hole masses using the FWHM of the Hβ line ($V_{\text{FWHM}}^\beta$) following the empirical relation $M_* = 4.7 \times 10^6 [L_{\text{bol}}^\beta/(10^7 W)]^{0.61} [V_{\text{FWHM}}^\beta/(10^3 km s^{-1})]^{4} M_\odot$, where $L_{\text{bol}}^\beta$ is the specific continuum luminosity at 5100 Å. For higher redshift quasars (0.7 < $z$ < 2.1), we use the FWHM of Mg ii ($V_{\text{FWHM}}^\text{Mg}$) to estimate the black hole mass, using the calibration $M_* = 3.2 \times 10^6 [L_{\text{bol}}^\beta/(10^7 W)]^{4/6} [V_{\text{FWHM}}^\text{Mg}/(10^3 km s^{-1})]^{4} M_\odot$ (McLure & Dunlop 2004), where $L_{\text{bol}}^\beta$ is the specific continuum luminosity at 3000 Å. The scatter of these relations has been estimated to be ~0.4 dex (McLure & Dunlop 2004).

#### 3.2. Samples

Our analysis is based on black hole masses calculated by McLure & Dunlop (2004) for 12,698 quasars in the redshift range 0.1 < $z$ < 2.1 for which good-quality spectra are available from the quasar catalog of the First Data Release (DR1) of SDSS (Schneider et al. 2003). This sample, however, is neither complete nor homogeneous. To evaluate its completeness, we compare it with the quasar luminosity function recently determined for the Third Data Release (DR3) of SDSS (Richards et al. 2006). After dividing the sample into $n = 12$ redshift bins, we evaluate the two parameters

$$R_i = \frac{N_i^\text{obs} - N_i^\text{vir}}{N_i^\text{vir}}, \quad I = \sum_{i=1}^n R_i^2,$$

(7)

where $N_i^\text{obs}$ is the number of quasars within the redshift bin $z_i$ to $z_i + \Delta z$ and $N_i^\text{vir}$ is the number of quasars calculated from the luminosity function. The parameter $R_i$ measures the degree of incompleteness of the sample at each redshift bin $z_i$, and $I$ indicates the global incompleteness of the sample. By adjusting the apparent magnitude $m_\text{vir}$, we can define subsamples with different levels of completeness. As illustrated in Figure 1 (left), the sample incompleteness begins to be noticeable for $m_\text{vir} \approx 19.5$–19.6 mag. Furthermore, Figure 1 (right) also shows that the number of quasars in the first two redshift bins matches poorly with the predictions based on the luminosity function of Richards et al. (2006). We thus restrict our attention to the redshift range 0.4 < $z$ < 2.1 and consider only three subsamples, $S_1$, $S_2$, and $S_3$, which correspond to apparent magnitude limits $m_\text{vir} < 19.4$, 19.2, and 19.0 mag, respectively. The completeness level of these subsamples is $\approx 98\%$.

#### 3.3. Results

We show the differential black hole mass density ($dM_*/dz$) as a function of redshift in Figure 2a. We find that the black hole density is very sensitive to the limiting magnitudes of the samples. The quasar luminosity function from DR3, as given by Richards et al. (2006), is

$$\Psi = \Psi_0 A^4 \left[ (M_{\odot} - M_z) + B_1 A + B_2 A^2 + B_3 A^3 \right],$$

(8)

This relation for Hβ is based on the original work of Kaspi et al. (2000), which has since been recalibrated (Onken et al. 2004; Kaspi et al. 2005). The new calibration increases the zero point of the mass scale by roughly a factor of 2. However, the new zero point has not been established with great statistical certainty (Nelson et al. 2004; Greene & Ho 2006), and for the current application we retain the original zero point of Kaspi et al. (2000), on which the masses derived by McLure & Dunlop (2004) are based.
Fig. 1.—Left: Global incompleteness of the sample as a function of apparent magnitude. Note that the sample becomes increasingly incomplete for $m_B \gtrsim 19.5$–19.6 mag. Right: A test of the completeness of each of the three samples, for different redshift bins. Bins $z_1$ and $z_2$ poorly match the SDSS quasar luminosity function from Richards et al. (2006). This can be attributed to the inhomogeneity of the McLure & Dunlop (2004) sample in the redshift interval $z = 0.117$–0.4; these two bins are excluded from the analysis. The other redshift bins have a completeness level of at least 98%.

where $M_i$ is $i$-band magnitude, $\xi = \log \left[ (1 + z)/(1 + z_{\text{ref}}) \right]$, $A_1 = 0.84$, $B_1 = 1.43$, $B_2 = 36.63$, $B_3 = 34.39$, $M_i = -26$, $z_{\text{ref}} = 2.45$, and $\Psi = 10^{-5.7}$. Inserting the luminosity function and the mass distribution function into equation (4), we immediately arrive at the radiative efficiency plotted in Figure 2b. Regardless of the chosen subsample, we find that quasars radiate at a high efficiency, with $\eta \approx 0.3$–0.35, roughly independent of redshift from $z \approx 0.4$ to $z \approx 2$. The average radiative efficiency we obtain is significantly higher than that corresponding to the maximum spin ($a \approx 0.9$) achieved by a magnetohydrodynamic thick disk (Gammie et al. 2004), $\eta \approx 0.2$, but is consistent with the efficiency of Thorne’s (1974) limit of $a = 0.998$ ($\eta = 0.32$), as well as with that of extreme Kerr rotation, $a = 1$ ($\eta = 0.42$). A similar conclusion has been reached by other studies, based on models of hierarchical galaxy formation (Volonteri et al. 2005) and considerations of the cosmic X-ray background radiation (Elvis et al. 2002). We note that Elvis et al. (2002) gave only a lower limit on the efficiency ($\eta > 0.15$) and no detailed information at any given redshift. The observed high value and constancy of $\eta$ suggest that the spin angular momentum of most or all black holes in quasars have saturated at their maximum value and undergo no evolution from $z \approx 2$ to $z \approx 0.4$. Our results are consistent with the conclusions of Volonteri et al. (2005).

4. DISCUSSION AND SUMMARY

We have estimated the average radiative efficiency, and hence the spin, of supermassive black holes by combining the luminosity and black hole mass function of a large sample of SDSS quasars selected over the redshift interval $0.4 < z < 2.1$. With find that the average radiative efficiency is very high, $\bar{\eta} \approx 0.3$–0.35, which implies that the black holes are rotating very rapidly, with $a \approx 1$. No noticeable evolution is seen over this range of redshifts; it would be very interesting to extend this study to higher redshifts ($z \approx 2$) in order to establish the epoch over which the black hole spins were imprinted. We note that our conclusions are only based on the accretion growth equation, which makes no reference to whether the black hole mass was gained principally through accretion or mergers. An advantage of the present approach is that the result does not depend on the lifetime of quasars.

The large spins deduced for the black holes in quasars may arise quite naturally as a consequence of major (nearly equal mass) galaxy mergers. Massive, gas-rich mergers not only account for most of the star formation in the universe at $z \approx 2$–3 (see, e.g., Conselice et al. 2003), but they are probably also responsible for triggering major episodes of quasar activity (Di Matteo et al. 2005). When galaxies merge, so too do their black holes (if they exist in the parent galaxies), at least in principle. The spin angular momentum of black holes newly born from
mergers is expected to be high, with $a > 0.8$, its exact value depending on the orbit of the original binary (Gammie et al. 2004). Subsequent accretion at an Eddington-limited rate will further increase the spin on a timescale shorter than the Salpeter time ($\tau = 0.45$ Gyr) (Volonteri et al. 2005). The newborn holes can thus rapidly evolve into Kerr holes, consistent with our results.

The high radiative efficiency prolongs the lifetime of a quasar’s accretion. Following Shapiro (2005), the mass of an accreting black hole at time $t$ with an initial mass $M_0$ is $M_\star(t) = M_0 \exp \left[ \frac{m(1 - \eta)}{\eta \tau} \right]$, where $m = M_\star c^2 / L_{\text{Edd}}, M_\text{acc}$ is the accretion rate, and $L_{\text{Edd}}$ is the Eddington luminosity. The anticipated lifetime of an $e$-folding accretion growth is then $t_{\text{QSO}} \approx \eta \tau / m (1 - \eta) \approx (0.4 - 0.7) \tau \approx 0.2 - 0.3$ Gyr for $\eta = 0.3 - 0.4$ if the hole is accreting at the Eddington rate ($L_{\text{Edd}} / c^2$). This lifetime lies within the range of values currently estimated for quasars (Martini 2004) but is uncomfortably long for the high-redshift quasars (Shapiro 2005), would be consistent with the theoretical expectation for magnetohydrodynamic thick disks (Gammie et al. 2004), and would bring it into better agreement with the independent estimates of radiative efficiencies derived from Sołtan-type arguments. The analysis of optically selected quasars by Yu & Tremaine (2002) found $\eta \gtrsim 0.1$ assuming a bolometric correction of $C_B = 11.8$. If $C_B = 6.5$ had been adopted, as suggested by Marconi et al. (2004), Yu & Tremaine’s value of $\eta$ would be lower by a factor of $\sim 2$. On the other hand, this type of estimate is seriously affected by uncertainties in the contribution from obscured active galaxies, which is currently poorly known (Martínez-Sansigre et al. 2005). Estimates of the average radiative efficiency using an energy density based on the cosmic X-ray background, which is less affected by obscuration, yield values of $\eta \gtrsim 0.15$ (Elvis et al. 2002) that are more consistent with our results.

We thank the referee for helpful comments on the manuscript. J.-M. W. acknowledges support from National Natural Science Foundation of China grants 10325313, 10233030, and 10521001, L. C. H. from NASA and the Carnegie Institution of Washington, and R. J. M from the Royal Society.

REFERENCES

Aschenbach, B., Grosso, N., Porquet, D., & Predehl, P. 2004, A&A, 417, 71
Baskin, A., & Lair, A. 2005, MNRAS, 356, 1029
Conselice, C. J., Chapman, S. C., & Windhorst, R. A. 2003, ApJ, 596, L5
Crummy, J., Fabian, A. C., Gallo, L., & Ross, R. R. 2006, MNRAS, 365, 1067
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Elvis, M., Risaliti, G., & Zamorani, G. 2002, ApJ, 565, L5
Fabian, A. C., et al. 2002, MNRAS, 335, L1
Gammie, C. F., Shapiro, S. L., & McKinney, J. C. 2004, ApJ, 602, 312
Genzel, R., Schödel, R., Ott, T., Eckart, A., Alexander, T., Lacombe, F., Rouan, D., & Aschenbach, B. 2003, Nature, 425, 934
Greene, J. E., & Ho, L. C. 2006, ApJ, 641, L21
Ho, L. C., ed. 2004, Coevolution of Black Holes and Galaxies (Cambridge: Cambridge Univ. Press)
Hughes, S. A., & Blandford, R. D. 2003, ApJ, 585, L101
Kaspi, S., Maoz, D., Netzer, H., Peterson, B. M., Vestergaard, M., & Jannuzi, B. T. 2005, ApJ, 629, 61
Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 535, 631
Marconi, A., Risaliti, G., Gilli, R., Hunt, L. K., Maiolino, R., & Salvadori, M. 2004, MNRAS, 351, 169
Martínez-Sansigre, A., Rawlings, S., Lacy, M., Fadda, D., Marleau, F. R., Simpson, C., Willott, C. J., & Jarvis, M. J. 2005, Nature, 436, 666
Martini, P. 2004, in Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), 169
McLure, R. J., & Dunlop, J. S. 2004, MNRAS, 352, 1390
McLure, R. J., & Jarvis, M. J. 2002, MNRAS, 337, 109
Nelson, C. H., Green, R. F., Bower, G., Gebhardt, K., & Weistrop, D. 2004, ApJ, 615, 652
Onken, C. A., Ferrarese, L., Merritt, D., Peterson, B. M., Pogge, R. W., Vestergaard, M., & Wandel, A. 2004, ApJ, 615, 645
Rees, M. J. 1984, ARA&A, 22, 471
Richards, G. T., et al. 2006, ApJ, in press (astro-ph/0601434)
Schneider, D. P., et al. 2003, AJ, 126, 2579
Shapiro, S. L. 2005, ApJ, 620, 59
Solten, A. 1982, MNRAS, 200, 115
Steffen, A. T., Strateva, I., Brandt, W. N., Alexander, D. M., Koekemoer, A. M., Lehmer, B. D., Schneider, D. P., & Vignali, C. 2006, AJ, in press (astro-ph/0602407)
Thorne, K. S. 1974, ApJ, 191, 507
Vestergaard, M. 2002, ApJ, 571, 733
Volonteri, M., Madau, P., Quataert, E., & Rees, M. J. 2005, ApJ, 620, 69
Wilms, J., Reynolds, C. S., Begelman, M. C., Reeves, J., Molendi, S., Staubert, R., & Kendziorra, E. 2001, MNRAS, 328, L27
York, D. G., et al. 2000, AJ, 120, 1579
Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965