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A first step toward constraining supermassive black-hole growth

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Abstract

Updated scaling relations, useful for estimating black hole masses M_{BH} of large samples of distant AGNs and quasars using a single spectrum, are presented. This is timely given the recent improvements made to the reverberation mapping mass determinations and the empirical radius–luminosity relationships on which the scaling relations rely. The redshift distribution of mass estimates of different quasar samples, based on these scaling relations, shows that luminous, distant quasars have very massive black holes $M_{BH} \gtrsim 10^9 M_\odot$, even at $z \gtrsim 4$. Also, there is a limit to how massive and luminous black holes can become: $M_{BH} \lesssim 10^{10} M_\odot$ and $L_{bol} < 10^{48}$ erg s^{-1}. Preliminary mass functions of active black holes out to $z \approx 4$ are presented.
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Keywords: Quasars; Black hole mass; Black hole physics

Contents

1. Determining black hole masses of distant AGNs and quasars

Due to the strong nuclear glare the black hole mass M_{BH} in AGNs cannot be determined by the conventional methods used for quiescent galaxies. The reverberation mapping (RM) technique is the most robust for AGNs and quasars since it does not require high spatial resolution. The technique utilizes the AGN variability properties to determine the central mass using the virial relation $M_{BH} = fR\Delta V^2/G$, where R is the size of the broad line region (BLR) as estimated by the mean emission-line lag τ (time delay relative to continuum variations), i.e., $R = c\tau$, ΔV is the emission-line width (preferably the width of the *variable* part of the emission line), and f is a scale factor of order unity that depends on the structure and geometry of the BLR (Peterson et al., 2004).

Obtaining mass measurements of large samples of distant quasars using the RM technique is very resource consuming and impractical. Methods that in stead *estimate* the central mass are hence useful, in spite the higher uncertainties associated. Only two such methods do not rely on accurate measurements of the host galaxy and can hence be

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applied beyond $z \approx 1$ and the mass scaling relation method proves so far to have the lower uncertainties (Vestergaard, 2003). In addition, we have confidence in its application to luminous and distant quasars owing to the applicability of the virial relationship to all objects with testable data and to all broad emission lines measured and due to the similarity of quasar spectra across large redshift and luminosity ranges. Vestergaard (2003, 2004, herafter Paper I), and Vestergaard and Peterson (2006, hereafter Paper II) provide more detailed accounts of the pros and cons of the scaling relations. The first mass scaling relations for $H\beta$, MgII, and CIV (Kaspi et al., 2000; Vestergaard, 2002; McLure and Jarvis, 2002) have since been successfully applied to large samples of quasars (e.g., Woo and Urry, 2002; Warner et al., 2003; Paper I; McLure and Dunlop, 2004; Shang et al., 2005).

An update of the original mass scaling relations is timely owing to several significant developments since 2002. The RM data base, that is used to calibrate the mass scaling relations, is completely reanalyzed (Peterson et al., 2004). The "zero-point" (or normalization f) of the reverberation based masses is now anchored in the M–σ relationship established by the local quiescient galaxies (Onken et al., 2004). The radius–luminosity (hereafter R–L) relationship between the size of the broad line region and the continuum luminosity has been updated based on the reanalyzed RM data (Kaspi et al., 2005) and new *HST* imaging that enable us to correct for host galaxy contamination of the optical luminosity measured from spectra (Bentz et al., 2006).

The mass scaling relations approximate the RM viral mass firstly by using single-epoch spectra for measurements of ΔV and R as opposed to variability data and secondly by using the empirically established R–L relationships where $R \propto L^{\gamma}$ and L is the continuum luminosity determined from the AGN spectrum. For the mass estimate based on the FWHM of the $H\beta$ broad component and the optical luminosity $L_{\lambda}(5100\,\text{Å})$ we use the R–L relation of Bentz et al., 2006 where $\gamma = 0.50$ and which includes host galaxy correction of $L_{\lambda}(5100\,\text{Å})$. The calibrated mass scaling relation based on $H\beta$ that we use is

$$M_{\rm BH}(H\beta) = 10^{6.91}\left[\left(\frac{\text{FWHM}(H\beta)}{1000\ \text{km s}^{-1}}\right)^{2}\left(\frac{\lambda L_{\lambda}(5100\,\text{Å})}{10^{44}\ \text{erg s}^{-1}}\right)^{0.50}\right]. \quad (1)$$

Due to the lack of an empirical relation between the CIV BLR size and the UV continuum luminosity $L_{\lambda}(1350\,\text{Å})$ we adopt the R–$L_{\lambda}(1350\,\text{Å})$ relation for the $H\beta$ emitting region, where $\gamma = 0.53$ (Paper II; Kaspi et al., 2005). The calibrated mass scaling relationship based on the FWHM of the CIV line and $L_{\lambda}(1350\,\text{Å})$ is

$$M_{\rm BH}(\text{CIV}) = 10^{6.66}\left[\left(\frac{\text{FWHM(CIV)}}{1000\ \text{km s}^{-1}}\right)^{2}\left(\frac{\lambda L_{\lambda}(1350\,\text{Å})}{10^{44}\ \text{erg s}^{-1}}\right)^{0.53}\right]. \quad (2)$$

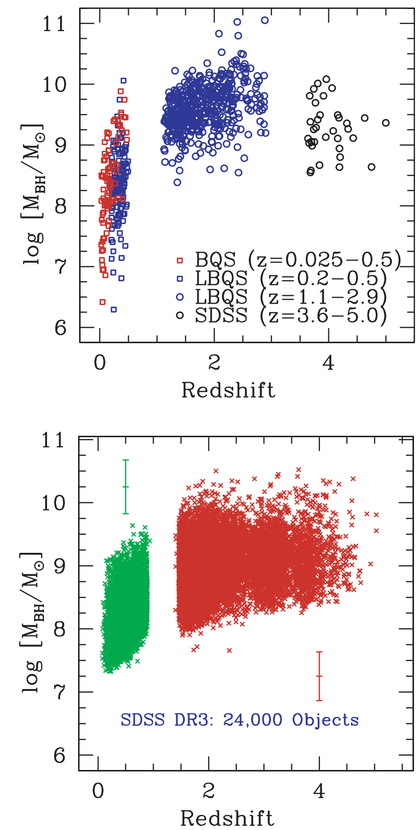

Fig. 1. Distribution of black hole masses with redshift for the Bright Quasar Survey, the Large Bright Quasar Survey, and the color-selected sample from SDSS (Fan et al., 2001) [*top*] and for the SDSS Data Release 3 Quasar Catalog [*bottom*].

The statistical uncertainty in these relationships is about a factor of 2–3 relative to the RM masses which have an estimated absolute uncertainty of a factor ~2.9 (Onken et al., 2004). The absolute uncertainty in the scaling relations are thus of order a factor of 3.5–5. These and other mass scaling relations are discussed in more detail in Paper II. The current benchmark cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\Lambda} = 0.7$, and $\Omega_{\rm m} = 0.3$ is used throughout.

2. Black hole mass and luminosity distributions

Fig. 1 shows the result of applying the scaling relations of Section 1 to quasar samples[1] such as the Bright Quasar Survey (BQS), the Large Bright Quasar Survey (LBQS), the color-selected sample of Sloan Digital Sky Survey (SDSS) quasars (Fan et al., 2001), and the SDSS Data Release 3 quasar catalog (Schneider et al., 2005). The results on the SDSS DR3 quasar catalog is work in progress and details of the mass distributions and the mass functions (Section 3) may change. Fig. 1 shows that at

[1] The LBQS data are taken from Forster et al. (2001) and references therein. The data of the BQS and the color-selected sample are described in detail in Paper I and the LBQS and SDSS DR3 data and results will be published elsewhere (Vestergaard et al., in preparation).

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