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Black-Hole Mass Measurements

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Abstract. The applicability and apparent uncertainties of the techniques currently available for measuring or estimating black-hole masses in AGNs are briefly summarized.

1. Introduction

Knowledge of the mass of the central black hole in active galaxies is important for many studies of early structure formation and of the central engine and its evolution. The hope is that we will learn how the formation and growth of the black hole affects the formation, the evolution, and the characteristics of the galaxy by which it is hosted. The SDSS promises to provide valuable insight.

Black-hole mass determination methods fall in two distinct categories: primary and secondary methods. Their differences are important to recognize. With primary methods, the black-hole mass ($M_{\rm BH}$) is directly *measured* from gas and stars whose dynamics are dictated by the black hole. These methods are often very challenging or time consuming. In contrast, secondary methods are often more easily applied to large data sets, but only provide *estimates* of the mass by adopting approximations to the primary methods or by measuring parameters with which $M_{\rm BH}$ is known to correlate.

Due to space limitations, all the work done on this subject cannot be cited; my apologies in advance. Emphasis is placed on a few key papers providing calibration of the methods and assessments of the uncertainties.

2. Primary Mass Determination Methods

Stellar and Gas Kinematics. To determine the virial black-hole mass of nearby quiescent galaxies requires high spatial resolution spectroscopy of the nuclear regions in order to measure the velocity dispersion of the stars (or gas) within the sphere of influence of the central black hole. This method can also be used for weakly active galactic nuclei (AGNs), such as low-luminosity AGNs, LINERs, and Seyfert 2s (Table 1). For more luminous AGNs (Type 1 sources) the strong nuclear emission washes out the stellar features in the spectrum. The scatter in the $M_{\rm BH}$–$\sigma_*^{\rm bulge}$ relationship, established for nearby quiescent galaxies (e.g., Tremaine et al. 2002), suggests that black-hole masses determined from stellar and gas kinematics are accurate to within a factor of about 2.

Table 1. Primary Mass Determination Methods

	Low-z		**High-z**	**Best**
	Low-L	**High-L**	**High-L**	**Accuracy**
	LINERs, Sy 2s	QSOs, Sy 1s BL Lacs	QSOs	(dex)
Stellar & Gas kinematics	(√)	÷	÷	0.15 – 0.3
Megamasers	Type 2	÷	÷	≤ -1.0
Reverberation Mapping	Type 1	Type 1	√	0.15 – 0.3

Megamasers. Spectroscopy of water-vapor maser emission from circumnuclear disks in nearby AGNs reveals the kinematics of the disk and the location of the maser. Megamasers can yield highly accurate $M_{\rm BH}$ measurements, especially in highly inclined sources: for NGC 4258, which is inclined $83°\pm4°$, the mass is determined to within a few per cent (Miyoshi et al. 1995). However, this method is only useful for selected 'edge-on' sources and so far relatively few objects are known to have megamasers (e.g., Greenhill et al. 2003).

Reverberation Mapping. The reverberation-mapping technique is the best and most robust mass measurement method to apply to AGNs and quasars: utilizing the variability properties of the source the technique does not require high spatial resolution and is not affected by the nuclear glare. Peterson & Onken (2004, this volume) outline the basic principle of the reverberation mapping technique and discuss the importance of the zero-point calibration of reverberation masses and of the unknown, order unity, scale factor f.

For a given AGN the *rms* velocity width and time lag for different broad emission lines correlate such that higher ionization lines have larger widths and smaller lags (consistent with the same central mass for each object). This virial relationship for multiple lines is seen for all four AGNs for which this is testable (NGC 7469, NGC 3783, NGC 5548, 3C 390.3) and for the well-measured emission lines of Si IV λ1400, C IV λ1549, He II λ1640, C III] λ1909, Hβ λ4861, and He II λ4686 (Peterson & Wandel 1999, 2000; Onken & Peterson 2002).

Notably, nearby AGNs with measurements of both reverberation mass and bulge velocity dispersion fall along the $M_{\rm BH} - \sigma_*$ relationship established by quiescent galaxies and with a similar scatter (Ferrarese et al. 2001). This suggests that reverberation mapping masses are accurate to within a factor 2 to 3.

Reverberation mapping is fully applicable to distant quasars (Table 1), but is less practical as it is extremely time and resource consuming: luminous AGNs vary with smaller amplitudes and on longer time scales than lower-luminosity, nearby AGNs. The time scales are further increased by time dilation owing to the cosmological distances of quasars. Even for the 17 nearby quasars monitored so far, ten years of variability data are necessary to obtain reasonable results (Kaspi et al. 2000). Secondary methods are more practical for distant quasars.

Table 2. Secondary Mass Determination Methods

	Low-z		**High-z**	**Best Accu-racy**	**Future Work**
	Low-L LINERs, Sy 2s	**High-L** QSOs, Sy 1s BL Lacs	**High-L** QSOs	(dex)	
Scaling Relations	√	√	√	$0.4 - 0.5$	note *a*
Via $M_{\rm BH} - \sigma_*$:					
$- \sigma_*$	√	√	÷	0.3	note *b*
− [O III] FWHM	√	√	√	0.7	note *c*
− Fundamental Plane: $\sum_e, r_e$	√	√	÷	>0.7	note *d*
Via $M_{\rm BH} - L_{\rm bulge}$ & scaling rel.:					
$- M_R$	√	√	÷	$0.5 - 0.6$	note *e*

Notes − (*a*) Improve $R - L$ relation; understand outliers, (*b*) Extend to more distant AGNs and luminous quasars, (*c*) Understand scatter and outliers, (*d*) Quantify and improve accuracy, (*e*) Calibrate to Reverberation masses

3. Secondary Methods

Since the primary mass determination methods are either inapplicable or impractical for more luminous and more distant AGNs and quasars, several secondary methods have been adopted in the literature to *estimate* the central mass. These methods, summarized in Table 2, are either approximations to the reverberation mapping technique or rely on the empirical relationships between the black-hole mass, $M_{\rm BH}$, and the properties of the host galaxy bulge: velocity dispersion, σ_*, or bulge luminosity, $L_{\rm bulge}$. The measurements of the bulge properties are most useful for AGNs at low redshift ($z \lesssim 1$) where the host galaxy is easier to characterize. It is noteworthy that, even so, these methods can yield mass estimates that are currently quite uncertain, as explained below.

3.1. Scaling Relationships

Based on single-epoch spectroscopy the scaling relationships are approximations to the virial-mass measurements obtained from reverberation mapping. The method relies on the radius – luminosity relationship, established by reverberation mapping. For a photoionized BLR, its size R should scale with the square root of the source luminosity, $R \propto L^{0.5}$. Kaspi et al. (2000) found empirically that the size of the H β emitting region scales with the continuum luminosity at 5100Å to the power of 0.7: $R({\rm H}\,\beta) \propto L_{\lambda}^{0.7}(5100{\rm Å})$. While this difference is yet to be understood (work is in progress; e.g., Peterson & Onken, this volume), this means that $M_{\rm BH}$ can be *estimated* when we have measurements of the continuum luminosity and the emission-line width: $M_{\rm BH} \propto {\rm FWHM}^2\, L_{\lambda}^{0.7}$. (Note, the slope adopted in the literature is not uniform but ranges between 0.5 and 0.7). The use of FWHM is a single-epoch approximation to the velocity dispersion of the line-emitting gas responding to continuum variations (Peterson & Onken 2004, this volume). Vestergaard (2004b, this volume) explains why these scaling relations are reasonable and why they can be applied to luminous, high-z quasars.

Three different broad emission lines (H β, Mg II, and C IV) have been adopted along with continuum luminosities (at 5100Å, 3000Å, and 1350Å, respectively) to estimate black-hole masses in large samples of quasars and AGNs [H β, C IV: Vestergaard (2002; 2004b, this volume); Mg II: McLure & Jarvis (2002); Jarvis & McLure (2004, this volume)]. There are pros and cons to each method as outlined next. Using optical spectroscopy, the H β method probes redshifts below 0.9, Mg II probes redshifts between 0.3 and 2.3, while C IV is accessible at redshifts between 1.2 and 4.9. While Fe II emission heavily contaminates the Mg II line profile (e.g., Francis et al. 1991; Vestergaard & Wilkes 2001) and thus needs to be subtracted to allow measurements of FWHM(Mg II), typically only strong Fe II emission affects the H β line width. C IV is only affected in the extreme wings by He IIλ1640, and occasionally by N IV]λ1486, and (weak) Fe II multiplets. However, the contribution to H β from the narrow-line region needs to be subtracted. The only concern about C IV is the possible presence of outflowing high-ionization BLR gas, which may yield blue asymmetric broad profiles. This is seen very clearly in the case of narrow-line Seyfert 1 galaxies (e.g., Leighly 2000) for which the C IV method is not well suited. But very few quasars appear to display such asymmetric profiles, so emitting outflows are probably not a general concern for quasars (Vestergaard 2004). A notable assumption enters the Mg II method, namely that Mg II *should* be emitted co-spatially with H β and should therefore have similar line widths (which seems to be the case; McLure & Jarvis 2002). Then FWHM(Mg II) can be used as a direct surrogate for H β in the scaling relation. Unfortunately, the only published data on Mg II constrain the Mg II lag (or the distance from which it is emitted) very poorly but the analysis by Clavel et al. (1991) and Dietrich & Kollatschny (1995) suggest that Mg II is not necessarily emitted co-spatially with H β. The additional advantage of the available H β and C IV scaling relations is that they are calibrated to the more accurate reverberation mapping masses of nearby AGNs (Wandel, Peterson, & Malkan 1999; Kaspi et al. 2000; Vestergaard 2002). The statistical scatter indicates 1σ uncertainties of factors 2.5 to 3 (relative to the reverberation masses) for these scaling relations. Similar uncertainties are argued to be obtainable with Mg II (McLure & Jarvis 2002). Nonetheless, individual mass estimates may be uncertain by as much as a factor 10. The power of scaling relations is in their application to large statistical AGN samples.

The uncertainties of these scaling relations are dominated by the scatter in the $R - L$ relation, and improvements to this relation is thus desirable. Also, there is a need to understand the outliers in the scaling relations (Table 2). Dramatically improving the accuracy of the reverberation masses, on which the scaling relations rely, will require a dedicated space-based observatory, such as the proposed MIDEX mission *Kronos* (e.g., Peterson et al. 2004).

The radius R can also be estimated with the reasonable assumption that the product of the ionization parameter and the electron density is roughly similar in all objects (the photoionization method). In this case the mass estimate is a function of $L^{0.5}\,\mathrm{FWHM}^2$ and seems accurate to within a factor two of the reverberation masses (Wandel, Peterson, & Malkan 1999).

3.2. Via the $M_{\rm BH} - \sigma_*$ Relationship

As the $M_{\rm BH} - \sigma_*$ relation for quiescent galaxies is relatively tight and AGNs also fall on this relationship, good measurements of the bulge velocity dispersion in AGN host galaxies can be used to estimate the black-hole mass (and with a similar uncertainty; Table 2). So far, only AGNs at $z < 0.06$ have had σ_* measured because the Ca II$\lambda\lambda$8498, 8542, 8662 absorption lines used for this measurement move into the atmospheric water vapor bands at $z \geq 0.06$ (Ferrarese et al. 2001).

Nelson (2000) suggested using FWHM([O III]) as a proxy for σ_* since the near-nuclear stellar velocity dispersion correlates with FWHM([O III]) for a sample of 75 Seyfert galaxies (Nelson & Whittle 1996). Boroson (2003) used data from the SDSS Early Data Release to assess and confirm that the 1σ uncertainty of this method is a factor of 5. For this method to be more useful, both the scatter and the outliers need to be understood (Table 2). Some line asymmetries are suspected to be connected with outflows and can be prominent in radio sources where the narrow-line region and the radio source may interact.

Studies in the literature have used AGN host galaxy imaging and the Fundamental Plane for elliptical galaxies to measure the effective surface brightness, $\sum_e$, and the effective radius, r_e, to derive first σ_* and then $M_{\rm BH}$. The reasoning is that especially nearby quasars and radio galaxies seem to reside in giant elliptical galaxies, which *should* fall on the Fundamental Plane. Unfortunately, this method potentially has large uncertainties because (a) $\sum_e$ and r_e are very hard to measure accurately in the presence of the bright nucleus of most AGNs, (b) the bulge/disk decomposition process is difficult even for nearby quiescent galaxies and is particularly challenging for AGNs, and (c) the method is subject to the uncertainties of both the Fundamental Plane and the $M_{\rm BH} - \sigma_*$ relation. For radio galaxies, unaffected by nuclear glare, a factor 4 (or larger) uncertainty in estimating σ_* alone seems appropriate (Woo & Urry 2002). The combined uncertainty of the Fundamental Plane method is thus expected to exceed a factor 5.

3.3. Via the $M_{\rm BH} - L_{\rm bulge}$ and Scaling Relationships

The black-hole mass of quiescent galaxies correlates, in addition to σ_*, with the bulge luminosity, $L_{\rm bulge}$, although with larger scatter. For this reason, the $M_{\rm BH} - L_{\rm bulge}$ relation is generally not preferred for mass estimates of normal galaxies. This method has also proven difficult and prone to significant uncertainties owing to the nuclear glare affecting the bulge/disk decomposition process (e.g., Wandel 2002). Nonetheless, McLure & Dunlop (2001, 2002) argue that with careful R-band measurements of the AGN host galaxy, first $L_{\rm bulge}$ and then $M_{\rm BH}$ can be estimated to within a factor 3 to 4. Unfortunately, this method has not yet been calibrated to reverberation mapping masses, but rather to mass estimates based on scaling laws. This may not be a severe problem since the authors find their AGNs to have the same slope and scatter as the inactive galaxies with dynamical mass measurements to within the errors.

4. Future Efforts

Table 2 lists suggestions to how we may improve the mass estimation methods. In addition, it is important to understand their limitations as well as their efficacy. Since reverberation masses provide the anchor of the scaling relations a few comments thereon are in order. An understanding of the BLR structure and kinematics is required to determine the absolute zero-point of the reverberation masses (the 'f' factor). This is a non-trivial but an achievable task with a dedicated observatory like *Kronos* and existing advanced analysis techniques (Peterson et al. 2004; Peterson & Horne 2004). Also, direct comparisons of stellar dynamics and reverberation mapping need to be effected. Moreover, the odd objects need to be understood: for example, for 3C 390.3 the lower ionization lines appear to have shorter lags, in contrast to other AGNs. As this object is the only broad-line radio source which has been monitored, it needs to be established whether or not it belongs to a separate class of objects. Understanding this behavior is also important for our understanding of the typical BLR structure.

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