Supermassive Black Holes and Their Relationships with Their Host Galaxies

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Abstract. We review how the masses of black holes in active galactic nuclei are measured and outline the current limitations and uncertainties. Masses have been measured directly by emission-line reverberation for nearly 50 relatively nearby AGNs, but uncertainties due to the unknown geometry and projection effects limit the accuracy of these masses to \( \sim 0.3 \) dex. Reverberation studies show that there is a very tight relationship between the broad-line region radius and the AGN luminosity, with an intrinsic scatter of \( \sim 0.1 \) dex, which shows (1) that the largest source of systematic uncertainty in the black hole mass determinations is how the velocity field of the broad-line region is characterized, not the size of the broad-line region, and (2) that the size of the broad-line region can be estimated to fairly high accuracy from the AGN luminosity alone, thus providing a powerful indirect method of estimating black hole masses in even distant AGNs.

1. Introduction

The existence of supermassive black holes at the centers of at least some galaxies has been suspected for nearly 50 years, when it was first suggested that accretion powers quasars. Oddly enough, the first real evidence that supermassive black holes reside in galactic centers was not in quasars, but in quiescent galactic nuclei, where their masses were determined by the kinds of high-angular resolution studies featured at this workshop. High angular resolution is required for most dynamical measurements of the black hole mass \( M_{\text{BH}} \) since one must resolve (or nearly resolve, depending on who you listen to) the black hole radius of influence,

\[
r_* = \frac{2GM_{\text{BH}}}{\sigma_*^2},
\]

where \( \sigma_* \) is the stellar velocity dispersion of the bulge, since it is within this distance that the black hole dominates the dynamics of the stars and gas. In this contribution, however, I’m going to focus instead on a complementary method, reverberation mapping (Blandford & McKee 1982; Peterson 1993), that substitutes time resolution for angular resolution to measure the masses of black holes in active galactic nuclei (AGNs). While application of this method is restricted to Type 1 (broad line) AGNs, which are found in only a small fraction of all luminous galaxies, the importance of reverberation mapping derives from the fact that it is the only direct method of measuring the masses of supermassive black holes at large cosmological distances, as illustrated in Figure 1.

It is useful at this point to distinguish between direct and indirect methods of measuring the masses of black holes in galaxies. Direct methods are those which involve measuring the...
motions of gas or stars that are accelerated by the black hole itself; these would include proper motions and radial velocities of stars in the center of the Milky Way and megamasers in Type 2 AGNs, stellar or gas dynamics in nearby galaxies, and AGN reverberation mapping. Indirect methods are those in which we measure observable properties that that are correlated with the black hole mass. These would include the correlations between (1) black-hole mass and stellar bulge velocity dispersion (the “$M_{\text{BH}}-\sigma_*$ relationship”) (2) black-hole mass and bulge luminosity (the “$M_{\text{BH}}-L_{\text{bulge}}$ relationship”), the fundamental plane, and, in the case of Type 1 AGNs, reverberation-based scaling relationships (see §3.1).

With the exception of the measurements of masses of the black holes at the center of the Milky Way and the megamaser source NGC 4258, it is probably safe to say that measurements using the direct methods listed above are still probably uncertain by at least a factor of two. The systematic errors associated with the reverberation-based masses are not well-understood because of our lack of understanding of the geometry of the broad-line region (BLR) and how
the mass measurements are affected by projection. Reverberation masses are usually computed from
\[ M_{\text{BH}} = f \left( \frac{\Delta V^2 R}{G} \right) + gL , \]
where \( \Delta V \) is the emission-line width, \( R \) is the size of the BLR as measured for this particular emission line, \( G \) is the gravitational constant, \( L \) is the AGN luminosity, and \( f \) and \( g \) are constants. In the first term on the right-hand side, the quantity in parentheses is called the “virial product” which is comprised of the two observables and has units of mass. The systematics associated with geometry and projection are all subsumed into the dimensionless factor \( f \), which is expected to be of order unity, and should be different for each AGN. It is possible to obtain an average value \( \langle f \rangle \) by noting that AGNs clearly show the same \( M_{\text{BH}}-\sigma_\star \) relationship as quiescent galaxies, except that the AGN relationship has an undefined zero point, i.e., \( \langle f \rangle \) is unknown. If we assume that the zero-points are identical for AGNs and quiescent galaxies, then we find that \( \langle f \rangle \approx 5.25 \) (Onken et al. 2004; Woo et al. 2010, though see also Graham et al. 2011 and §4); the scatter around the AGN \( M_{\text{BH}}-\sigma_\star \) relationship then suggests that the typical systematic uncertainties are probably no more than \( \sim 0.3 \) dex.

The second term on the right-hand side of equation (2) accounts for a possible contribution by radiation pressure (Marconi et al. 2008). There is active debate about whether or not this term is significant. Space limitations preclude further discussion of this interesting possibility, and for the time being I will make the cavalier assumption that \( g = 0 \).

2. Reverberation Mapping and Black Hole Masses

2.1. Measuring the Size of the Emission-Line Region

The ultraviolet, optical, and near-infrared spectra of Type 1 AGNs are dominated by strong Doppler-broadened emission lines which are driven by the ionizing continuum emission that arises in the accretion disk surrounding the central supermassive black hole. The accretion process has numerous instabilities, so the continuum emission from the central source varies with time in an unpredictable fashion (though it can be statistically well-modeled as a damped random walk; see Kelly et al. 2009). The emission lines respond to these variations in the continuum flux, but with a time delay that is attributable to the light-travel time across the line-emitting region. The goal of reverberation mapping is to measure the time-delayed response of emission lines to the continuum variations and thus determine the structure and kinematics of the BLR (see Peterson 2001 for a tutorial on the method). Without going into detail, with a couple of simple assumptions that are easily justified post facto (e.g., that the observable continuum variations track those of the ionizing continuum with a negligible time delay), it is straightforward to measure the mean response time for the line-emitting region by cross-correlating continuum and emission-line light curves; this time delay \( \tau \), or lag, gives the typical distance from the accretion disk to where the response of that particular emission line is most pronounced, \( R = c\tau \).

Operationally, reverberation mapping requires long-duration, high-precision spectrophotometric monitoring of AGNs. Despite the difficulty, large allocations of telescope time required, and risk (due primarily to weather and equipment failure), reverberation mapping programs have yielded results for nearly 50 AGNs at the time of this workshop. The major conclusions from these studies are:

(i) Different emission lines respond with different time delays. Lines characteristic of more highly ionized gas (e.g., \( \text{CIV} \lambda 1549, \text{HeII} \lambda 4686 \)) respond more rapidly than those characteristic of less highly ionized gas (e.g., the hydrogen Balmer lines), providing evidence for ionization stratification of the BLR.
(ii) In every case where time delays for multiple lines are measured, there is a strong anticorrelation between lag and emission-line Doppler width $\Delta V$ of the form $\tau \propto \Delta V^{-2}$, justifying the use of equation (2) to obtain the mass of the central source.

(iii) For a given emission line, the lag is longer in more luminous AGNs, consistent with $R \propto L^{1/2}$, as discussed in §3.1. Furthermore, when the response of a particular emission line is measured at different times when the continuum is in different luminosity states, the lag varies as $\tau \propto L_{UV}^{1/2}$, where $L_{UV}$ is the luminosity in the ultraviolet, as close as possible to the ionizing continuum — the optical continuum varies in phase with the UV continuum, to a good approximation, but with a lower amplitude. The emission-line width also changes with luminosity, in a way that is consistent with a constant value of $\Delta V^2\tau$, again justifying use of equation (2).

2.2. Measuring the Velocity Dispersion of the Line-Emitting Region

To calculate the enclosed mass from equation (2), one wants to consider the velocity dispersion of the gas that is actually producing the variability signal. It is common to isolate the variable part of the emission line by combining all of the spectra obtained in the reverberation program into an rms residual spectrum (root mean square flux at each wavelength, with the mean flux subtracted), which removes the non-variable, or slowly varying, components of the spectrum. The emission-line width is usually characterized by either the full-width at half maximum (FWHM) or the line dispersion $\sigma_{\text{line}}$ (i.e., the second moment of the line profile). Both have particular advantages and disadvantages: FWHM is easy to measure and is usually not affected by blending with other lines, but it is more sensitive to unremoved narrow-line components, random noise and, in the case of resonance lines, absorption by intervening gas. Line dispersion is well-defined, even in noisy spectra, less sensitive to narrow-line components and self-absorption, and more accurate for low-contrast lines, but is much more sensitive to blending with other features. Choice of line-width measure turns out to be quite important, as described in §3.2.

2.3. Reverberation-Based Masses

Once the lag and line width are measured, equation (2) is used to compute the mass. As described above, the mean scaling factor is currently determined from the $M_{\text{BH}}-\sigma_*$ relationship. While the fact that AGNs show an $M_{\text{BH}}-\sigma_*$ relationship with a slope that is the same as that for quiescent galaxies is somehow reassuring, we really would like additional assurances that these masses are correct. Fortunately, as can been seen upon careful inspection of Figure 1, there are a bare handful of AGNs that are close enough and massive enough that their black hole masses can be measured by high-angular resolution studies of stellar and gas dynamics. Results for two well-studied AGNs are listed in Table 1. Noting that the uncertainties for the reverberation results do not include any systematic errors (which are likely at the factor of two to three level), the results are all in quite reasonable agreement.

A further consistency check is provided by comparing the $M_{\text{BH}}-L_{\text{bulge}}$ relationships for AGNs and quiescent galaxies. The agreement is found to be very good if the zero point from the $M_{\text{BH}}-\sigma_*$ relationship is adopted (Bentz et al. 2009a).

3. Indirect Reverberation-Based Black Hole Masses

Reverberation mapping is costly in terms of telescope time, even for relatively nearby bright AGNs. The problem of measuring masses for a large population of AGNs, including faint high-redshift quasars, becomes daunting. Fortunately, however, their are indirect methods of mass measurement that allow us to estimate masses in AGNs from more easily acquired data. Specifically, in the case of Type 1 AGNs we can use the relationship between BLR region radius and AGN luminosity to side-step the reverberation process: from a single spectrum, we can...
Table 1. Black Hole Masses (in units of $10^6 M_\odot$)

| Galaxy     | NGC 3227 | NGC 4151 |
|------------|----------|----------|
| **Direct methods:** |          |          |
| Stellar dynamics  | $7\mathbin{-}20^a$ | $<70^b$ |
| Gas dynamics     | $20^{+10}_{-4}$ | $30^{+7.5}_{-22}^c$ |
| Reverberation    | $7.63 \pm 1.7^d$ | $46 \pm 5^e$ |
| **Indirect methods:** |          |          |
| $M_{ BH}^{} \sigma^*_\ast$ | 25       | 6.1      |
| $R-L$ scaling    | 15       | 65       |

$a$ Davies et al. (2006).
$b$ Onken et al. (2007).
$c$ Hicks & Malkan (2008).
$d$ Denney et al. (2010).
$e$ Bentz et al. (2006).

measure both luminosity, from which we infer the BLR radius, and line width and then compute the mass trivially. Of course, there are subtleties, as discussed below.

3.1. The Radius–Luminosity Relationship

Long before it was actually confirmed observationally, a relationship between the radius of the BLR and the AGN luminosity was expected on the basis of photoionization physics. Naïve expectations based on the gross similarity of broad-line spectra over several orders of magnitude in luminosity suggested that the relationship should have the form $R \propto L^{1/2}$, which is actually in remarkable agreement with the observations, once care is taken to carefully remove the host-galaxy starlight contamination (Bentz et al. 2009b). The relationship is observationally well-constrained only for H$\beta$ (Figure 2). When only the highest-quality reverberation data are used, the intrinsic scatter in this relationship is very small, approximately 0.1 dex. Thus, measurement of the AGN luminosity from a single spectrum can give an estimate of the size of the H$\beta$-emitting region that is nearly as good as one can obtain by reverberation!

3.2. Measuring the Line Width

When considering the many possible sources of random and systematic error in reverberation-based mass estimates, it is common to focus on uncertainties in the $R-L$ relationship. While there are possible difficulties, this is a misguided concern: proper characterization of the velocity dispersion of the broad-line emitting gas is a far greater problem. First, the emission lines are generally broader in the mean spectrum (or a single spectrum) than in the rms spectrum, which effectively requires a larger value of $\langle f \rangle$. Second, the mean spectrum (or a single spectrum) is heavily contaminated by constant or slowly varying components like the narrow-line component, which arises in low-density gas at much larger distances, and broad Fe$\llbracket$II$\rrbracket$ emission, which can be particularly troublesome for H$\beta$ in particular. And third, the line shape is a function of the line width, as illustrated in Figure 3, where we use the ratio of FWHM$/\sigma_{\text{line}}$ as a rough characterization of the line profile.

This last point is actually quite important: if you consider the masses of the AGNs with the largest ($\sim 3.5$) and the smallest ($\sim 0.7$) values of FWHM$/\sigma_{\text{line}}$, their ratio differs by a factor of $\sim 25$, depending on whether you use FWHM or $\sigma_{\text{line}}$ as the line-width measure. This actually
brings out another point: the average value of FWHM/$\sigma_{\text{line}}$ is about 2.35, the same as for a Gaussian. So fitting a Gaussian to an emission line, like people often do to better determine the line widths in noisy spectra, works well for an average quasar emission line, but it is a terrible approximation for both the widest and narrowest lines. I’ll return to this point shortly.

So which of FWHM and $\sigma_{\text{line}}$ is the better measure? Which introduces less bias into the
mass scale? My first parenthetical comment is to not get your expectations too high: what is remarkable to me is that we can take these two simple parameters, time lag and line width, that in some sense average over what is undoubtedly a very complex system, and compute a mass that’s good to a factor of two or three! But, still we need these uncertainties to be random rather than systematic (i.e., not a function of line width or luminosity).

My own best answer to which line-width measure to use is that I have some preference for $\sigma_{\text{line}}$ over FWHM. The evidence for favoring $\sigma_{\text{line}}$ is threefold, but none of these make the case definitive. First, the virial relationships, i.e., plots of line width versus lag, are rather tighter for $\sigma_{\text{line}}$ than for FWHM (Peterson et al. 2004). Second, if we consider the well-studied case of NGC 5548 and plot the reverberation mass measurements as a function of AGN luminosity (Figure 4), we find that the mass is independent of luminosity for $\sigma_{\text{line}}$, but shows some (weak) luminosity dependence if FWHM is used: I hasten to add that neither of these statements has a high level of statistical significance.

My third argument is more subtle: suppose that $\sigma_{\text{line}}$ is the correct, unbiased way to characterize the line width. If one uses FWHM instead, Figure 3 shows that the broadest lines will be overestimated and the narrowest lines will be underestimated. All other things being equal, the largest masses are too high and the lowest masses are too low. This would explain qualitatively the “sub-Eddington boundary” found by Steinhardt & Elvis (2010) using black-hole masses computed from FWHM of Gaussian fits to quasar spectra (Shen et al. 2008). Rafiee & Hall (2011) show that the sub-Eddington limit is significantly weakened when directly measured values of $\sigma_{\text{line}}$ are used instead of FWHM of Gaussian fits.

4. Future Considerations
On the whole, the news is pretty good: reverberation mapping can potentially yield masses that are accurate to around a factor of 2–3 or so. Longer, more densely sampled reverberation campaigns are beginning to yield velocity–delay maps (e.g., Bentz et al. 2010; Barth et al. 2011; Denney et al. 2011) and in the cases where dynamical modeling has been done, the black hole masses are consistent with the masses computed from equation (2). It is extremely important to do this for as many AGNs as possible in order to determine $\langle f \rangle$ directly and remove dependence of the reverberation mass scale on relationships between the black hole mass and host galaxy properties. As more and better data are acquired, the simple relationships between black hole mass and host galaxy properties are beginning to look more complex. For example, there is some evidence that narrow-line Seyfert 1 galaxies, which are thought to be high Eddington rate
accretors, reside in galaxies with pseudobulges rather than classical bulges (see Orban de Xivry et al. 2011, Mathur et al. 2012, and references therein). The evolutionary paths for black hole growth may well depend on the black hole mass, with higher-mass black holes growing early, largely through mergers, and lower-mass black holes growing later through secular processes (see Kormendy, Bender, & Cornell 2011 and references therein); relationships like the $R-L$ relationship ($\S3.1$) are probably not affected (as once gas gets down to the inner parsec or so, the black hole hardly cares how the gas got there), but the relationships between the black hole mass and the host properties might well be different.

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