Section III

Black Hole Masses, Scaling Relationships, and Their Evolution

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Co-Evolution of Central Black Holes and Galaxies
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Toward Precision Measurement of Central Black Hole Masses

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Abstract. We review briefly direct and indirect methods of measuring the masses of black holes in galactic nuclei, and then focus attention on supermassive black holes in active nuclei, with special attention to results from reverberation mapping and their limitations. We find that the intrinsic scatter in the relationship between the AGN luminosity and the broad-line region size is very small, $\sim$0.11 dex, comparable to the uncertainties in the better reverberation measurements. We also find that the relationship between reverberation-based black hole masses and host-galaxy bulge luminosities also seems to have surprisingly little intrinsic scatter, $\sim$0.17 dex. We note, however, that there are still potential systematics that could affect the overall mass calibration at the level of a factor of a few.

Keywords. galaxies: active, galaxies: nuclei, techniques: spectroscopic

1. Introduction

With the advent of suitable technology for high angular resolution spectroscopy, from space with *Hubble Space Telescope* and from the ground with adaptive optics assistance, it has become possible to measure the masses of the central black holes in many nearby galaxies. Observations of nearby galaxies have led to the identification of scaling relationships that then allow us to estimate masses of black holes in distant galaxies and thus determine, at least in principle, the mass function for supermassive black holes, both locally and over cosmic time. Consequently, there have been tremendous advances in our understanding of the evolution of the supermassive black hole population and that of the galaxies that host them over the history of the universe. Despite this incredible progress, it is important to understand that supermassive black hole measurement is a field in its infancy: even the methods deemed most reliable have systematic uncertainties that have not been mitigated in a completely satisfactory way. Masses based on stellar dynamics and gas dynamics are highly model dependent and are only as reliable as the underlying assumptions. An obvious example is the recent work of Gebhardt & Thomas (2009) who found that the mass of the black hole in M 87, widely regarded as one of the most secure measurements, changed by a factor of two with the introduction of a dark matter halo into the models. It is also worth noting that only two black hole measurements, the Milky Way (based on orbital motion of stars in the Galactic Center) and NGC 4258 (based on motions of megamasers), meet the formal criterion of measuring the mass on a sufficiently compact scale that the black-hole nature of the central source is proven. In all other present measurements, it remains an article of faith that the central source is a singularity, although it is hard to see practically how these masses could be anything else. We will therefore adhere to the convention of referring to these objects as black holes.

Fundamentally, mass measurements are based on how the central black holes accelerate nearby matter, either stars or gas. The advantage of using stellar dynamics is that stars respond only to gravitational forces. The corresponding disadvantage is that high angular resolution is necessary; measurement of stellar motions at large distances from the nucleus makes the mass determinations more uncertain. Gas motions, on the other hand, allow us to probe closer to the nucleus; indeed, in the case of reverberation mapping, angular resolution is irrelevant since time resolution substitutes for it. The disadvantage of using gas motions is, of course, that gas also responds to forces other than gravity, with radiation pressure being the main concern (see §5).

It is important to distinguish between *direct* and *indirect* methods of mass measurement. *Direct methods* are based on dynamics of gas or stars accelerated by the central black hole. This would include stellar dynamics, gas dynamics, and reverberation mapping. *Indirect methods*, on the other hand, are based on observables correlated with the mass of the central black hole. Indirect methods include the $M_{\rm BH}$–σ_* and $M_{\rm BH}$–$L_{\rm bulge}$ relationships, the fundamental plane, as well as AGN scaling relationships such as the BLR radius-luminosity relationship that we will discuss later.

We also sometimes refer to "primary," "secondary," and "tertiary" methods, with the difference based on model-dependence and assumptions required. Primary methods require fewer assumptions and have little model dependence: the masses of the black holes in the Milky Way and NGC 4258, based on proper motions and radial velocities, are thus certainly primary. Stellar dynamics and gas dynamics are sometimes also regarded as primary methods as they do not hinge on other results. On the other hand, reverberation mapping, as it has been practiced to date, currently depends on other "primary direct" methods for a zero point for the mass scale, so it is technically a "secondary method," though it is a still a "direct method."

Figure 1 illustrates in flowchart format how masses are determined for both quiescent and active galaxies. It is slightly oversimplified in that stellar and gas dynamics

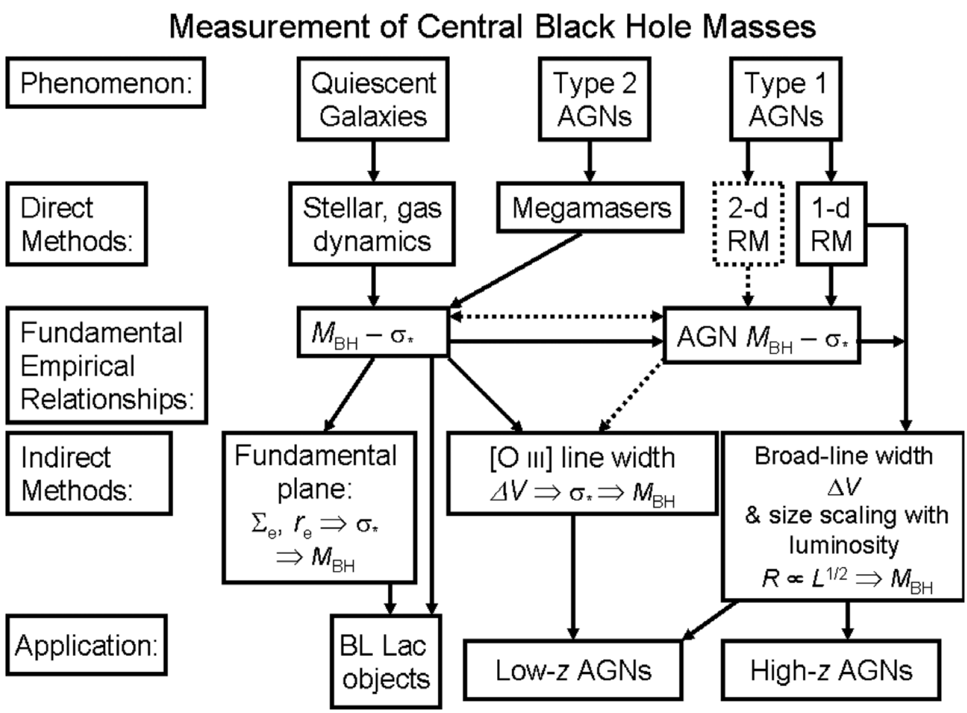

Figure 1. Methods and applications of black hole mass measurements in galactic nuclei.

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Table 1. Comparison of Black Hole Mass Measurements

Method	**NGC 4258**	**NGC 3227** (Units $10^6\ M_\odot$)	**NGC 4151**
Direct methods:			
Megamasers	38.2 ± 0.1[1]	N/A	N/A
Stellar dynamics	33 ± 2[2]	7–20[3]	$\leqslant 70$[4]
Gas dynamics	25–260[5]	20^{+10}_{-4} [6]	$30^{+7.5}_{-22}$ [6]
Reverberation	N/A	$7.63^{+1.62}_{-1.72}$ [7]	46 ± 5[8]
Indirect methods:			
$M_{\rm BH}$–σ_*[9]	13	25	6.1
R–L scaling[10]	N/A	15	29–120

[1]Herrnstein *et al.* (2005). [2]Siopis *et al.* (2009). [3]Davies *et al.* (2006). [4]Onken *et al.* (2007). [5]Pastorini *et al.* (2007). [6]Hicks & Malkan (2008). [7]Denney *et al.* (2010). [8]Bentz *et al.* (2006b). [9]Gültekin *et al.* (2008). [10]McGill *et al.* (2008).

have been used to measure central masses of a very limited number of AGNs, as discussed below. One-dimensional (1-d) reverberation-mapping refers to measurement of mean emission-line response times, i.e., reverberation mapping as it has been practiced to date. As noted above, this requires some external calibration of the mass scale and this is currently provided by assuming that the $M_{\rm BH}$–σ_* relationship is the same in quiescent and active galaxies. With two-dimensional (2-d) reverberation mapping, we aim to produce a velocity–delay map which should give us sufficient information to model the BLR dynamics and determine the central masses; model-dependence will still be something of an issue, as it is with stellar and gas dynamics. But this will eventually put reverberation mapping on a par with stellar and gas dynamics as a "primary direct" method and it will be possible to compare directly the $M_{\rm BH}$–σ_* relationships in quiescent and active galaxies rather than assume that they are the same. This may occur in the very near future: the first reliable detections of velocity-dependent lags were reported at this conference (see the papers by Bentz and Denney, these proceedings).

In Table 1, we list published masses of a few relatively nearby AGNs for which black hole measurements have been made using more than one method. The most accurate measurement is provided by megamaser motions in NGC 4258. However, megamaser sources like this are exceedingly rare. Moreover, megamasers occur in type 2 AGNs where our view of the central engine is obscured, thus making reverberation mapping impossible. Mass measurements by stellar dynamics and/or gas dynamics have been made for a handful of nearby AGNs (e.g., Hicks *et al.*, these proceedings), but in both cases, significant future progress depends on dramatic improvements in angular resolution. Thus, if only by default, reverberation mapping is the near-term future for AGN black hole mass measurement. The downside to this is that reverberation mapping is a resource-intensive technique based on high-precision spectrophotometry. However, as we see below, reverberation results already provide us with a shortcut to mass estimation.

2. Reverberation-Based Mass Measurements

Reverberation mapping (Blandford & McKee 1982; Peterson 1993) makes use of the time-delayed response of the broad emission lines to continuum variations to provide a size estimate for the broad-line region (see Peterson 2001 for a fairly thorough tutorial). At the present time, emission-line time delays, or lags τ, have been measured for ~ 45 AGNs, in nearly all cases for Hβ, but in many cases for the other Balmer lines and in a few cases for multiple lines extending into the ultraviolet. We can then obtain the mass of the black hole (or, more accurately, the mass enclosed out to the distance $R = c\tau$) by combining this with the emission-line width ΔV, i.e.,

$$M_{\rm BH} = \frac{f\left(\Delta V^2 R\right)}{G}, \tag{2.1}$$

where f is a dimensionless factor of order unity that depends on the structure, dynamics, and orientation of the BLR. If, for example, the BLR is a thin ring of material in a Keplerian orbit of inclination i around the black hole, then $f \propto 1/\sin^2 i$. Of course, the real geometry of the BLR must be much more complex than a simple ring or disk; unified models suggest that we see type 1 AGNs at inclinations $0^{\rm o} \lesssim i \lesssim 45^{\rm o}$, in which case the observed line-of-sight velocities in a ring or disk are a small projection of the orbital speed. Indeed, for $i \lesssim 20^{\rm o}$, the projected line-of-sight velocity width of the line is so small that we would underestimate the mass of the black hole by more than an order of magnitude. We note in passing that emission-line lags are unaffected by inclination as long as the system has axial symmetry and the line emission is isotropic. Nevertheless, there is evidence, mostly from radio-loud systems, that inclination is an important element in the determination of f. For example, the ratio of core-to-lobe power in double radio sources correlates inversely with line width (Wills & Browne 1986); core-dominated systems, where we are looking down the system axis, have narrower lines than systems at larger inclination. Similarly, flat-spectrum radio sources, in which again we are observing close to the axis of the system, have narrower emission lines than steep spectrum sources, which are seen at higher inclination (Jarvis & McLure 2006). But the differences are not extraordinarily large: for example, Jarvis & McLure find that for their sample of radio-loud AGNs, sources with $\alpha > 0.5$ have a mean FWHM of $6464\,{\rm km\,s^{-1}}$ for Hβ and Mg II, while those with $\alpha < 0.5$ have a mean width of $4990\,{\rm km\,s^{-1}}$. These results clearly indicate that (1) inclination is important, but (2) the BLR gas has considerable velocity dispersion in the polar direction. Given this, we now have to recognize that a direct comparison between reverberation-based masses and, say, stellar or gas dynamics, will depend very much on the generally unknown inclination of the BLR. We should generally not expect good agreement between reverberation masses and masses measured by other techniques for individual galaxies unless the inclination is known or strongly constrained.

On the other hand, given a sample of AGNs, we can determine an *average* value $\langle f \rangle$ by normalizing the AGN $M_{\rm BH}$–σ_* relationship to that of quiescent galaxies. A first attempt to do this yielded a value $\langle f \rangle = 5.5 \pm 1.8$ (Onken *et al.* 2004): while this intuitively seems a little high, we can again plausibly attribute this to inclination effects and our predisposition the inclinations of type 1 AGNs are typically rather small. The main liability of this particular calibration of the mass scale is that it is based on low-redshift, low-luminosity objects. All of the σ_* measurements are based on the Ca II triplet which is unfortunately redshifted into atmospheric water vapor bands at $z > 0.06$. We are now attempting to measure σ_* at higher redshift by using observations of the CO bandhead in the *H*-band ($1.6\,\mu$m), a process greatly aided by use of adaptive optics with integral field units that concentrate the bright AGN into the central few pixels and at the same time integrate a few arcseconds in each coordinate without loss of spectral resolution (see the papers by Dasyra and Grier in these proceedings). In addition to new results at higher redshifts and luminosities, the LAMP collaboration (Bentz, these proceedings) is adding additional masses and velocity dispersions at the low-mass end of the AGN distribution. As a consequence of expanding the range in black hole mass, the slope of the

AGN $M_{\rm BH}$–σ_* relationship is becoming better defined and shows improved consistency with that for quiescent galaxies (Woo, these proceedings).

If we assume that the AGN $M_{\rm BH}$–σ_* relationship has the same zero point and slope as that for quiescent galaxies, a maximum likelihood analysis places an upper limit on the intrinsic scatter in the relationship of $\Delta \log M_{\rm BH} \approx 0.40$ dex, which is consistent with what is found for quiescent galaxies (Gültekin, these proceedings). This is a reassuring indication that the masses derived from reverberation mapping are reliable. There are, of course, other such indications, including the direct comparisons of a few cases as in Table 1. Also, in each case in which lags have been measured for multiple emission lines in a single source, there is an anticorrelation between lag and line width that is consistent with a constant virial product $\Delta V^2 R$ (Peterson & Wandel 1999). Finally, AGNs show the same correlation between black hole mass and bulge luminosity (the $M_{\rm BH}$–$L_{\rm bulge}$ relationship) that is seen in quiescent galaxies (Bentz *et al.* 2009b). Indeed, a maximum likelihood analysis gives an upper limit to intrinsic scatter, $\Delta \log M_{\rm BH} \approx 0.17$ dex, which is actually smaller than the intrinsic scatter in this relationship for quiescent galaxies ($\Delta \log M_{\rm BH} \approx 0.38$ dex; Gültekin *et al.* 2008).

3. BLR Scaling with Luminosity: The *R*–*L* Relationship

The emission-line spectrum from an ionized gas, setting aside elemental abundances, is largely controlled by the particle density n and an ionization parameter

$$U = \frac{Q({\rm H})}{4\pi R^2 nc}, \tag{3.1}$$

where Q(H) is the number of hydrogen-ionizing photons emitted per second by the central object. To some low order of approximation (principally ignoring the Baldwin Effect), all AGN spectra have similar emission-line flux ratios and similar emission-line equivalent widths, suggesting that U and n do not vary much from one source to another. If we further assume that $Q({\rm H}) \propto L$ where L is the luminosity of the central source in some arbitrary band, we are led to the naïve prediction that $R \propto L^{1/2}$.

Thus since the early days of photoionization equilibrium calculations, some such relationship between the BLR radius and the continuum luminosity (hereafter simply the R–L relationship) of the power-law form $R \propto L^{\alpha}$ had been anticipated. Observationally the R–L relationship for Hβ first emerged as statistically significant with a slope $\alpha \approx 0.7$ with the addition of 17 PG QSOs by Kaspi *et al.* (2000) to the existing similar-sized reverberation-mapping database on Seyfert 1 galaxies. It is sometimes stated that this result was enabled by extension of the luminosity range by nearly two orders of magnitude; it is more correct to say, however, that it was due to the fact that the QSOs are so much more luminous than their host galaxies that starlight contributes negligibly to the luminosity measurement. Indeed, it is surprising how much starlight contaminates AGN luminosity measurements in the optical, though this problem is certainly exacerbated in reverberation monitoring data as large spectrograph apertures and spectral extraction windows are used to mitigate the effects of variable seeing on the total flux measurements. Bentz *et al.* (2006a, 2009a) have attempted to account for starlight contamination of optical luminosities of AGNs by using unsaturated high-resolution optical images obtained with *HST*/ACS. The surface brightness distribution is modeled so that the AGN point source can be removed and the galaxy contamination estimated by simulated aperture photometry. When this is done, the slope of the R–L relationship for Hβ is found to be $\alpha \approx 0.5$, remarkably consistent with the naïve prediction.

This leads us to the remarkable realization that it is possible to estimate masses of the black holes in AGNs from only a single spectrum: by measuring the luminosity, we infer the BLR radius and we can combine this with the emission-line width to measure the mass (Wandel, Peterson, & Malkan 1999). This is variously referred to as the "photoionization method," "single-epoch spectrum method," or simply "masses from scaling relationships."

An interesting question at this point is how much intrinsic scatter is in the R–L relationship? This is of keen interest for two reasons: first, this will set a fundamental limit on the accuracy with which we can estimate masses from single spectrum, and second, it dictates future observing strategies for further refinement of the R–L relationship. If the intrinsic scatter is large, then many more reverberation measurements will be needed to beat down the statistical noise in the relationship. On the other hand, if the scatter is small, then improvements in the determination of the R–L relationship will come from obtaining *better* reverberation data on a smaller number of objects.

To proceed with this, we want to start by using only the very best data sets, since these are ones where intrinsic scatter is most easily isolated: there remain elements of both art and luck in reverberation studies, and the ugly truth is that not all of the light curves give as clean a result as we would like. To minimize the impact of the lower-quality data, Catherine Grier and I independently visually inspected all available light curves (for the optical continuum and Hβ emission line only) with the intent of identifying the "best" reverberation data: we used a very simple criterion, that you could easily see the same pattern of variability in the continuum and Hβ light curves and could estimate the lag simply by inspection (see Figure 2). About half of the existing light curves met this criterion. A maximum likelihood analysis of these data indicates that the intrinsic scatter amounts to $\Delta \log R \approx 0.11$ dex. This is really quite remarkable when one considers that the typical formal errors on this subset of the best reverberation data amount to $\Delta \log R \approx 0.09$ dex. From this, we conclude that, at least over the luminosity and redshift

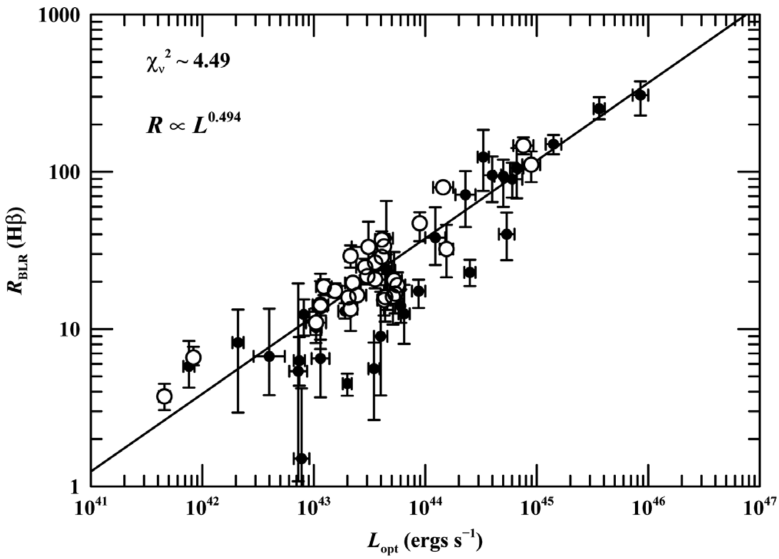

Figure 2. The R–L relationship for Hβ. The luminosity is $\lambda L_\lambda\,(5100\,\text{Å})$ and the BLR radius is measured in light days. The open circles indicate the highest-quality measurements. The slope of the fit to the highest-quality data is indistinguishable from that to all the data, but the scatter is only 0.11 dex.

range where it has been calibrated ($41.5 \lesssim \log \lambda L_\lambda(\mathrm{erg\ s}^{-1}) \lesssim 45$ at $\lambda = 5100$ Å and $z \approx 0$), the R–L relationship is as *statistically* effective as reverberation for obtaining BLR sizes and central black hole masses. If you are wondering why we emphasize the "statistical" aspect of R–L scaling, we refer you to the results of the "indirect methods" in Table 1: the results for individual sources can be quite misleading, as they certainly are in the case of NGC 4151, which is a notorious outlier in the M_{BH}–σ_* relationship.

4. The *R*–*L* Relationship at High Redshift and Indirect Mass Measurements

4.1. *The R–L Relationship for UV Lines*

With the R–L relationship, we are able to explore the black hole mass function, not only locally but at high redshift, enabling us to trace the history of black hole growth. Some exploratory work has been done on this and in fact there are claims that the M_{BH}–σ_* and M_{BH}–L_{bulge} relationships evolve over time (e.g., Woo, these proceedings), although at least some published claims of evolution of the M_{BH}–σ_* relationship are clearly attributable to Malmquist bias. A lot of additional careful work will be required to sort this out.

An obvious problem with estimating black hole masses at high redshift, of course, is that the Hβ emission line is redshifted out of the visible window at only modest redshift. We are thus forced to use other emission lines for which reverberation measurements are actually quite scarce: of the other potential broad lines for mass measurement, there is but a single reliable measurement of a Mg II lag (Metzroth, Onken, & Peterson 2006) and a bare handful of C IV lags, though these span quite a large range in luminosity, $39.5 \lesssim \log \lambda L_\lambda(\mathrm{erg\ s}^{-1}) \lesssim 47$ at $\lambda = 1350$ Å in the rest frame (Kaspi *et al.* 2007 and references therein). One of these objects is at $z = 2.17$, and the rest are at $z < 0.06$.

The C IV λ1549 emission line is especially important as it allows us to reach quite large redshifts in the optical. Vestergaard (2002) first used C IV to show that quasars with black hole masses of $\sim 10^9\ M_\odot$ were already assembled by $z \sim 4$. She assumed that the C IV R–L relationship has the same slope as Hβ and calibrated the C IV-based mass scale by using single-epoch spectra of reverberation-mapped AGNs.

4.2. *Characterizing the Velocity Field*

If there is an "Achilles' heel" in determining masses based on individual spectra, it is probably *not* the R–L relationship, but rather how we characterize the velocity field of the BLR. The line profile is expected to be sensitive to both inclination and Eddington rate (e.g., Collin *et al.* 2006).

In reverberation mapping experiments, we obtain the best results by measuring the line width in the "rms spectrum" formed by computing the pixel-by-pixel variance in all of the spectra obtained in the reverberation experiment. This isolates the variable part of the emission line, which arises in the very gas for which we are measuring the time delay. There are two common ways to characterize the line width, either FWHM or the line dispersion σ_ℓ, which is the second moment of the line. The latter seems to give somewhat better results (Collin *et al.* 2006; Peterson *et al.* 2004). For either line-width measure, the modest scatter, e.g., in the M_{BH}–L_{bulge} relationship, suggests that the mass measurements are not particularly sensitive to how we characterize the line width and thus the velocity field of the BLR.

The situation is rather different with single-epoch spectra where contamination by other features becomes a serious issue. Denney *et al.* (2009) have explored this in some

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detail for Hβ by seeing how well single spectra from reverberation campaigns reproduce the actual reverberation-based masses. They find some obvious effects (e.g., sensitivity of FWHM to proper removal of the narrow-line component) and some more subtle effects (e.g., σ_ℓ is badly affected by blending, particularly when the AGN continuum is in a faint state and the lines are especially broad).

Arguments about whether particular UV lines can be used to estimate masses are really about how well the widths of different lines in AGN spectra are correlated. In the case of Mg II λ2798, the width of the Mg II line appears to be a good surrogate for the width of Hβ (Woo, these proceedings). Shen *et al.* (2008), using a large collection of SDSS spectra, find that $\log([\mathrm{FWHM(H}\beta)] / [\mathrm{FWHM(Mg\,II)}]) = 0.0062$, with scatter of only ~ 0.11 dex. Onken & Kollmeier (2008) find that the masses derived from Hβ and Mg II differ as a function of Eddington ratio, although they argue that it is possible to correct for this bias.

The accuracy that can be obtained using the C IV line remains somewhat controversial (see the contributions to these proceedings by Vestergaard, Netzer, and Trakhtenbrot). On the positive side, the limited existing reverberation data for C IV suggest that the R–L relationship for C IV has the same slope as Hβ (Kaspi *et al.* 2007). Moreover, reverberation-based masses based on C IV are consistent with those based on every other line (i.e., the virial product $\Delta V^2 R/G$ is consistent for all the lines). On the other hand, since C IV is a resonance line, we often see absorption in its blue wing due to outflows, complicating accurate measurement of the line width. Indeed, we sometimes see, particularly in the case of narrow-line Seyfert 1s (NLS1s), an extended blue wing of the emission line, again presumably due to outflowing gas, which makes measuring the line width problematic. It seems likely, however, that we should be able to calibrate out luminosity-dependent effects and simply avoid spectra with strong absorption features such as BALs.

4.3. *Use of Scaling Relationships*

The scaling relationships that lead to black-hole mass estimates must not be used blindly; indeed they should be used with great caution. We need to keep in mind that when we think we are measuring mass, we are really measuring

$$M_{\mathrm{BH}} \propto \Delta V^2 R \propto \Delta V^2 L^{1/2}. \tag{4.1}$$

Similarly, when we think we are measuring Eddington ratio, we are really measuring

$$\frac{L}{L_{\mathrm{Edd}}} \propto \frac{L}{M_{\mathrm{BH}}} \propto \frac{L}{\Delta V^2 L^{1/2}} \propto \frac{L^{1/2}}{\Delta V^2}. \tag{4.2}$$

It is important to keep in mind that *any* correlations among mass, Eddington ratio, and luminosity must be eyed with great suspicion.

5. On the Possible Importance of Radiation Pressure

Given a nominal bolometric correction, most AGNs are thought to be radiating at about $0.1 L_{\mathrm{Edd}}$ where L_{Edd} is the Eddington luminosity, the maximum luminosity at which the source is stable against disruption by radiation pressure. In the case of objects like NLS1s, the luminosities may approach L_{Edd}. It stands to reason that radiation pressure on the BLR gas might be an important dynamical force. In an elegant paper, Marconi *et al.* (2008) argue that radiation pressure could be an important factor in the BLR dynamics. Radiation pressure, like gravity, is diluted geometrically (i.e., $\propto R^{-2}$), making it hard to distinguish between a high central mass plus radiation pressure and

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a lower central mass and no radiation pressure: failure to account for radiation pressure could thus lead us to underestimate the mass of the black hole. Marconi *et al.* argue that the relative importance of radiation pressure ultimately comes down to the inertia of the BLR gas clouds: if the clouds have sufficiently high column density ($N_{\rm H} > 10^{23}\,{\rm cm}^{-2}$), then the effect of radiation pressure on the gas dynamics is negligible. Interestingly, the most successful photoionization equilibrium calculations suggest column densities of this order. Marconi *et al.* then modify equation (2.1) to a form like

$$M_{\rm BH} = f \Delta V^2 R/G + gL, \tag{5.1}$$

where the first term on the right hand side is the mass based on the R–L scaling relationship and the second term accounts for radiation pressure. Marconi *et al.* claim two successes with this formulation: first, the scatter between single-epoch mass estimates and reverberation measurements is reduced and the difference is no longer luminosity-dependent (their Figure 1), and second, NLS1s no longer fall below the normal $M_{\rm BH}$–σ_* relationship. It is not clear, however, that anything physical can be inferred from this. The additional luminosity dependence of equation (5.1) can be attributed to the fact that the reverberation-based sample of AGNs is strongly Malmquist biased: the reverberation-mapped AGNs were selected because they are among the apparently brightest known AGNs, and there is a clear correlation between their black hole masses and luminosities. Thus the second term in equation (5.1) is bound to reduce scatter, regardless of whether or not radiation pressure is actually physically important. Moreover, the argument about NLS1s appears to be circular: if accounting for radiation pressure increases their black hole masses enough to place them on the $M_{\rm BH}$–σ_* relationship, then their Eddington rates correspondingly drop down to those comparable to other AGNs, which then begs the question of the origin of the unusual properties of NLS1s. Also, Netzer (2009) drew large samples of Type 1 and Type 2 AGNs from SDSS and showed that while their [O III] luminosity distributions and conventionally computed black hole masses have similar distributions, the radiation-pressure corrected mass distributions were markedly different, arguing against the importance of the radiation pressure term in equation (5.1). Marconi *et al.* (2009) countered that Netzer's result is an evitable consequence of assuming a fixed column density for the BLR clouds; unfortunately, this argument exposes the fact that there is currently no accurate formulation for estimating black hole masses in the presence of radiation pressure.

At the present time, whether or not radiation pressure needs to be accounted for in our mass calculations is not clear, though many of us continue to work on this issue. We believe that NLS1s probably provide the best testing ground, and one obvious step is to further investigate the $M_{\rm BH}$–σ_* relationship in these sources. Much of the previous work on NLS1s has necessitated using the [O III] narrow line widths as a surrogate for stellar velocity dispersions, and this is one area where we can make an improvement fairly easily by measuring stellar velocity dispersions in the near IR.

6. Conclusions

While great progress has been made in measuring the masses of the central black holes in both active and quiescent galactic nuclei, there are still significant uncertainties. My own guess is that masses measured by all direct methods are probably uncertain by a factor of a few, though this could be an underestimate for reverberation-based masses if, for example, radiation pressure turns out to be important. Aside from this possibility, the most significant unknown in reverberation-based masses is the inclination of the system. This, of course, is merely one aspect of a rather larger issue: it is also not clear that we have identified an unbiased way to characterize the emission-line widths that enter into the mass determination. The size of the BLR, at least as measured with Hβ, seems to be remarkably well-characterized (though we could be fooling ourselves there, too) with uncertainties as small as $\Delta \log R \approx 0.1\,\mathrm{dex}$.

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