Mem. S.A.It. Vol. 77, 581

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Black hole masses based on reverberation mapping of the Broad-Line Region

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Abstract. In this contribution, we outline the fundamental assumptions and uncertainties in determining AGN black hole masses from reverberation-mapping measurements. We attempt to explain individual sources of error and uncertainty and quantify these and identify some systematic errors and their mitigation. We describe recent developments, including improvements to radius–luminosity relationships and results from new reverberation campaigns.

1. Introduction

Reverberation mapping (Blandford & McKee 1982; Peterson 1993) utilizes the intrinsic flux variability of the UV/optical continuum source in AGNs, presumably an accretion disk surrounding a supermassive black hole, and the light travel-time delayed response of the broad emission lines to the continuum flux changes to determine the structure and kinematics of the broad-line region (BLR). It is a potentially powerful technique that can in principle allow us to discern AGN structure on scales that project only to tens of microarcseconds even in the nearest AGNs. On the other hand, it is an observationally demanding process, requiring typically many tens of individual high signal-to-noise ratio spectra that are accurately flux-calibrated, well-spaced in time, and cover a long time span (Horne et al. 2004). There are, in fact, no existing reverberation-mapping datasets that meet all of the criteria for accurate recovery of an emission-line velocity–delay map (i.e., the BLR structure and kinematics projected into the observable coordinates of line-of-sight velocity and time delay), although it has been possible to obtain mean emission-line response times, or "lags," for about three dozen AGNs (Peterson et al. 2004, 2005), in some cases for multiple emission lines in the same source and in some cases for the same emission line at more than one epoch.

While the original motivation for reverberation mapping was to learn about the structure of the BLR and its role in the accretion process (which might include outflow), it has been found that it is possible to estimate the mass of the central source from reverberation data. That the BLR dynamics are dominated by gravity is shown by the anticorrelation between emission-line lag τ and line width ΔV, of the form $\tau \propto \Delta V^{-2}$ (Peterson & Wandel 1999, 2000; Onken & Peterson 2002; Kollatschny 2003). The mass of the central black hole is then given by

$$M_{\rm BH} = f \frac{c\tau \Delta V^2}{G}, \tag{1}$$

Send offprint requests to: B.M. Peterson where f is a factor of order unity that depends on the unknown structure, kinematics, and inclination of the BLR. The evidence that the masses so derived are reasonable is the fact that AGNs show the same relationship between black-hole mass and host-galaxy bulge velocity dispersion σ_* (Gebhardt et al. 2000b; Ferrarese et al. 2001; Onken et al. 2004; Nelson et al. 2004) that is seen in quiescent galaxies, i.e., the well-known M_{BH}–σ_* relationship (Ferrarese & Merritt 2000; Gebhardt et al. 2000a; Tremaine et al. 2002). Indeed, Onken et al. (2004) use the M_{BH}–σ_* relationship as a means to determine a statistical value for the factor f, based on the assumption that the zero-point of the M_{BH}–σ_* relationship is identical for active and quiescent galaxies.

Unfortunately, there are many misconceptions about reverberation-based black hole mass measurements, and here we will try to address some of these issues. We will describe some recent results and explain their broader implications.

2. Reverberation Masses and Their Uncertainties

The first thing that must be understood about reverberation-based mass measurements is that they are *primary* mass measurements, not simply measurements of quantities that are correlated with mass (e.g., breaks in the power density spectra of X-ray variations). We are actually measuring the motions of gas in the black hole potential well; the motions are clearly virial, though we cannot at this stage tell yet how they are organized. The second thing is that while these are *real* measurements, they are not *high-precision* measurements, because of lack of knowledge of the detailed structure and dynamics of the BLR, which we subsume in the scaling constant f. We moreover rely on simple measurements of the mean response time τ, which we take as characterizing the size of the BLR $R = c\tau$, and of the line width ΔV, which we take to be a measure of the line-of-sight velocity dispersion of the BLR. The *observable* quantity that we use is virial product

$$\mathrm{VP} = \frac{c\tau\Delta V^2}{G}, \tag{2}$$

which has units of mass and differs from the actual black hole mass only by the dimensionless factor f.

We thus distinguish three specific types of uncertainties associated with the reverberation-based black hole masses:

- **Uncertainty in measurement of the virial product.** This is the random component of error that affects the *precision* (i.e., repeatability of the measurement) with which VP is determined. Typically, the relative uncertainty in VP is about 30%, although it can vary widely (Peterson et al. 2004). This is usually the uncertainty quoted in mass measurements.
- **Uncertainty in the mass-calibration scale.** This is a systematic uncertainty that bears on the *accuracy* (i.e., difference between the measurement and the true value) to which we can measure black hole masses. This uncertainty is essentially how well can we determine the scaling factor f, which is provides the zero-point for the reverberation mass calibration. For any given AGN, f remains unknown, but for the ensemble of AGNs for which both reverberation-based masses and measurements of σ_* are available[1], a statistical value can be obtained through the M_{BH}–σ_* relationship, as noted above. Onken et al. (2004) find that $\langle f \rangle = 5.5 \pm 1.8$, i.e., the zero-point calibration for the mass scale is uncertain at the 35% level. It is important to emphasize that use of this scaling factor to estimate masses through eq. (1) merely removes *bias* from the mass estimates: as many masses are overestimated as underestimated, within the context of the assumption of a universal M_{BH}–σ_* relationship.
- **Uncertainties in individual mass determinations.** Again, assuming that a universal M_{BH}–σ_* relationship holds for both quiescent and active galaxies, we can look at the statistical variation or scatter around the M_{BH}–σ_* relationship to estimate the accuracy of the reverberation-based mass

[1] Both quantities are currently available for fewer than half the reverberation-mapped sample.

measurements. We find that the scatter is about 0.5 dex, or about a factor of 3.

3. Measuring the Virial Product

The two components of the virial product VP are the emission-line lag and line width. Generally, the lag is taken to be the centroid of the cross-correlation function computed from the continuum and emission-line light curves. While the merits of various measures are still discussed (Peterson et al. 2004), this choice is not highly controversial.

How the line width should be characterized, however, is not yet well established. There are two obvious candidates in use, the commonly used full-width at half maximum (FWHM) or the less-familiar second moment of the line profile, which is sometimes called the line dispersion

$$\sigma_{\rm line} = \left[\int (\lambda - \lambda_0)^2 \, P(\lambda)\, d\lambda / \int P(\lambda)\, d\lambda \right]^{1/2} \quad (3)$$

where $P(\lambda)$ is the emission-line profile, which is centered at wavelength λ_0.

Peterson et al. (2004) emphasize three points:

1. The line dispersion $\sigma_{\rm line}$ can generally be measured to higher precision than FWHM, by about 30%.
2. Use of $\sigma_{\rm line}$ as the line-width measure yields a more consistent virial relationship ($\tau \propto \Delta V^{-2}$) than FWHM.
3. The line width should be measured in the *variable part* of the spectrum.

Isolating the variable part of the spectrum is not difficult. All of the spectra obtained in a reverberation-mapping experiment can be combined into mean and root-mean-square (rms) spectra. The rms spectrum is the variable part of the spectrum. Constant components, like the narrow components of the emission lines which arise over a much larger region than the BLR, vanish in the rms spectrum, which is therefore why Peterson et al. (2004) use it for measurement of the line widths. However, it is also clear that the mean spectrum, or even a single spectrum, can be used provided that contaminating features, such as the narrow-line components, are first removed (Vestergaard & Peterson 2006) and the fact the line widths are typically somewhat larger in the mean spectrum is taken into account (Collin et al. 2006).

4. Calibration of Reverberation Masses

In either the mean or rms spectra, the line-width ratio FWHM/$\sigma_{\rm line}$ varies greatly among AGNs, and indeed can vary significantly in a single line in a particular AGN over time (Peterson et al. 2004). Obviously then, the mass given by eq. (1) will depend quite keenly on which line-width measure is used; it is equally obvious that the masses obtained using the two line-width measures do not simply differ by some constant factor. So how can we decide whether we should be using FWHM or $\sigma_{\rm line}$ to compute the mass?

Collin et al. (2006) address this question by again using the $M_{\rm BH}$–σ_* relationship. They divide the sample of AGNs for which both black hole mass and bulge velocity dispersion measurements are available into two populations, based on FWHM/$\sigma_{\rm line}$. They find that if $\sigma_{\rm line}$ is used as the line-width measure, the two populations require the same value of the scaling factor f to normalize the AGN $M_{\rm BH}$–σ_* relationship to that for quiescent galaxies. On the other hand, if FWHM is used, they find that the scaling factor is different for the two populations: for the population with low values of FWHM/$\sigma_{\rm line}$, f must be 2–3 times larger than for the population with large values of FWHM/$\sigma_{\rm line}$. Use of FWHM and a single scaling factor will tend to underestimate the masses of objects like narrow-line Seyfert 1 galaxies, which have low values of FWHM/$\sigma_{\rm line}$. Thus, FWHM *is a biased indicator* of the mass, while $\sigma_{\rm line}$ appears to be unbiased. However, Collin et al. (2006) give an empirical correction than can be used with FWHM estimates to compensate for the bias.

5. The BLR Radius–Luminosity Relationship

By the end of the last decade, BLR radii had been measured for 17 AGNs (Wandel, Peterson, & Malkan 1999). But it was the extension of the luminosity range provided by the inclusion of PG quasars (Kaspi et al. 2000) that led to the first convincing characterization of the long-anticipated (Koratkar & Gaskell 1991; Peterson 1993) BLR radius–luminosity (*R*–*L*) relationship. Since then, the reverberation-mapping database has been completely reanalyzed by Peterson et al. (2004), which led to an improved version of the *R*–*L* relationship (Kaspi et al. 2005). Beyond what it tells us about the physics of the BLR, the *R*–*L* relationship is of tremendous importance because it allows us to estimate the radius of the BLR from the AGN luminosity, thus bypassing the difficult and resource-intensive process of reverberation mapping. Thus a single AGN spectrum yields all the ingredients needed to estimate the mass through eq. (1) and it becomes possible to estimate masses for large numbers of AGNs, as discussed further below.

A continuing challenge in determination of the *R*–*L* relationship is accounting for the host-galaxy starlight contribution that contaminates the luminosity measurements. Accounting for the starlight is important to ensure accurate extrapolation of the *R*–*L* relationship to higher-luminosity AGNs, for which the starlight contribution is negligible. Estimating the host-galaxy contribution to the luminosities of the reverberation-mapped AGNs is difficult for a number of reasons:

1. The starlight contribution is often overwhelmed by the point-like AGN, making it hard to isolate.
2. Reverberation-mapping programs to date have generally not adopted a particular aperture geometry, thus making any general model or empirical correction impossibly unreliable.

We are currently carrying out a program to measure the host galaxy surface brightness distributions for the reverberation-mapped AGNs. Our first results (Bentz et al. 2006) are shown in Fig. 1. Ground-based observations are inadequate for this work because the variable point-spread function makes it nearly impossible to model the point-like AGN, which we need to separate reliably from the underlying galaxy. Moreover, even the nearest AGNs are sufficiently far away that most of their bulge light is lost in the glare of the nuclear source on arcsecond scales. In an attempt to overcome these problems, we have observed several of the lower-luminosity AGNs with the Advanced Camera for Surveys (ACS) on *Hubble Space Telescope* in order to make use of its high angular resolution. Care was taken to obtain unsaturated images that would allow reliable deconvolution of host-galaxy and nuclear light.

Figure 1 shows that the starlight contribution to the measured AGN luminosities is indeed significant, larger in fact than we originally anticipated. We see that removal of starlight contamination, which is most significant in the lower-luminosity objects, tends to flatten the slope of the *R*–*L* relationship, indeed making it consistent with the same relationship defined using the UV continuum luminosity (Kaspi et al. 2005). Given how large the starlight contribution has proven to be, we are continuing to obtain ACS observations of additional reverberation-mapped sources.

6. New Reverberation Programs

The need for new reverberation-mapping programs is obvious: first, it is desirable to extend the mass and luminosity range over which BLR radii and black hole masses are measured. Second, there is a clear need to obtain a velocity-delay map in order to understand the structure of the BLR. Without such information, our ability to assess the accuracy of reverberation-based masses will always be limited. And, third, it is also quite clear that many of the reverberation results, particularly those obtained in the early programs when the time sampling requirements were not fully appreciated, are not very high quality and need to be replaced.

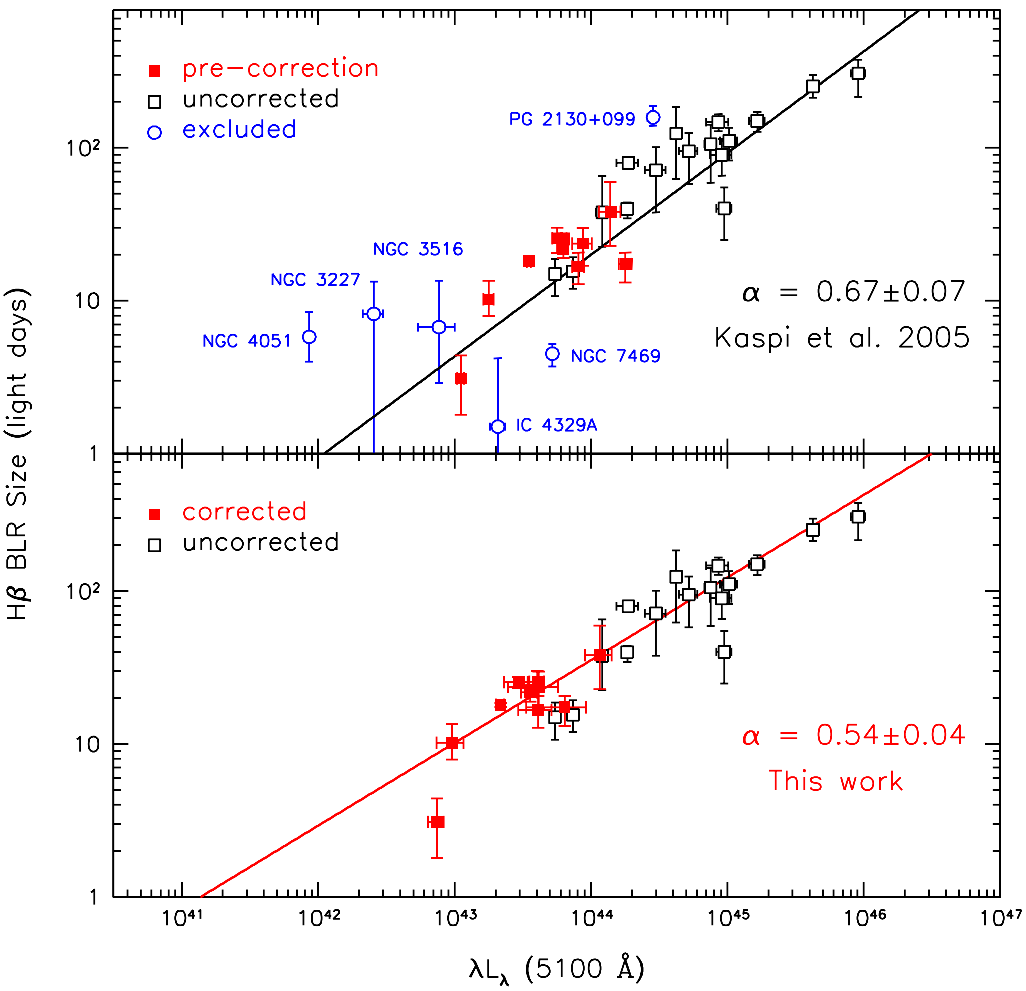

Fig. 1. The broad-line region radius–luminosity relationship for the Hβ emission line and the optical continuum. In the bottom panel, the filled symbols show the optical luminosity after correction for contamination by the host galaxy starlight. The galaxies excluded from the fit have significant, but undetermined, starlight contributions and are scheduled to be observed with *HST* this year. We also excluded PG 2130+099 because we believe that the published Hβ lag is incorrect. From Bentz et al. (2006).

6.1. Probing Low Luminosities: NGC 4395

In order to extend the luminosity range over which reverberation results have been obtained, we recently undertook a UV monitoring program on NGC 4395, the least-luminous known Seyfert galaxy (Peterson et al. 2005). Two independent time series yielded a time delay of only about one *hour* for the C IV λ1549 emission line, and a measurement of the black hole mass, $M_{\rm BH} = 3.6 \times 10^5\, M_\odot$.

Unfortunately, NGC 4395 tells us little about the $M_{\rm BH}$–σ_* relationship at low masses as NGC 4395 is an essentially bulgeless galaxy and definition of σ_* is thus somewhat problematic. The galaxy does have a central star cluster, and the upper limit to the velocity dispersion of this cluster is 30 km s^{-1} (Filippenko & Ho 2003). In Fig. 2, we show the $M_{\rm BH}$–σ_* rela-

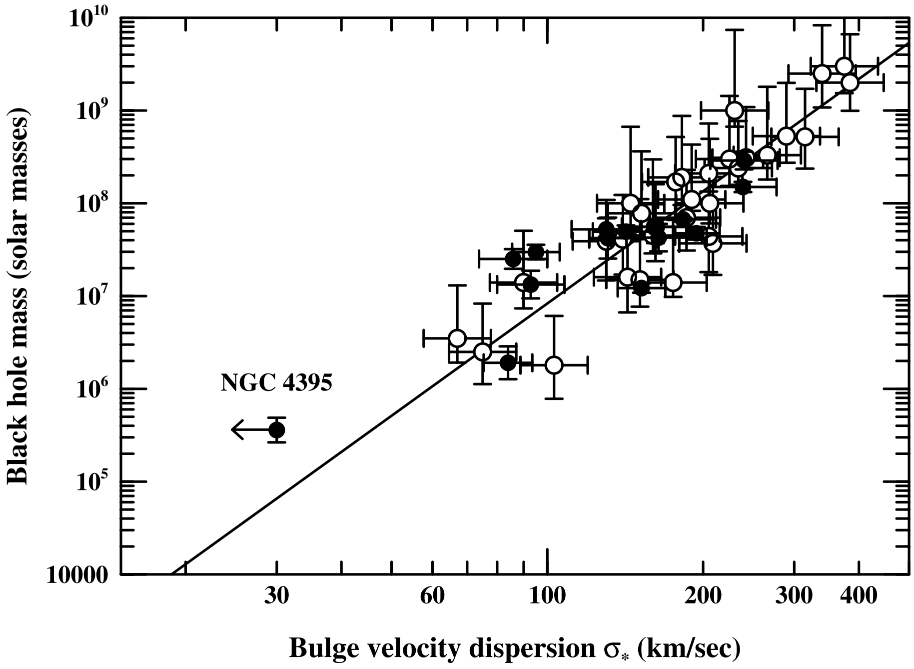

Fig. 2. The M_{BH}–σ_* relationship for quiescent and active galaxies. Filled circles represent masses determined by reverberation mapping, including NGC 4395 in the lower-left corner of the diagram; open circles are mass measurements by other techniques, as compiled by Tremaine et al. (2002). The solid line is the best fit to the non-reverberation measurements. The upper limit on the bulge velocity dispersion for NGC 4395, $\sigma_* \leq 30\,\mathrm{km\,s^{-1}}$, is from Filippenko & Ho (2003). Adapted from Peterson et al. (2005).

tionship for both quiescent and active galaxies, with the upper limit of NGC 4395 indicated.

On the other hand, NGC 4395 allows us, for the first time, to say something meaningful about the *R*–*L* relationship for a line other than the Balmer lines, specifically C IV λ1549 emission line. The few other available lag measurements for the C IV are for AGNs of nearly the same luminosity so the slope of the *R*–*L* relationship was poorly constrained. As shown in Fig. 3, the slope of the C IV *R*–*L* relationship is consistent with that of the Balmer-line *R*–*L* relationship[2].

[2] This conclusion is stated only in an erratum to the original paper, currently in press, but available as astro-ph/0506665.

6.2. Ground-Based Optical Monitoring Programs

We are currently carrying out new reverberation-mapping monitoring programs at the MDM Observatory on Kitt Peak. Most of the targets in this program are apparently bright, well-known Seyfert galaxies for which some reverberation data already exist. The primary goal of this program is to obtain, as described above, at least one reliable velocity–delay for the Hβ region of at least one AGN. While an unambiguous specification of the BLR dynamics is unlikely on the basis of a single low-ionization line, it is nevertheless a critical step that must be taken before a broader attack is warranted. Successful recovery of a velocity-

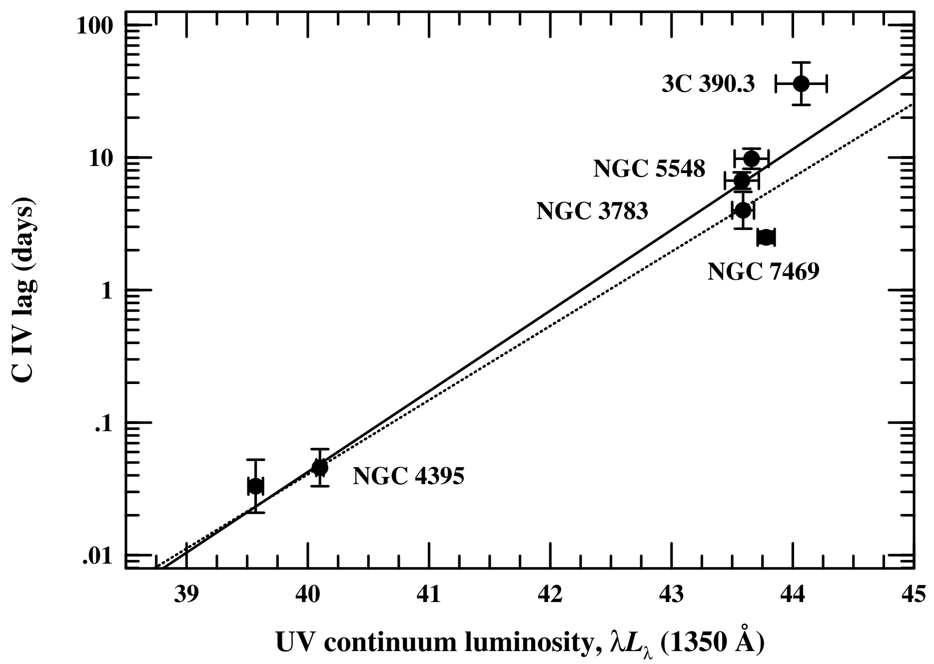

Fig. 3. The radius–luminosity relationship based on the C IV λ1549 emission line and the UV continuum. The UV continuum luminosity is in units of erg s^{-1}. The best-fit line, with slope $\alpha = 0.61 \pm 0.05$, is shown as a solid line. The dashed line is the best fit for a fixed slope $\alpha = 0.56$, which is the slope of the relationship between the size of the Hβ-emitting region and the UV luminosity (Kaspi et al. 2005). From an erratum to Peterson et al. (2005).

delay map for at least one emission line in one AGN would provide the kind of proof-of-concept that it will take to obtain the resources necessary for a more comprehensive program.

A secondary goal is to improve the precision of the reverberation measurements for these sources. Even if the monitoring data prove to be insufficient to meet the primary goal, they will certainly allow us to reach this more modest goal. These nearby bright Seyferts are of particular interest and importance because these are the sources for which stellar velocity-dispersion measurements are also available; these are the sources that define the calibration scale for reverberation-based mass measurements. We carried out a preliminary short program (42 nights) in early 2005, and it is already clear that we will have much-improved black hole masses for two important AGNs, NGC 4151 and NGC 4593 (not to be confused with NGC 4395, discussed above).

7. Estimating Masses of High-z Quasars

As noted earlier, the existence of R–L relationships for emission lines makes it possible to easily estimate masses of AGNs from single-epoch measurements (Wandel, Peterson, & Malkan 1999; Vestergaard 2002; McLure & Jarvis 2002; Vestergaard 2004; Kollmeier et al. 2006; Vestergaard & Peterson 2006); one can estimate the BLR radius from the luminosity and combine this with a line-width measurement as in eq. (1), and use the value of the scaling factor f obtained from the reverberation-mapped sources. It thus becomes possible to estimate the black hole masses for large samples of objects. Such estimates for high-z QSOs have already revealed that high-mass ($M_{\rm BH} > 10^9\,M_\odot$) black holes are already assembled by epochs corresponding to $z > 4$ (Vestergaard 2004).

A recent update on mass-scaling relationships that incorporates many of the new results described here has been prepared by Vestergaard & Peterson (2006). By using spectra of the reverberation-mapped objects from independent sources, they conclude that masses based on scaling relationships are typically accurate to about a factor of four.

8. Conclusions

Good progress has been made in using reverberation mapping techniques to measure the BLR radii and corresponding black hole masses in relatively nearby AGNs. Emission-line time-delay and black hole mass measurements are now available for about three dozen AGNs. The accuracy to which masses can be measured by reverberation seems to be about a factor of three. This is not likely to improve dramatically without full realization of the potential of the reverberation technique, which will require obtaining high-quality velocity–delay maps, probably for multiple emission lines.

Reverberation data also define *R*–*L* relationships that can be used to estimate black hole masses from single-epoch observations of the luminosity and emission-line width. Masses estimated in this way seem to be accurate to about a factor of four.

Acknowledgements. I wish to thank the organizers for their kind hospitality during this conference. The work described here has been supported by the US National Science Foundation through grant AST-0205964 and by NASA through grants HST-GO-09818, HST-GO-09851, and HST-AR-10691 from the Space Telescope Science Institute.

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