BLACK HOLE MASS ESTIMATES FROM REVERBERATION MAPPING AND FROM SPATIALLY RESOLVED KINEMATICS

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Draft version October 24, 2018

ABSTRACT

Black hole (BH) masses that have been measured by reverberation mapping in active galaxies fall significantly below the correlation between bulge luminosity and BH mass determined from spatially resolved kinematics of nearby normal galaxies. This discrepancy has created concern that one or both techniques suffer from systematic errors. We show that BH masses from reverberation mapping are consistent with the recently discovered relationship between BH mass and galaxy velocity dispersion. Therefore the bulge luminosities are the probable source of the disagreement, not problems with either method of mass measurement. This result underscores the utility of the BH mass – velocity dispersion relationship. Reverberation mapping can now be applied with increased confidence to galaxies whose active nuclei are too bright or whose distances are too large for BH searches based on spatially resolved kinematics.

Subject headings: black hole physics – galaxies: active – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: Seyfert

1. INTRODUCTION

Searches for supermassive black holes (BHs) based on spatially resolved kinematics have found ~ 35 candidates (see Kormendy et al. 2000 for a review). Almost all are in weakly active or inactive galaxies. The reason is that bright active galactic nuclei (AGNs) swamp the light from the surrounding stars and gas, and complicate the kinematic observations. In addition, AGNs are rare, so most are distant. Even with the *Hubble Space Telescope* (*HST*), the central kinematics of galaxies are well enough resolved to reveal BHs only in nearby galaxies. The ironic result (Kormendy & Richstone 1995) is that the bright Seyfert nuclei and quasars that motivate the BH search are conspicuously rare in the dynamical BH census.

Reverberation mapping (Blandford & McKee 1982; Netzer & Peterson 1997) avoids this problem. In this technique, time delays between brightness variations in the continuum and in the broad emission lines are interpreted as the light travel time between the BH and the line-emitting region farther out. This provides an estimate of the radius r of the broad-line region (BLR). We also have a velocity V from the FWHM of the emission lines. Together, these measure a mass $M_{\bullet} \approx V^2 r/G$, where G is the gravitational constant. An important advantage is that the BLR is $\sim 10^2$ times closer to the BH than the stars and gas that are used in HST spectroscopy.

However, several authors have pointed out that reverberation mapping yields smaller BH masses at a given bulge luminosity

than do dynamical models of spatially resolved kinematics (e.g., Wandel 1999; Ho 1999). That is, in the observed correlation between BH mass and bulge luminosity $L_{B,\text{bulge}}$ (Kormendy 1993; Kormendy & Richstone 1995), M_● values from reverberation mapping are systematically low (see Figure 1a which shows reverberation masses that are as much as a factor of 40 smaller than predicted by the correlation). This discrepancy is overstated when using the M_{\bullet} – $L_{B,\text{bulge}}$ correlation from Magorrian et al. (1998). Those BH masses are based on two-integral models applied to low-resolution data. Comparison with HST data and three-integral models shows that the Magorrian et al. (1998) BH masses are high by about a factor of three, mainly due to radially-biased anisotropy in the stellar orbits (Gebhardt et al. 2000c) that was not modeled in Magorrian et al. (1998) mass estimates. Nevertheless, even using the best kinematic data, Ho (1999) finds that M_{\bullet} values from reverberation mapping are still low by a factor of ~ 5 compared with masses based on spatially resolved kinematics of different galaxies but similar bulge luminosities. important to resolve this discrepancy.

Gebhardt et al. (2000b) and Ferrarese & Merritt (2000) find a new correlation between M_{\bullet} and the effective velocity dispersion σ_e of the host galaxy. This relation is significantly tighter than the $M_{\bullet} - L_{B,\text{bulge}}$ correlation, consistent with zero intrinsic scatter. In this *Letter*, we add reverberation mapping masses to the new correlation and find that the systematic offset between the two mass estimators is no longer significant.

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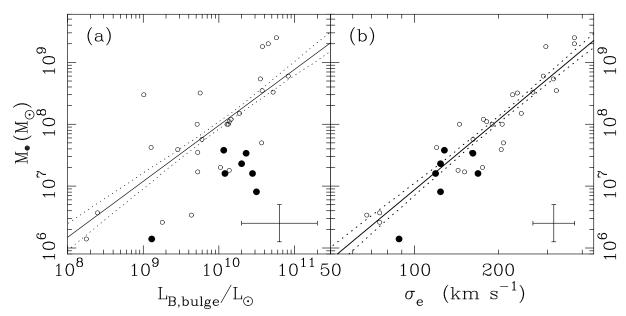


FIG. 1.— Black hole mass versus (a) bulge luminosity and (b) velocity dispersion. There are 33 points in the dispersion plot: 26 from the compilation of Gebhardt et al. (2000b) (open circles), and seven points from reverberation mapping (filled circles). Solid and dotted lines are the best-fit correlations and their 68% confidence bands from Gebhardt et al. (2000b) fitted only to the galaxies with spatially resolved kinematics. The error bars in the lower right for each plot are representative for the reverberation mapping uncertainties.

2. REVERBERATION MASSES AND VELOCITY DISPERSIONS

Ho (1999) and Wandel, Peterson, & Malkan (1999) measure M_{\bullet} values for 22 Seyfert 1 galaxies using reverberation mapping. Unfortunately, the absorption-line kinematics of these galaxies are not well studied, so we are unable to obtain velocity dispersions for the whole sample. Only seven galaxies have usable published dispersions. The three sources for these dispersions are Nelson & Whittle (1995), Di Nella et al. (1995), and Smith, Heckman, & Illingworth (1990).

For most of these galaxies, the velocity dispersions are difficult to measure. Some are late-type galaxies, so template matching is difficult because of the presence of young stars. In many cases, dilution of the stellar absorption lines by the nonstellar continuum of the AGN is a problem. Dilution does not alter the velocity dispersion of the lines, but it does make them hard to detect. Ideally, we should use spectral regions that are minimally sensitive to template mismatch and to line dilution. The calcium infrared triplet near 8500 Å is preferable to the traditional Mg b $\lambda 5170$ region (Dressler 1984). In the present paper, we adopt velocity dispersions derived from the calcium triplet region whenever possible.

The study of Terlevich, Díaz, & Terlevich (1990) contains three galaxies with reverberation masses; however, the dispersions measured for many of their other galaxies do not compare well with those from other groups. For example, their dispersions for M33, M32, and M31 are significantly different than the accepted values in their apertures: 77 km s⁻¹ compared with 21 km s⁻¹ (Kormendy & McClure 1993) for M33, 56 km s⁻¹ compared with \sim 80 km s⁻¹ (van der Marel et al. 1994) for M32, and 137 km s⁻¹ compared with 195 km s⁻¹ (van der Marel et al. 1994) for M31. Therefore we exclude their measurements from our analysis.

For their dispersion estimate, Gebhardt et al. (2000b) use the projected, luminosity-weighted value inside the half-light or effective radius of the bulge, which we call the effective dispersion and denote by σ_e . For the AGN sample, we do

not have dispersion profiles and cannot perform the same calculation. Consequently, we must use *central* dispersions. However, based on their sizes, these galaxies have bulge halflight radii of only a few arcseconds (Kotilainen, Ward, & Williger 1993; Baggett, Baggett, & Anderson 1998). These sizes are similar to the typical seeing and extraction window used (\sim 2"). Gebhardt et al. (2000b) find that central aperture dispersions measured at this resolution are similar on average to effective dispersions, with a scatter of at most 10%. Thus, the reported dispersion should be a good approximation to the effective dispersion, although a systematic study using the dispersion profile would be worthwhile. When using central dispersions, the most crucial concern is whether the black hole affects the measured dispersion. Assuming typical stellar massto-light ratios, the spheres of influence for these black holes are a few tenths of an arcsecond. They should have little effect on the dispersions.

The effective dispersion used in Gebhardt et al. (2000b) assumes edge-on configuration, and since the projected dispersion varies with orientation we must consider whether it needs correction for inclination. This effect may be more important in AGN disk galaxies, where we might expect significant rotation (a rotating galaxy will have a larger projected dispersion edge-on than face-on). Four of the seven galaxies are inclined greater than 45° and are likely to have corrections smaller than their uncertainties. The three galaxies more face-on than 45° are Mrk 590, NGC 4151, and NGC 4593. Based on systems with large bulge fractions, even these would have corrections less than 10% (Gebhardt et al. 2000b); however, better kinematic data on the bulge rotation profiles for a larger sample of AGNs is needed before we fully understand inclination corrections.

Ho (1999) compiled bulge luminosities and bulge-to-total light ratios (B/T) from three sources. Kotilainen et al. (1993) provide surface photometry and disk-bulge decompositions for 3C 120, Mrk 590, NGC 3227, NGC 4151, and NGC 4593; Granato et al. (1993) provide disk-bulge decompositions

for Mrk 590 and NGC 3516; while Baggett et al. (1998) give profiles and decompositions for NGC 3227, NGC 4051, NGC 4151, and NGC 4593. For the galaxies that overlap among the various groups, we find consistent B/T values. However, each study uses a de Vaucouleurs profile for the bulge component. If these bulges are more nearly exponential or if the AGN contributes significant light unaccounted for, then the bulge light will have been overestimated.

Table 1 lists the data we have discussed, and Figure 1 plots M_{\bullet} versus the bulge luminosity and effective dispersion σ_e . The masses from resolved kinematics and the associated least-squares fits come from Gebhardt et al. (2000b). The relation fitted only to the galaxies with spatially resolved kinematics for the $M_{\bullet} - \sigma_e$ correlation is $M_{\bullet} = 1.2(\pm 0.2) \times 10^8 M_{\odot} (\sigma_e/200 \, \mathrm{km \ s^{-1}})^{3.75(\pm 0.3)}$. The reverberation masses lie a factor of 5–10 too low in the luminosity plot (black dots), but are much more consistent with the correlation in the σ_e plot. In the σ_e relation, the reverberation mapping masses have an average offset of -0.21 (± 0.13) dex and a dispersion of 0.34 dex relative to that average. The scatter (0.30 dex in $\log M_{\bullet}$ at fixed dispersion) is the same regardless of whether or not we include the reverberation mapping masses in the fit, but the slope changes from 3.75 to 3.90 if we include them.

The average uncertainties in M_{\bullet} , L_B , and σ_e for the reverberation mapping estimates are shown in the bottom corner in Fig. 1. Unfortunately, the uncertainties in reverberation mapping are dominated by systematics that are uncertain or unknown (Wandel et al. 1999) and can be quite large. Since we have only seven reverberation mapping masses, we do not attempt a rigorous statistical analysis including the measurement uncertainties.

3. DISCUSSION

The apparent discrepancy between reverberation mapping and dynamical modeling of spatially resolved kinematics arose from a comparison of M_{\bullet} with bulge luminosities. Since the reverberation mapping masses are consistent with the $M_{\bullet} - \sigma_e$ correlation and not with the $M_{\bullet} - L_{B,\text{bulge}}$ correlation, the discrepancy in the latter is likely due to problems with the use of bulge luminosities, not with estimation of the BH masses. Velocity dispersions are more difficult to measure in AGNs, but we have little reason to suspect that they have systematic errors.

However, it is important to examine the potential complications of both techniques. Sections 3.1 and 3.2 below suggest that the BH masses from resolved stellar kinematics have only small systematic errors but that the BH masses from reverberation mapping may be biased slightly low.

3.1. Complications in the Stellar Dynamical Samples

- (1) Model limitations were once a concern but are now under control. The current state of the art is to use Schwarzschild's method (Schwarzschild 1979; Richstone & Tremaine 1988) to construct three-integral models that include galaxy flattening and velocity anisotropy (van der Marel et al. 1998; Gebhardt et al. 2000a; Richstone et al. 2000). The galaxies with stellar kinematical masses in Figure 1a,b all have three-integral models. When such models are fitted to HST data, the errors in M_{\bullet} are small. However, there is still some concern about whether non-axisymmetric structure affects the masses, and thorough comparisons of the different modeling codes have not yet been carried out.
- (2) Selection effects may be present since early BH searches were biased toward objects with unusually high BH masses

- (the first *HST* targets were galaxies that showed high central dispersions at ground-based resolution). This bias still persists in the current overall BH census based on stellar-dynamical measurements, but the present sample is large enough to overcome effects from a few galaxies with high BH masses.
- (3) It is possible that galaxies contain central concentrations of ordinary dark matter (e.g., stellar remnants) that are included in most BH mass measurements. This concern is prompted by the fact that the radii that we resolve with HST spectroscopy are $\sim 10^2$ larger than the BLR that is used in reverberation mapping. However, measurements in our Galaxy (Genzel et al. 1997, 2000; Ghez et al. 1998) and in NGC 4258 (Greenhill et al. 1996) probe a small region comparable to that probed by reverberation mapping in other galaxies, and find no suggestion of any dark mass in addition to a BH.

3.2. Complications in the Reverberation Mapping Samples

- (1) The geometry and orbital distribution of the BLR are poorly known. If, as is often assumed in the AGN unification model (Antonucci 1993), Seyfert 1 nuclei are viewed preferentially face on and if the BLR and the obscuring tori are roughly coplanar, then the inclination correction for reverberation masses would be significant. However, because the thickness of the BLR disk is unknown, the actual correction is uncertain. Nonetheless, if the corrections are factors around 2, then the comparison of these masses in Fig. 1b will improve.
- (2) The measured "lag" in reverberation studies is a peculiar moment over the distribution of distances between the central nucleus and the line-emitting gas, and the measured line width is a different peculiar moment over the velocity distribution. These are affected by the adopted weightings, the shape of the continuum fluctuation power spectrum, and the sampling of the monitoring.
- (3) Selection effects restrict the BH masses that are currently measurable by reverberation mapping. The timescales of AGN variability scale with luminosity (e.g., Netzer & Peterson 1997) and presumably with mass for Eddington-limited systems. Ongoing studies of slowly-varying, high-luminosity AGNs (Kaspi et al. 2000) and of rapidly-varying, low-luminosity AGNs (Peterson et al. 2000) should remedy this situation in the future.
- (4) It is important to consider non-gravitational effects acting on BLR gas. They include radial motions caused by radiation pressure or by mechanical energy from jets. The resulting mass measurement errors could have either sign, but it is most likely that we would overestimate M_{\bullet} (Krolik 1997).

The following are additional complications that arise when estimating bulge luminosities.

- (5) AGNs are commonly associated with starbursts (e.g., Heckman 1999; Sanders 1999). This may cause M_{\bullet} to look too small in the $M_{\bullet} L_{B,\text{bulge}}$ correlation. Although M_{\bullet} is plotted against blue luminosity, the physical correlation is presumably with bulge mass, and star formation can easily reduce M/L_B by a factor of 2-4 compared to its value in bulges that are made of old stars. Then the bulge would look too bright for the given M_{\bullet} .
- (6) It is possible that the light from the AGN biases the estimate of the bulge light. First, the AGN makes the center of the galaxy look exceptionally bright in poor-quality images, so there is a tendency to assign a Hubble type that is too early if using qualitative visual inspection. If one then uses the loose correlation between Hubble type and bulge-to-disk ratio

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Table 1
SEYFERT GALAXIES WITH REVERBERATION MAPPING BH MASSES

Galaxy	Type	D (Mpc)	$L_{B,\mathrm{bulge}} \ (10^{10} L_{\odot})$	B/T	M_{ullet} (M_{\odot})	σ (km s ⁻¹)	Source for σ
3C 120	S0:	132	2.29	0.24	3.4×10^{7}	162	Smith et al. 1990
Mrk 590	Sa:	105	2.78	0.47	1.6×10^{7}	169	Nelson & Whittle 1995
NGC 3227	SABa	21	1.16	0.47	3.8×10^{7}	128	Nelson & Whittle 1995
NGC 3516	SB0:	39	2.00	0.61	2.3×10^7	124	Di Nella et al. 1995
NGC 4051	SABbc	9	0.13	0.20	1.4×10^6	88	Nelson & Whittle 1995
NGC 4151	SABab	20	1.20	0.36	1.6×10^7	119	Nelson & Whittle 1995
NGC 4593	SBb	40	3.13	0.48	8.1×10^6	124	Nelson & Whittle 1995

(Simien & de Vaucouleurs 1986) to estimate bulge luminosities, they will be overestimated. Second, even if one uses disk/bulge decompositions, unless the AGN is modeled separately, it will likely cause an overestimate of the bulge light as well.

4. CONCLUSION

We have shown that masses derived from reverberation mapping are consistent with the relation between BH mass and galaxy velocity dispersion derived from spatially resolved kinematics. Based on a sample of seven Seyfert galaxies, we find that the systematic and random errors in BH masses determined from reverberation mapping are around 0.21 dex and 0.34 dex, respectively. It is remarkable that, despite the large number of possible systematic biases (especially in reverberation mapping), both methods appear to provide consistent and reliable estimators of BH masses. Peterson & Wandel (2000) provide further support of the reliability for the AGN mass estimates by showing a Keplerian relation between line width and time lag. One could even use the $M_{\bullet} - \sigma_e$ correlation to infer properties of the broad-line region; for example, any differences in the AGN masses compared with the correlation may provide insight into the BLR geometry.

The fact that reverberation mapping successfully delivers BH masses offers tremendous hope of getting BH masses in objects that otherwise would not be accessible, namely bright AGNs, including QSOs (e.g., Kaspi et al. 2000), and highredshift AGNs. The latter hold some hope of probing the time evolution (growth history) of BH mass (e.g., Wandel 1999). Furthermore, the correlation between photoionization and reverberation models (Wandel et al. 1999) offers the possibility of wholesale AGN mass estimates. Future studies aimed at comparing the two mass estimators on the same galaxies are required to confirm both techniques, but the present results are encouraging.

We are grateful for comments from B. Peterson, A. Wandel, J. Krolik, and the referee, K. Anderson. This work was supported by HST grants to the Nukers, GO-02600.01-87A, G06099, and G07388, and by NASA grant NAG5-8238. A.V.F. acknowledges NASA grant NAG5-3556. K.G. is supported by NASA through Hubble Fellowship grant HF-01090.01-97A awarded by the Space Telescope Science Institute, which is operated by the Association of the Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555.

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