THE BLACK HOLE MASS–BULGE LUMINOSITY RELATIONSHIP FOR ACTIVE GALACTIC NUCLEI FROM REVERBERATION MAPPING AND HUBBLE SPACE TELESCOPE IMAGING

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ABSTRACT

We investigate the relationship between black hole mass and bulge luminosity for active galactic nuclei (AGNs) with reverberation-based black hole mass measurements and bulge luminosities from two-dimensional decompositions of Hubble Space Telescope host galaxy images. We find that the slope of the relationship for AGNs is 0.76–0.85 with an uncertainty of ~0.1, somewhat shallower than the $M_{\text{BH}} \propto L_{\text{bulge}}^{1.0\pm0.1}$ relationship that has been fit to nearby quiescent galaxies with dynamical black hole mass measurements. This difference is somewhat perplexing, as the AGN black hole masses include an overall scaling factor that brings the AGN $M_{\text{BH}}–\sigma$ relationship into agreement with that of quiescent galaxies. We discuss biases that may be inherent to the AGN and quiescent galaxy samples and could cause the apparent inconsistency in the forms of their $M_{\text{BH}}–L_{\text{bulge}}$ relationships. Recent work by Graham, however, presents a similar slope of ~0.8 for the quiescent galaxies and may bring the relationship for AGNs and quiescent galaxies into agreement.

Key words: galaxies: active – galaxies: nuclei – galaxies: photometry – galaxies: Seyfert

1. INTRODUCTION

Most galactic bulges are now believed to harbor a massive black hole. For active galactic nuclei (AGNs), the evidence of the black hole is obvious from the nuclear activity. However, even in quiescent galaxies, the effect of the black hole can be detected from stellar and gas kinematics near the nucleus. What remains to be determined is the formation mechanism for these massive black holes and their role in shaping and responding to the evolution of their host galaxies.

In an early review on the subject of quiescent galaxy black hole masses, Kormendy & Richstone (1995) pointed out that the estimated central black hole masses of eight galaxies seemed to show a correlation with the host galaxy bulge luminosities (or, equivalently, bulge stellar masses). Magorrian et al. (1998) later investigated a sample of 32 nearby galaxies and their black hole masses, and confirmed that the estimated black hole mass in each galaxy was indeed proportional to the luminosity (or mass) of the host galaxy bulge, albeit with a scatter about the fit of approximately ±0.5 dex. Later studies claimed, in some cases, that there may be a difference in the black hole–bulge relationship for quiescent and active galaxies, or even for Seyfert galaxies and quasars (e.g., Wandel 1999). Subsequent investigations seem to have decreased these discrepancies through more sophisticated techniques of measuring the bulge luminosity such as two-dimensional image decompositions (e.g., McLure & Dunlop 2001; Wandel 2002) or dynamical modeling of the host galaxy (e.g., Haring & Rix 2004).

We have recently completed a Hubble Space Telescope (HST) campaign to image the host galaxies of AGNs with black hole masses from reverberation mapping. The images were acquired for the purpose of decomposing the surface brightness profiles of the host galaxies and creating “nucleus-free” images for measuring the host-galaxy starlight contributions to ground-based spectroscopic luminosity measurements of the AGNs (results described by Bentz et al. 2006, 2009). Combining the bulge luminosities estimated from the surface brightness decompositions of these high-resolution images with the recently updated and homogeneously analyzed database of reverberation masses for these objects (Peterson et al. 2004 with the addition of Grier et al. 2008), we re-examine the relationship between black hole mass and host galaxy bulge luminosity for nearby AGNs. Throughout this work, we will assume a standard flat lambda cold dark matter (ΛCDM) cosmology with $\Omega_M = 0.04$, $\Omega_{\text{DM}} = 0.26$, $\Omega_{\Lambda} = 0.70$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ (Tegmark et al. 2004).

2. BULGE LUMINOSITIES AND BLACK HOLE MASSES

We investigate here the sample of AGNs with black hole masses measured using the variability technique known as reverberation mapping (Blandford & McKee 1982; Peterson 1993). The details of the host galaxy imaging and surface brightness decompositions are described by Bentz et al. (2006, 2009), but we include a short summary of the relevant details here. The majority of the objects in the reverberation sample were imaged with the Advanced Camera for Surveys (ACS) High-Resolution Channel (HRC) through the F555W filter. Unfortunately, ACS ceased functioning before the observations were completed, so five objects (PG 0026, PG 1307, PG 1426, PG 1617, and Mrk 509) were imaged with the Wide Field Planetary Camera 2 (WFPC2) through the F547M filter. Exposure times for all observations were graduated so that saturated pixels in the nuclear region of the long exposures could be corrected using an unsaturated image. Individual images were co-added and corrected for distortion if necessary. The surface brightness profiles of the AGN host galaxies were modeled with the two-dimensional image decomposition program Galfit (Peng et al. 2002). To avoid overcorrecting the AGN luminosities for host galaxy starlight, we made conservative host galaxy model fits which may underestimate the brightness of the galaxy.
components. Our tests of the magnitude of this underestimate indicate that it is \( \lesssim 10\% \).

For most of the reverberation-mapped objects, the \( HST \) images are sufficient for a full decomposition. However, for the nearby and spatially extended NGC objects in the sample, the \( HST \) images do not provide the necessary wide field of view (FOV) to measure the sky background, affecting the accuracy to which we can constrain the bulge and disk parameters. Our current surface brightness models for the \( HST \) images of the NGC galaxies include components that cannot be resolved in the ground-based images due to their small effective radii (less than 3.5 arcsec in all cases). The typical seeing in the ground-based images of \( \sim 2'' \) blurs the central point-spread function (PSF) together with these compact components and with the bulge itself, which has an effective radius of only \( \sim 10'' \) for these objects. The difficulties of disentangling the nuclear structure in the ground-based images and the fact that the distortion-corrected HRC FOV is, at best, only twice the effective radius of the bulge and furthermore does not allow measurement of the sky, creates enough uncertainty in the bulge parameters for these objects that we exclude them from further analysis at this time. We also exclude IC 4329A because of its uncertain black hole mass and because it is a dusty edge-on galaxy with an unreliable surface brightness decomposition. Table 1 lists the 26 objects included in this study.

The details of the surface brightness decompositions are given in Bentz et al. (2009). We take the component with the largest effective radius (other than any exponential disk component) as the “bulge” for each of these galaxies, except for Mrk 79 where there is clearly an extended barlike component. For ellipticals, the bulge magnitude is the total galaxy magnitude. We followed the prescriptions of Sirianni et al. (2005) for converting from the space telescope AB, magnitude system to Galactic extinction-corrected magnitudes in the Vega system, which we list in Table 1 as \( m_{HST} \). The \( V-HST \) color for each object was calculated with \texttt{synphot} using the bulge template of Kinney et al. (1996). Also included in Table 1 are the apparent and absolute Johnson V magnitudes, and the V-band luminosity from the standard relation of \( \log L_V/L_\odot = 0.4(M_V + 4.83) \). We assume an uncertainty of \( \pm 0.2 \) dex for the bulge luminosities. Four of the galaxies have an additional surface brightness component besides a bulge or disk. Imaging alone is not sufficient to ascertain whether these components are dynamically distinct, so we also list in Table 1 the bulge luminosity for those objects including the flux contribution from the additional components.

Figure 1 compares the (single component) bulge luminosities and black hole masses for the sample of objects that are common to both this work (filled circles) and the Wandel (2002) study (open circles). There is a clear trend between black hole mass and bulge luminosity for the objects in this study, whereas the bulge luminosities from Wandel (2002) have a range of \( \sim 2 \) dex in black hole mass over a limited \( \sim 1.5 \) dex range in luminosity. It is perhaps unsurprising that a correlation is more apparent now, as the study by Wandel (2002) is a compilation of inhomogeneous data from the literature. The bulge luminosities were primarily from McLure & Dunlop (2001) and include measurements from ground-based photographic plates and CCD imaging, as well as saturated and unsaturated \( HST \) imaging, all in various passbands. Many of the studies included in the compilation did not use the same cosmologies and distances

| Object       | \( D_e \) (Mpc) | \( E(B-V) \) (mag) | \( m_{HST} \) (vegamag) | \( m_V \) (vegamag) | \( M_H \) (mag) | \( \log L/V \) (L_\odot) | \( \log M_{BH} \) (M_\odot) |
|--------------|-----------------|---------------------|-------------------------|---------------------|---------------|-----------------------------|-----------------------------|
| Mrk 335      | 113             | 0.035               | 16.16                   | 16.26               | -19.00        | 9.53                       | 7.15 ± 0.11                 |
| PG 0026+129  | 672             | 0.071               | 16.21                   | 16.23               | -22.91        | 11.09                       | 8.59 ± 0.11                 |
| PG 0052+251  | 740             | 0.047               | 17.81                   | 17.92               | -21.42        | 10.50                       | 8.57 ± 0.09                 |
| Fairall19    | 209             | 0.027               | 15.13                   | 15.20               | -21.40        | 10.49                       | 8.41 ± 0.10                 |
| Mrk 590      | 115             | 0.037               | 15.59                   | 15.68               | -19.63        | 9.78, 9.99                  | 7.68 ± 0.07                 |
| 3C 120       | 145             | 0.297               | 16.64                   | 16.72               | -19.08        | 9.57                       | 7.74 ± 0.21                 |
| Mrk 79       | 96.7            | 0.071               | 15.84                   | 15.95               | -18.98        | 9.52, 10.19                 | 7.72 ± 0.12                 |
| PG 0804+761  | 461             | 0.035               | 16.70                   | 16.74               | -21.58        | 10.56                       | 8.84 ± 0.05                 |
| PG 0844+349  | 287             | 0.037               | 16.75                   | 16.81               | -20.48        | 10.13                       | 7.97 ± 0.18                 |
| Mrk 110      | 155             | 0.013               | 18.08                   | 18.16               | -17.79        | 9.05                       | 7.40 ± 0.11                 |
| PG 0953+414  | 1170            | 0.013               | 17.64                   | 17.82               | -22.53        | 10.94                       | 8.44 ± 0.09                 |
| PG 1211+143  | 368             | 0.035               | 17.16                   | 17.21               | -20.62        | 10.18                       | 8.16 ± 0.13                 |
| PG 1226+023  | 758             | 0.021               | 15.49                   | 15.61               | -23.79        | 11.45                       | 8.95 ± 0.09                 |
| PG 1229+204  | 283             | 0.027               | 17.17                   | 17.23               | -20.03        | 9.94, 9.98                  | 7.86 ± 0.21                 |
| PG 1307+085  | 740             | 0.043               | 16.66                   | 16.70               | -22.65        | 10.99                       | 8.64 ± 0.12                 |
| Mrk 279      | 133             | 0.016               | 16.13                   | 16.22               | -19.40        | 9.69, 10.00                 | 7.54 ± 0.11                 |
| PG 1411+442  | 410             | 0.008               | 16.70                   | 16.74               | -21.32        | 10.46                       | 8.65 ± 0.14                 |
| PG 1426+015  | 395             | 0.032               | 15.36                   | 15.34               | -22.64        | 10.99                       | 9.11 ± 0.13                 |
| Mrk 817      | 138             | 0.007               | 17.62                   | 17.71               | -17.99        | 9.13                       | 7.69 ± 0.07                 |
| PG 1613+658  | 606             | 0.027               | 16.14                   | 16.20               | -22.71        | 11.02                       | 8.45 ± 0.20                 |
| PG 1617+175  | 522             | 0.042               | 16.36                   | 16.34               | -22.25        | 10.83                       | 8.77 ± 0.10                 |
| PG 1700+518  | 1510            | 0.035               | 17.54                   | 17.67               | -23.22        | 11.22                       | 8.89 ± 0.10                 |
| 3C 390.3     | 251             | 0.071               | 16.74                   | 16.80               | -20.19        | 10.01                       | 8.46 ± 0.10                 |
| Mrk 509      | 151             | 0.057               | 13.96                   | 13.96               | -21.94        | 10.71                       | 8.16 ± 0.04                 |
| PG 2130+099  | 823             | 0.044               | 18.73                   | 18.79               | -18.47        | 9.32                       | 7.58 ± 0.17                 |

Notes. For those objects with two bulge luminosities listed, the first is the luminosity of the largest-scale nondisk component, and the second is the luminosity of all nondisk components, including bars or inner bulges. Black hole masses are from Peterson et al. (2004), except for PG 2130+099 (Grier et al. 2008).

Table 1

Black Hole Masses and Bulge Luminosities
for the objects or the same analysis techniques in determining the black hole mass. All of the reverberation-based black hole masses have since been homogeneously analyzed and updated by Peterson et al. (2004), and PG 2130+099 has an updated mass from the analysis of a new reverberation data set by Grier et al. (2008). Figure 2 shows the black hole masses versus the host galaxy V-band luminosities for the full sample of 26 objects included in this study.

Figure 1. Comparison of black hole mass and V-band bulge luminosity values from Wandel (2002) (open circles) and this work (filled circles) for objects that are common to both. The new values cover a range of 2.5 dex in luminosity and show a clear trend, while the values from Wandel (2002) have a range of ~2 dex in mass within a limited ~1.5 dex range in luminosity.

Figure 2. $M_{\text{BH}}$–$L_{\text{bulge}}$ relationship for AGNs with reverberation-based masses and bulge luminosities from two-dimensional decompositions of HST host-galaxy images. The solid line is the "best" fit with a slope of $\alpha = 0.80 \pm 0.09$. The dashed line is the fit from Wandel (2002) to his sample of broad-line AGNs and has a slope of $\alpha = 0.90 \pm 0.11$.

Table 2

| Sample                        | $K$       | $\alpha$   | Scatter $^a$ |
|-------------------------------|-----------|------------|--------------|
| BCES                          |           |            |              |
| AGNs                          | $-0.02 \pm 0.06$ | $0.80 \pm 0.09$ |              |
| AGNs (+ extra components)     | $-0.07 \pm 0.08$ | $0.85 \pm 0.11$ |              |
| FF05 ellipticals              | $0.42 \pm 0.12$ | $1.43 \pm 0.21$ |              |
| FF05 ellipticals (− outliers) | $0.30 \pm 0.10$ | $1.42 \pm 0.24$ |              |
| FITEXY                        |           |            |              |
| AGNs                          | $-0.05 \pm 0.06$ | $0.76 \pm 0.08$ | $0.38$       |
| AGNs (+ extra components)     | $-0.13 \pm 0.06$ | $0.80 \pm 0.09$ | $0.44$       |
| FF05 ellipticals              | $0.15 \pm 0.11$ | $1.11 \pm 0.21$ | $0.73$       |
| FF05 ellipticals (− outliers) | $0.14 \pm 0.11$ | $1.18 \pm 0.19$ | $0.64$       |

Notes. $^a$ The fractional scatter, quantified as the fraction of the measurement value of $M_{\text{BH}}$ that must be added in quadrature to the error value in order to obtain a reduced $\chi^2$ of 1.0.

3. THE BLACK HOLE MASS–BULGE LUMINOSITY RELATIONSHIP

We employed two independent fitting routines in our examination of the $M_{\text{BH}}$–$L_{\text{bulge}}$ relationship: FITEXY (Press et al. 1992), which estimates the parameters of a straight-line fit through the data including errors in both coordinates; and BCES (Akritas & Bershady 1996), which accounts for the effects of errors on both coordinates using bivariate correlated errors and a component of intrinsic scatter. FITEXY numerically solves for the minimum orthogonal $\chi^2$ using an iterative root-finding algorithm and is a “symmetric” algorithm in that it does not assume a dependent and an independent variable. Following Tremaine et al. (2002), we include an estimate of the intrinsic scatter as the fraction of the measurement value (not the error value) that is added in quadrature to the error value to obtain a reduced $\chi^2$ of 1.0. The statistical accuracy of reverberation masses is only a factor of 2–3 (Onken et al. 2003), so the fractional error is added to the $M_{\text{BH}}$ measurement. BCES also accounts for, but does not quantify, intrinsic scatter. For comparison with the “symmetric” fits from FITEXY, we adopt the bootstrap of the BCES bisector value with $N = 1000$ iterations. Fits of the form

$$\log \frac{M_{\text{BH}}}{10^8 M_\odot} = K + \alpha \log \frac{L_{\text{bulge}}}{10^{10} L_\odot}$$

were performed utilizing both the single-component bulge luminosities and the multiple-component bulge luminosities and are presented in Table 2. The power-law slope ranges from 0.76 ± 0.08 to 0.85 ± 0.11 depending on the definition of the bulge luminosity and the specific fitting routine utilized. We take the BCES fit nearest the middle of this range, with a slope of 0.80 ± 0.09, as the “best” fit.

For comparison, we fit the quiescent galaxy $M_{\text{BH}}$–$L_{\text{bulge}}$ relationship using the sample of nearby galaxies with dynamical black hole mass measurements (Ferrarese & Ford 2005; FF05). We restricted the sample to ellipticals, both to circumvent the need for bulge–disk decompositions and because ellipticals are reported to show less scatter about the $M_{\text{BH}}$–$L_{\text{bulge}}$ relationship (see McLure & Dunlop 2001). Bulge magnitudes were converted to the V band using a typical elliptical galaxy color of $B − V = 0.9$. The fitting results are presented in Table 2, including fits to the quiescent galaxy relationship excluding Cygnus A and NGC 5845, both of which are known to deviate significantly (FF05).
with the same instrument and the same filter. The exceptions are the five objects that were imaged through the F547M filter using WFC2, but the bandpass is very similar to the ACS F550M filter employed for the other objects (λ_c(F550M) = 5580 Å vs. λ_c(F547M) = 5483 Å, and Δλ(F550M) = 547 Å vs. Δλ(F547M) = 483 Å).

Unfortunately, there is not a similarly consistent sample of high-quality images from which the bulge luminosities can be estimated for the quiescent galaxies with dynamical black hole masses. While high-quality observations do exist for these nearby and well-studied galaxies, they have not been obtained in a uniform fashion. The recent work by Graham (2007) attempts to compensate for the different methods and analysis techniques employed by several groups (McLure & Dunlop 2002 with an updated cosmology presented in McLure & Dunlop 2004; Marconi & Hunt 2003; Erwin et al. 2004), all of which arrive at different values for the slope of the quiescent galaxy $M_{\text{BH}}$–$L_{\text{bulge}}$ relationship and/or different black hole masses predicted for a specific bulge luminosity. Graham carefully updated and revised the samples of objects included in those studies and found that the differences of the best-fit parameters found by each study are mitigated, the scatter in the measurements is significantly decreased, and that $M_{\text{BH}} \propto L^{1.0}$. Interestingly, he finds a somewhat shallower slope, $\alpha \approx 0.75$–0.88, when bulge luminosities are estimated by two-dimensional decompositions of $B$-band images and corrected for inclination-dependent dust extinction in the host galaxy disks. Only 13 objects are included in that particular analysis (an updated form of the study presented by Erwin et al. 2004) but it is intriguing nonetheless in its close agreement with the fit that we find for the AGNs and deserves further examination.

While we expect that the AGN bulge luminosities in this study may be underestimated by a few percent because of the conservative galaxy fits we employed, there is also a small k-correction introduced as the average redshift of the 26 AGNs is $z \approx 0.1$. The portion of the SED observed through the medium-band $V$ filters employed in the HST observations is fainter (~0.1 dex in luminosity) than if the galaxies were at $z = 0$, assuming their stellar populations resemble that of the bulge template of Kinney et al. (1996). Accounting for any such biases in the galaxy fitting or colors would shift the AGN luminosities to higher values and intensify the apparent differences in slopes for the AGN and quiescent galaxy relationships. The AGN black hole masses have already been scaled so that their $M_{\text{BH}}$–$\sigma$ relationship is brought into agreement with the $M_{\text{BH}}$–$\sigma$ relationship for quiescent galaxies with dynamical masses. The differences in the slopes of the $M_{\text{BH}}$–$L_{\text{bulge}}$ relationships may be mitigated if Marconi et al. (2008) are correct in their suggestion that neglecting radiation pressure leads to systematic underestimation of black hole masses from reverberation-mapping data (see, however, Netzer 2009).

A separate concern has been raised by Yu & Tremaine (2002), Bernardi et al. (2007), Lauer et al. (2007b), and Tundo et al. (2007), who present an apparent disagreement between the quiescent galaxy $M_{\text{BH}}$–$\sigma$ and $M_{\text{BH}}$–$L_{\text{bulge}}$ relationships and suggest that the quiescent galaxy sample is biased toward galaxies with overly large velocity dispersions for their luminosities (see, however, Graham 2008 who examines the role of bars in this issue). There is no reason to suspect the AGN sample of having the same bias, as the mass measurements rely on flux variability and not dynamical techniques. Such a bias may help explain why some of the quiescent galaxies at the high luminosity end have

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5 The relative contribution of the bulge is known to vary substantially within a single morphological type. Figure 6 of Kent (1985) shows, for example, that $B/T$ ranges from 0.3–1.0 for S0 galaxies.
black hole masses that are more than an order-of-magnitude larger than the active galaxies, although it may not completely resolve the disparity.

Finally, there may be no reason to expect that the $M_{BH} - L_{\text{bulge}}$ relationship is the same for the AGNs and quiescent galaxies, as only a modest number of objects are included in each sample and selection effects likely play an important role (Lauer et al. 2007a). Clearly, there remain several areas that are in need of investigation, any of which may shed light on the possibly inconsistent fits to the $M_{BH} - L_{\text{bulge}}$ relationship for AGNs and for quiescent galaxies. As the $M_{BH} - L_{\text{bulge}}$ relationship is an important and widely used means of estimating black hole masses throughout cosmic history (e.g., Marconi et al. 2004; Shankar et al. 2004), an accurate characterization of this relationship is necessary for understanding black hole growth and evolution as well as the interplay between black holes and their host galaxies.

5. SUMMARY

We present an updated version of the AGN $M_{BH} - L_{\text{bulge}}$ relationship using the database of homogeneously analyzed reverberation masses from Peterson et al. (2004) and Grier et al. (2008; PG 2130+099) and the two-dimensional surface brightness decompositions of the AGN host galaxies described by Bentz et al. (2009). We find a strong correlation between $M_{BH}$ and $L_{\text{bulge}}$ for the 26 AGNs included here, with a best-fit power-law slope of $0.80 \pm 0.09$. This is somewhat shallower than the best-fit slope for quiescent galaxies ($\alpha \approx 1.0$), even though the AGN black hole masses have been scaled to bring the AGN and quiescent galaxy $M_{BH} - \sigma_*$ relationships into agreement. There appear to be many systematics in both the AGN and quiescent galaxy samples that must be investigated in order to more completely understand this important relationship.

Our future plans include investigating the biases in the AGN sample and extending the range of the relationship for AGNs. We have an HST Cycle 17 program to image the NGC objects that were excluded here with the Wide Field Camera 3 through the F547M filter. These observations will provide the intermediate FOV images necessary for accurate galaxy decompositions, enabling us to include them at the low-mass end of the AGN $M_{BH} - L_{\text{bulge}}$ relationship. Recent reverberation-mapping experiments carried out at MDM Observatory (spring 2007) and Lick Observatory (spring 2008) focused on AGNs with black hole masses in the range $1 \times 10^5 - 5 \times 10^7 M_\odot$ (K. D. Denney et al. 2009, in preparation; M. C. Bentz et al. 2009, in preparation) and show promise in further extending the range and coverage of the AGN $M_{BH} - L_{\text{bulge}}$ relationship at the low-mass end.

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