Title
Cosmic evolution of black holes and spheroids. III. The $M_{BH}$-$\sigma^*$ relation in the last six billion years

Permalink
https://escholarship.org/uc/item/8mx6d9s1

Journal
Astrophysical Journal, 681(2)

ISSN
0004-637X

Authors
Woo, JH
Treu, T
Malkan, MA
et al.

Publication Date
2008-07-10

DOI
10.1086/588804

Peer reviewed
COSMIC EVOLUTION OF BLACK HOLES AND SPHEROIDS. III. THE $M_{\mathrm{BH}}-\sigma_*$ RELATION IN THE LAST SIX BILLION YEARS

Jong-Hak Woo, Tommaso Treu, Matthew A. Malkan, Roger D. Blandford

ABSTRACT

We measure the evolution of the correlation between black hole mass and host spheroid velocity dispersion ($M_{\mathrm{BH}}-\sigma_*$) over the last 6 billion years, by studying three carefully selected samples of active galaxies at $z = 0.57$, $z = 0.36$ and $z < 0.1$. For all three samples, virial black hole masses are consistently estimated using the line dispersion of H$\beta$ and the continuum luminosity at 5100Å or H$\alpha$ line luminosity, based on our cross calibration of the broad line region size-luminosity relation. For the $z = 0.57$ sample, new stellar velocity dispersions are measured from high signal-to-noise ratio spectra obtained at the Keck Telescope, while for the two lower redshift samples they are compiled from previous works. Extending our previous result at $z = 0.36$, we find an offset from the local relation, suggesting that for fixed $M_{\mathrm{BH}}$, distant spheroids have on average smaller velocity dispersions than local ones. The measured offset at $z = 0.57$ is $\Delta \log \sigma_* = 0.12 \pm 0.05 \pm 0.06$ (or $\Delta \log M_{\mathrm{BH}} = 0.50 \pm 0.22 \pm 0.25$), i.e. $\Delta \log M_{\mathrm{BH}} = (3.1 \pm 1.5) \log(1 + z) + 0.05 \pm 0.21$. This is inconsistent with a tight and non-evolving universal $M_{\mathrm{BH}}-\sigma_*$ relation at the 95% CL.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: evolution — quasars: general

1. INTRODUCTION

Understanding the origin of the black hole mass - spheroid velocity dispersion ($M_{\mathrm{BH}}-\sigma_*$) relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000) is a key goal of unified models of black hole – galaxy coevolution (e.g. Kauffmann & Haehnelt 2000; di Matteo et al. 2005; Ciotti & Ostriker 2007). One of the most powerful observational tests of the proposed explanations is to measure the time evolution of the $M_{\mathrm{BH}}-\sigma_*$ relation since various scenarios predict different cosmic evolution. For example, – for a fixed $M_{\mathrm{BH}}$ – Robertson et al. (2006) predict an increase of $\sigma_*$ with redshift, Croton et al. (2006) and Bower et al. (2006) predict a decrease, while Granato et al. (2004) expect no evolution.

In recent years, a number of groups have investigated the evolution of the $M_{\mathrm{BH}}-\sigma_*$ relation, using various techniques to estimate $\sigma_*$ of AGN host galaxies (e.g. Shields et al. 2003; Walter et al. 2004; Salvianer et al. 2007). Starting with our pilot study (Treu et al. 2004), we reported the first direct measurement of the $M_{\mathrm{BH}}-\sigma_*$ relation beyond the local Universe (Woo et al. 2006, hereafter paper I), and updated it with corrected AGN continuum luminosities using Hubble Space Telescope (HST) images in paper II (Treu et al. 2007).

By observing 14 Seyfert 1 galaxies, we determined stellar velocity dispersions in the integrated spectra, and $M_{\mathrm{BH}}$ from AGN broad emission line widths, which are thought to measure the gravity of the central mass on sub-parsec scales. We found that the measured $M_{\mathrm{BH}}-\sigma_*$ relation at $z = 0.36$ is offset with respect to the local relation ($\Delta \log M_{\mathrm{BH}} = 0.54 \pm 0.12 \pm 0.21$ at fixed $\sigma_*$). In other words black holes of a fixed mass appeared to live in bulges with smaller velocity dispersion 4 Gyrs ago (at 95% CL), consistent with recent growth and evolution of intermediate mass spheroids. Using HST images, we obtained a consistent result, $\Delta \log M_{\mathrm{BH}} > 0.51 \pm 0.14 \pm 0.17$, by measuring the $M_{\mathrm{BH}}$-spheroid luminosity relation of the same sample (paper II). This result may be consistent with a scenario where intermediate-mass blue galaxies undergo merging at relatively recent times and arrive on the local black hole-galaxy relations by becoming more massive red galaxies. However, much work remains to be done due to the small sample size and large uncertainties, before this initial result can become a high precision measurement.

We report here our first measurement at the next redshift window ($z = 0.57$, adding $\sim$50% to the look-back time), so that evolutionary trends can be measured over a longer range in cosmic time. We also improve the local baseline by consistently estimating $M_{\mathrm{BH}}$ for a sample of 48 nearby Seyfert 1 galaxies with published stellar velocity dispersion (Greene & Ho 2006). To minimize repetition, readers are referred to our previous works (papers I, II; McGill et al. 2008; hereafter M08) for detailed discussions of the systematics inherent to the measurement. The paper is organized as follows. Section 2 describes sample selection and observations. Section 3 presents our measurements. Section 4 presents the $M_{\mathrm{BH}}-\sigma_*$ relation. Discussion and conclusions are presented in § 5. We adopt $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \, \text{km} \, \text{sec}^{-1} \, \text{Mpc}^{-1}$.

2. DATA

A sample of broad-line AGNs was selected from the Sloan Digital Sky Survey Data Release 4 (SDSS DR4). Following our strategy at $z = 0.36 \pm 0.01$ (paper I), we chose the next redshift window, $z = 0.57 \pm 0.01$, to avoid strong sky features on the redshifted stellar lines around the Mg-Fe line region, minimizing the uncertainties re-
systematic uncertainties. First, we subtracted broad paper I. Here, we briefly summarize the procedure and to measure velocity dispersion as described in detail in estimates for the 48 local Seyferts (\(z\)) for the 5 Seyferts at \(z\) properties of the (\(z\)) similar to those described in paper I. Dimensional spectra extraction processes were very sim- serving strategy , data reduction, calibration, and one- each object ranges between 2.5 and 3.5 hours. The ob- favorables with 0.7-1.2" seeing. Total exposure times for a pixel scale of 0.92 \(\text{Å}\) centered at 7600 \(\text{Å}\) 1995) at the Keck-I telescope during two runs in January 2007 and April 2007. The 831 lines mm (365 broad-line AGNs at \(z=0.57\) \(A\) was used with a 1" wide slit, yielding \(A\). Observing conditions were generally \(A\) and \(r'-i'\)>0.3 (AB), expecting non-negligible stellar light in the observed spectra, based on stellar and AGN spectral models. The effects of this color cut will be modeled in detail in future papers, when Keck and possibly HST data for a larger sample at \(z=0.57\) will be available. However, since the colors of the new sample are similar to those of the \(z=0.36\) sample, we do not expect the color cut to introduce a significant bias. In any case, the color cut will tend to select more massive host galaxies for a given nuclear luminosity. Hence, if any biased is intro- duced, it should bias against the offset seen in papers I and II. High signal-to-noise (S/N) ratio spectra for 5 objects were obtained with the LRIS spectrograph (Oke et al. 1995) at the Keck-I telescope during two runs in January 2007 and April 2007. The 831 lines mm\(^{-1}\) grating centered at 7600\(\text{Å}\) was used with a 1" wide slit, yielding a pixel scale of 0.92\(\text{Å}\) x 0.215 and a Gaussian resolution (\(\sigma\)) \(\sim\)58 km s\(^{-1}\). Observing conditions were generally favorable with 0.7-1.2" seeing. Total exposure times for each object ranges between 2.5 and 3.5 hours. The ob- serving strategy, data reduction, calibration, and one- dimensional spectra extraction processes were very similar to those described in paper I.

3. MEASUREMENTS

This section describes our measurement of \(\sigma^*\) and \(M_{BH}\) for the 5 Seyferts at \(z=0.57\) (§ 3.1 and § 3.2) and \(M_{BH}\) estimates for the 48 local Seyferts (§ 3.3). The relevant properties of the \(z=0.57\) sample are listed in Table I

3.1. Stellar Velocity Dispersion

We used the Mg-Fe region (rest-frame \(\sim 5050-5300\text{Å}\)) to measure velocity dispersion as described in detail in paper I. Here, we briefly summarize the procedure and systematic uncertainties. First, we subtracted broad AGN Fe emission, using a set of I Zw 1 templates. Then, we compared in pixel space the observed spectra with 5 stellar templates (G8, G9, K0, K2, and K5 giant) broad- ened with a range of Gaussian velocity. AGN narrow emission lines (e.g. [N I] 5201\(\text{Å}\) and [Fe XIV] 5304\(\text{Å}\)) were masked out before fitting, as shown in Figure 1. Fits were performed for all templates to estimate the effect of template mismatch, yielding comparable measurements within the errors (10-20%). The best-fit template was used for the final dispersion measurements.

The Mg-Fe region typically used for dynamical studies is a natural choice for our sample since other strong stel- lar features such as the CaII triplet are out of the optical spectral range. Feature mismatch due to \(\alpha\)-enhancement in massive early-type galaxies is a well-known problem in kinematics studies (e.g. Barth et al. 2003; Woo et al. 2004) and can potentially increase systematic uncertain- ties. However, in paper I we found that only one out of 14 Seyfert galaxies at \(z=0.36\) shows signs of Mg mis- match, as expected because the inferred stellar velocity dispersions are more typical of a Milky Way type galaxy than of a massive early-type galaxy. As for the lower redshift sample, we do not find significant mismatch in our \(z=0.57\) sample, as shown in Figure 1.

Following the procedure described in paper I, we es- timate a total systematic uncertainty of 0.05 dex on \(\sigma\), combining the effects of template mismatch, potential errors due to the large spectroscopic aperture, and host galaxy morphology and inclination. This translates into 0.20 dex uncertainty of the offset in log \(M_{BH}\) from the \(M_{BH}\)-\(\sigma\) relation.

3.2. Black Hole Mass

Black hole mass can be estimated using the ‘virial’ method based on the empirical relation between the size of the broad line region and continuum luminosity of the reverberation sample (Kaspi et al. 2005), and the velocity scale given by the width of the broad emission lines. In practice, we measured the line dispersion of broad H\(\beta\) by fitting the observed line profile with Gauss-Hermite polynomials as described in paper I and in M08. The con- tinuum luminosity around 5100\(\text{Å}\) (\(L_{5100}\)) was measured by averaging flux in the 5070-5130\(\text{Å}\) region. Consider- ing the difficulty of achieving absolute flux calibration for the Keck spectra – due to slit losses, variable seeing and sky transparency– we re-calibrated our spectropho- tometry with the extinction corrected \(i'\) band magnitude taken from the SDSS-DR6 archive, by calculating and correcting for the offset between Sloan and our synthetic \(i'\) band magnitude measured from the observed spectra. For low luminosity AGNs (\(L_{5100}\) < 10\(^{44}\) erg s\(^{-1}\)) continuum luminosity can be overestimated due to the sig- nificant contribution from host galaxies. Thus, correct- ing for the host galaxy contamination is crucial to avoid overestimation of \(M_{BH}\). The size-luminosity relation was in fact revised with a lower slope (\(<0.5\) as expected in photoionization scenarios) and a higher normalization, after correcting for the galaxy contamination in low lu- minosity AGNs in the reverberation sample (Bentz et al. 2006a).

It requires high resolution HST imaging to correct for the host galaxy contamination for distant AGNs. Since this is not available for our sample at the moment, we cannot but adopt the size-luminosity relation based on the total (observed) luminosity. However, based on our
experience at $z = 0.36$, host galaxy contamination is not expected to be a major effect. In paper II, for Seyfert galaxies with similar luminosity, we compared $M_{\text{BH}}$ estimates based on the size-luminosity relation of Kaspi et al. (2005) with new estimates based on the revised size-luminosity relations of Bentz et al. (2006a), after correcting for host galaxy contamination using HST images. We found that new $M_{\text{BH}}$ estimates are on average 0.09 dex smaller, due to the combined effects of removing host galaxy light while using the new size-luminosity relation with a higher normalization.

Therefore, we will adopt as our best estimate of $M_{\text{BH}}$ the following equation from Paper I based on Kaspi et al. (2005) and Onken et al. (2004), equivalent to the most recent calibration of empirical $M_{\text{BH}}$ estimators from M08:

$$M_{\text{BH}} = 10^{8.33}M_\odot \times \left( \frac{\sigma_{H\beta}}{300 \text{km s}^{-1}} \right)^2 \left( \frac{\lambda L_{5100}}{10^{44} \text{ergs}^{-1}} \right)^{0.69},$$

(1)

where $\sigma_{H\beta}$ is the line dispersion (second moment) of $H\beta$. We assume 0.4 dex uncertainty on the estimated $M_{\text{BH}}$, based on comparisons of reverberation data and single-epoch data (Vestergaard & Peterson 2006; M08), which dominates the errors on $\sigma_{H\beta}$ and $L_{5100}$.

As a sanity check, we compared $M_{\text{BH}}$ estimates based on Equation 1 with those based on the new size-luminosity relation with a higher normalization.

### 3.3. Local Seyferts

To measure the evolution of the $M_{\text{BH}}-\sigma_*$ relation, it is important to have a well defined local sample. The sample of 14 Seyfert galaxies with reverberation $M_{\text{BH}}$ and measured stellar velocity dispersion (Onken et al. 2004) is a good local benchmark. However, it is desirable to have a complementary sample for two reasons. First, the reverberation sample is small in size and shows a flattened distribution on the $M_{\text{BH}}-\sigma_*$ plane, especially with a new reverberation black hole mass of NGC 4151 (Bentz et al. 2006b; see magenta points in Figure 2). Second, there could be an unknown systematic offset between the reverberation mass and our single-epoch mass due to the uncertainties in measuring velocity and luminosity from single-epoch spectra, potentially caused by, e.g., flux variability, velocity variability, the narrow line subtraction (e.g., Collin et al. 2006; Woo 2008).

For these reasons, we estimated $M_{\text{BH}}$ for a sample of local Seyferts, using the line dispersion of $H\beta$ and $H\alpha$ line luminosity ($L_{H\alpha}$), and a formula consistently calibrated with that used for $M_{\text{BH}}$ estimates at $z = 0.36$ and $z = 0.57$ (M08). We selected 55 Seyfert 1 galaxies at $z < 0.1$ from SDSS-DR6, with published stellar velocity dispersion (Greene & Ho 2006). Seven objects were excluded due to the very faint broad component of $H\beta$ that prevented us from measuring reliable line widths. For local low luminosity Seyferts, host galaxy light is a significant fraction of the light observed within the Sloan fiber (3" diameter), superimposing strong stellar absorption on the broad $H\beta$ line profile. Thus, we subtracted the stellar features, using eigenspectra templates based on a principal component analysis of several hundred galaxy spectra (Hao et al. 2005). Since the $L_{5100}$ measured from SDSS spectra could be also significantly contaminated by stellar light, we used $L_{H\alpha}$ from Greene & Ho (2006) instead, together with the $M_{\text{BH}}$ recipe calibrated by M08 and Green & Ho (2005).

### 4. THE $M_{\text{BH}}-\sigma_*$ RELATION

In Figure 2 the $M_{\text{BH}}-\sigma_*$ relation for local active galaxies (left panel) and our samples at $z = 0.36$ and $z = 0.57$ (right panel) are presented along with local quiescent galaxies. Two local AGN samples (SDSS sample from § 3.3 and the reverberation sample from Onken et al. 2004) are consistent with the $M_{\text{BH}}-\sigma_*$ relation of quiescent galaxies, although the scatter is somewhat larger (r.m.s. 0.45 and 0.43 dex, respectively for the SDSS
Fig. 2.— The $M_{\text{BH}}\sigma$ relation of active galaxies. Left panel: local Seyferts with $\sigma_*$ from Greene & Ho (2006) and our own $M_{\text{BH}}$ estimates, consistently calibrated with our estimates for distant samples (black circles); local Seyferts with $M_{\text{BH}}$, measured via reverberation mapping (Onken et al. 2004; magenta squares). Right panel: new measurements at $z = 0.57$ (red stars); Seyfert galaxies at $z = 0.36$ from our earlier work (paper I, II; blue circles). The local relationships of quiescent galaxies (Tremaine et al. 2002; black points) are shown for comparison as a solid (Tremaine et al. 2002) and dashed (Ferrarese & Ford 2005) line.

Fig. 3.— Offset in $M_{\text{BH}}$ with respect to the local quiescent sample (Tremaine et al. 2002) as a function of redshift. Large solid points with error bars represent the average and rms scatter for the four samples of active galaxies. The rms scatter of the $z = 0.57$ sample is 0.5 dex, similar to that of local active galaxies. Note that all ‘virial’ $M_{\text{BH}}$ are based on the second moment of H$\beta$ and the same calibration of the virial coefficient. The dashed line represent the best fit relation $\Delta \log M_{\text{BH}} = (3.1 \pm 1.5) \log(1 + z) + 0.05 \pm 0.21$ for the low $\sigma_*$ sample (0.43 vs 0.22).

The distant samples are offset from the local $M_{\text{BH}}\sigma$ relation. The average offset of the $z = 0.57$ sample is $0.50 \pm 0.22 \pm 0.25$ dex in $M_{\text{BH}}$, corresponding to $0.12 \pm 0.05 \pm 0.06$ in $\log \sigma_*$ — in the sense that velocity dispersions were on average smaller for given $M_{\text{BH}}$ six Gyrs ago (Figure 3). Using the new size-luminosity relation of Bentz et al. 2006a (Equation 2) and assuming an average AGN fraction $\sim 50\%$, we find an equivalent offset, $\Delta \log M_{\text{BH}} = 0.51$. If the AGN fraction is higher, then the offset increases (see Section 3.2), indicating that $M_{\text{BH}}$ estimates based on Equation 1 is not significantly overestimated. The result is similar to the average offset of the $z = 0.36$ sample (papers I and II), although the error bars on the measurement are large enough to allow for a variety of redshift trends. We include in our error analysis, in addition to the random errors, a potential systematic error of 0.25 dex, estimated by combining systematic uncertainties in $M_{\text{BH}}$ and $\sigma_*$. To quantify the significance of evolution, we consider the three active samples. We emphasize that $M_{\text{BH}}$ was consistently estimated based on the line dispersion of H$\beta$ and the same virial coefficient (shape factor). Thus, a change in the virial coefficient will move all samples vertically by the same amount, keeping the offset unchanged, unless the kinematics of the broad line region (hence, the virial coefficient) varies as a function of $M_{\text{BH}}$ or redshift. Therefore, we consider the systematic error on the relative calibration of $M_{\text{BH}}$ to be negligible, leaving systematic errors in the measurement of $\sigma_*$ as the main source of systematic uncertainty in the evolution. Including random and systematic errors in the analysis, we find that the best fit relation is $\Delta \log M_{\text{BH}} = (3.1 \pm 1.5) \log(1 + z) + (0.05 \pm 0.21)$, i.e. the slope is non zero at the two sigma level. However, as discussed in paper I and II, it is important to keep in
mind that the observed offset may not represent evolution, if the higher z samples are not direct progenitors of the lower z samples due to, e.g., the somewhat different scales in galaxy mass and $M_{\text{BH}}$.

5. DISCUSSION AND CONCLUSIONS

We investigated the evolution of the $M_{\text{BH}}-\sigma_*$ relation using three samples of Seyfert galaxies at $z<0.1$, $z=0.36$, and $z=0.57$, finding evolution in the last 6 Gyr at the 95%CL. This result is consistent with a scenario where black hole growth predates bulge assembly and that bulges grow substantially in the last 6 Gyr – at least at this mass scale – if the local $M_{\text{BH}}-\sigma_*$ relation is the universal end-point of black hole-galaxy coevolution.

As discussed in paper I, collisional merging of late-type galaxies can drive the evolution of the $M_{\text{BH}}-\sigma_*$ relation. The mass and stellar velocity dispersion of the final spheroid will increase, not only by forming new stars but also transforming rotation-supported disk stars into pressure-supported spheroid components. This can potentially overcome the growth in $M_{\text{BH}}$ due to merging with the supermassive black hole of the companion, especially if the companion galaxy is not spheroid dominated.

In a galaxy merging scenario, the evolution of the $M_{\text{BH}}-\sigma_*$ relation could be mass-dependent, similarly to the downsizing trends in galaxy evolution (Cowie et al. 1996) and AGN evolution (Barger et al. 2005). As seen for example in fundamental plane studies (e.g. Treu et al. 2005, Woo et al. 2004, 2005), active and quiescent massive early-type galaxies have relatively old stellar populations in the redshift range considered here ($z \sim 0.4 – 0.6$).

Together with the results on the evolution of the mass function (e.g. Bundy et al. 2007), this is consistent with an early epoch of assembly for the most massive spheroids. Thus, the evolution of the $M_{\text{BH}}-\sigma_*$ relation could be mass dependent, slower at this redshift for the more massive galaxies (see Peng et al. 2006 for the $M_{\text{BH}}$-spheroid luminosity relation of massive high redshift galaxies, which show evolution in the same sense as our sample since $z<2$). Recently, Shen et al. (2008) present the $M_{\text{BH}}-\sigma_*$ relation out to $z \sim 0.4$ based on SDSS spectra, concluding that the offset (in the same direction as the one reported here) with redshift is not significant for their sample. However, since their 28 galaxies with measured $\sigma_*$ at $z>0.3$ have an average $S/N$=18.7 per pixel (and hence the S/N of the stellar spectrum is less than ~10 per pixel if the nuclear light fraction is ~50%) and $M_{\text{BH}}$ was based on the FWHM of H/3 line, direct comparison with our result is not straightforward. As discussed in paper II, the broad observational picture is far from conclusive at the moment, requiring larger samples over a wider mass range than the present sample to test this hypothesis.

It is important to consider selection effects. First, since our samples were selected based on the flux and width of the broad lines, they could be biased towards high $M_{\text{BH}}$ objects (paper II: see also Lauer et al. 2007b). However, as we showed in paper II with Monte Carlo simulations, this bias is too small to account for the observed offset, unless the intrinsic scatter of the $M_{\text{BH}}-\sigma_*$ relation at $z=0.57$ – which is unknown – is of order 1 dex. Second, although active galaxies are the only target for $M_{\text{BH}}$ estimation in the distant universe, they may not represent the general galaxy population, as they are rare objects with a highly accreting and radiatively efficient black hole. However, two pieces of evidence argue against the explanation of the observed evolution purely in terms of systematic differences between active and quiescent galaxies: i) a consistent $M_{\text{BH}}-\sigma_*$ relation is found locally for the two active galaxy samples; ii) the $M_{\text{BH}}-\sigma_*$ of distant active galaxies is offset from that of the local active sample.

An alternative or complementary explanation of the observed offset is that the $M_{\text{BH}}-\sigma_*$ relation is not tight for late-type galaxies, as perhaps suggested by the increasing scatter for local active samples, especially at the low mass end. This scenario is consistent with the idea of downsizing, with low mass blue late-type galaxies yet to join the more massive red early-type galaxies on the tight $M_{\text{BH}}-\sigma_*$ relation. So far, only a few late-type galaxies are included in the local quiescent galaxy sample that defines the local $M_{\text{BH}}-\sigma_*$ relation. A larger sample with more disk-dominant quiescent galaxies is needed to investigate any systematic difference in the local scaling relations.

This work is based on data collected at the Keck Observatory, operated by Caltech, UC, and NASA, and is made possible by the public archive of the Sloan Digital Sky Survey. T.T. acknowledges support from the NSF through CAREER award NSF-0642621, from the Sloan Foundation, and from the Packard Foundation. We acknowledge financial support from NASA through HST grant AR-10986. We thank C. Peng and M. Fava for useful discussions, L. Hao for providing the PCA algorithm, and the referee for useful suggestions.

<0.1 dex.

REFERENCES