Black Holes from Stars to Galaxies – Across the Range of Masses
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Cosmic evolution of black holes and galaxies to $z = 0.4$

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Abstract. We test the evolution of the correlation between black hole mass and bulge properties, using a carefully selected sample of 20 Seyfert 1 galaxies at $z = 0.36 \pm 0.01$. We estimate black hole mass from the Hβ line width and the optical luminosity at 5100Å, based on the empirically calibrated photo-ionization method. Velocity dispersion are measured from stellar absorption lines around Mgb (5175Å) and Fe (5270Å) using high S/N Keck spectra, and bulge properties (luminosity and effective radius) are measured from HST images by fitting surface brightness. We find a significant offset from the local relations, in the sense that bulge sizes were smaller for given black hole masses at $z = 0.36$ than locally. The measured offset is $\Delta \log M_\bullet = 0.62 \pm 0.10, 0.45 \pm 0.13, 0.59 \pm 0.19$, respectively for $M_\bullet - \sigma$, $M_\bullet - L_{\rm bulge}$, and $M_\bullet$–$M_{\rm bulge}$ relations. At face value, this result implies a substantial growth of bulges in the last 4 Gyr, assuming that the local $M_\bullet$–bulge property relation is the universal evolutionary end-point. This result is consistent with the growth of black holes predating the final growth of bulges at these mass scales ($\langle\sigma\rangle$=170 km s^{-1}).

Keywords. Black hole physics – galaxy evolution

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1. Introduction

The correlation of the mass of the central black Hole ($M_\bullet$) with the spheroid velocity dispersion σ (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000) links phenomena at widely different scales (from the pcs of the BH sphere of influence to the kpcs of the bulge). This connection between galaxy formation and Active Galactic Nuclei (AGNs) has inspired several unified formation scenarios (e.g. Kauffmann & Haenhelt 2000; Volonteri *et al.* 2003; Haiman, Ciotti & Ostriker 2004). One of the most powerful observational tests of the proposed explanations is to measure the evolution of empirical relations with redshift. Different scenarios – all reproducing the local $M_\bullet$–σ relation – predict different cosmic evolution. For example – for a fixed $M_\bullet$ – Robertson *et al.* (2005) predict an increase of σ with redshift, Croton (2006) predict a decrease, while the models of Granato *et al.* (2004) expect no evolution. Solid observational input is clearly needed to make progress. In this study, we test the evolution of the correlations between $M_\bullet$ and bulge properties, i.e. σ, luminosity, and mass, using a carefully selected sample of 20 Seyfert 1 galaxies at $z = 0.36 \pm 0.01$.

2. Sample selection

We selected relatively low luminosity AGNs where the fraction of stellar light in the integrated spectrum is non-negligible so that σ can be reliably measured. At the same time, virial $M_\bullet$ can be obtained from the integrated properties of the broad line region using the same spectrum.

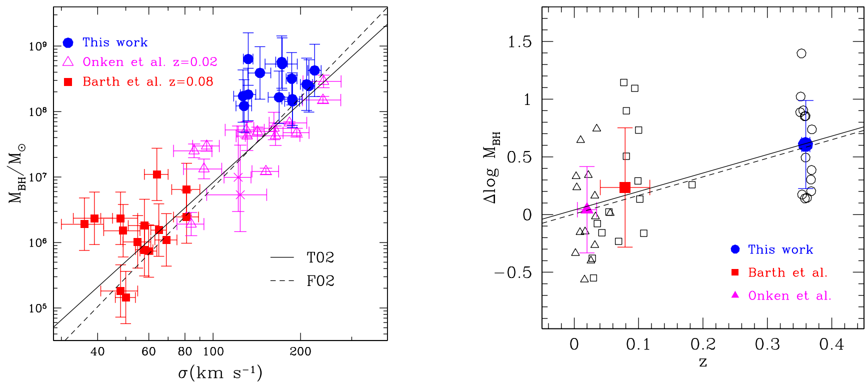

Figure 1. Left: The $M_\bullet$–σ relation of active galaxies. The symbols represent 14 Seyferts at $z = 0.36$ from this work (circles), 15 dwarf Seyfert galaxies at $z \sim 0.08$ from Barth et al. (2005; squares), 14 local AGNs with BH masses measured via reverberation mapping from Onken *et al.* (2004; triangles; two additional objects, excluded by Onken *et al.* and for consistency in our work, are shown as crosses). The local relationships of quiescent galaxies are shown for comparison as a solid (Tremaine *et al.* 2002) and dashed (Ferrarese 2002) line. Right: Offset from the local $M_\bullet$–σ relation. Large solid points with error bars represent the average and rms scatter for the three samples. The best linear fit to the data are shown as a solid line. The average offset of the $z = 0.36$ points is 0.62 ± 0.10 dex in $M_\bullet$. Note that $M_\bullet$ is estimated consistently with the same shape factor and therefore the relative position of the three samples along the y-axis is independent of the shape factor.

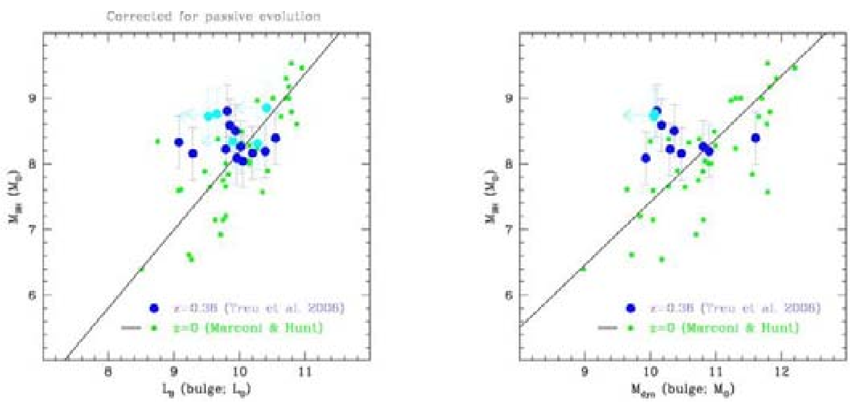

Figure 2. The $M_\bullet$–$L_{\rm bulge}$ (left) and the $M_\bullet$–$M_{\rm bulge}$ (right) relations at $z = 0.36$ are shown as blue circles (cyan circles are upper limits). The local relationship as measured by Marconi & Hunt (2003) is shown as solid line. The individual local points are shown as green squares. The bulges are found to be fainter or less massive at $z = 0.36$ for a fixed $M_\bullet$. The average offset from the local relation corresponds to 0.45 ± 0.13 dex and 0.59 ± 0.19 in $M_{\rm BH}$, respectively, consistent with that found from the $M_\bullet$–σ relation, 0.62 ± 0.10 dex.

In order to minimize the systematic uncertainties related to sky subtraction and atmospheric absorption corrections, it is convenient to select specific redshift windows where the relevant emission and absorption lines (Hβ, Mgb, and Fe) fall in clean regions of the Earth's atmosphere. Accordingly, we selected the "clean window" $z = 0.36 \pm 0.01$, which corresponds to a look-back time of ~ 4 Gyrs. Based on the redshift range and the width of Hβ, we selected 20 AGNs from the SDSS DR4 for this study (see Woo *et al.* 2006).

3. Measuring the $M_\bullet$–bulge property relations at $z = 0.36$

Estimating the black hole mass. To estimate $M_\bullet$, we adopt the latest calibrations (Onken *et al.* 2004; Kaspi *et al.* 2005) of the local reverberation mass shape factor of the $R_{\rm BLR}$–L_{5100} relationship:

$$M_\bullet = 2.15 \times 10^8 {\rm M}_\odot \times \left(\frac{\sigma_{\rm H\beta}}{3000 {\rm kms}^{-1}}\right)^2 \left(\frac{\lambda L_{5100}}{10^{44} {\rm ergs}^{-1}}\right)^{0.69} , \tag{3.1}$$

where $\sigma_{\rm H\beta}$ is the second moment of the Hβ line profile and L_{5100} is the monochromatic luminosity at 5100Å, in the rest frame. Based on comparisons of reverberation data and single-epoch data, it is estimated that the intrinsic uncertainty associated with this method is approximately a factor of 2.5, i.e. 0.4 dex, on the $M_\bullet$ (Vestergaard 2002). This uncertainty dominates the errors on our input quantities, $\sigma_{\rm H\beta}$ and L_{5100}, and we adopt it as our total uncertainty on the $M_\bullet$. We emphasize that when measuring the *evolution* of the $M_\bullet - \sigma$ relation, we will use the *same* shape factor for the local and distant sample, so that the specific choice of the shape factor is irrelevant.

The $M_\bullet$–σ relation. For 14 objects, reliable stellar velocity dispersions were measured from high S/N ratio spectra, obtained with the LRIS spectrograph at the Keck-I telescope. We used spectral regions including Mgb 5175Å and Fe 5270Å for comparing with stellar template. Figure 1 shows shows our $M_\bullet$–σ relation in comparison with the local relationship as measured by Tremaine *et al.* (2002) and by Ferrarese (2002). All objects in our sample are above the local relationship, that is smaller velocity dispersion for a fixed $M_\bullet$. In order to improve the measurement of the offset from the local relationship, we compare our sample with two samples of AGNs at lower redshift: the 14 reverberation mapped AGNs with mean redshift of 0.02 from Onken *et al.* (2004), and the 15 dwarf Seyfert galaxies with mean redshift of 0.08 from Barth *et al.* (2005). $M_\bullet$ of our sample and Barth *et al.* are consistently estimated using Eq. 3.1, which is calibrated on the reverberation masses (Onken *et al.* 2004). In other words, a change in the shape factor will move the three samples vertically by the same amount.

By design, the Onken *et al.* points straddle the local relationships. The Barth *et al.* points tend to lie preferentially above the local relationships with an average offset, of which the exact amount depends on the local slope. The $z = 0.36$ points are definitely above the local relationship. The offset is clearly detected and appears to increase with redshift. The average offset of our sample is 0.62 ± 0.10 dex in $M_\bullet$, corresponding to 0.15 ± 0.03 in $\Delta \log \sigma$.

$M_\bullet$–$L_{\rm bulge}$ and $M_\bullet - M_{\rm bulge}$ relations. High quality HST images were obtained for our sample (GO-10216; PI Treu) and used to measure host galaxy properties. Using the GALFIT program (Peng *et al.* 2002), we fit 3-4 components, point source, bulge, disk, and bar, at the same time and determine the best fit parameters (Treu *et al.* in preparation). Bulge luminosity is measured for 17 objects (including upper limits for 5 objects) while for 3 objects we could not determine reliable bulge properties due to the presence of dust lanes. We correct the passive evolution of luminosity due to the aging of stellar populations in order to compare our sample with the local sample. Combining the measured σ and the effective radius, we derive dynamical masses of bulges for 10 objects. Figure 2 shows $M_\bullet$ relation with bulge luminosity (left panel) and bulge mass (right panel), comparing with the local relations of quiescent galaxies from Marconi & Hunt (2003). For given $M_\bullet$, bulges at $z = 0.36$ are fainter than the local sample, with average offset 0.45 ± 0.13 dex in $M_\bullet$. Considering upper limits of luminosity for 5 objects, this offset could be a lower limit. A consistent result is found in the $M_\bullet$–$M_{\rm bulge}$ relation, which shows an average offset of 0.59 ± 0.19 dex in $M_\bullet$.

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4. Discussion and conclusions

All three relations between $M_\bullet$ and bulge properties show a significant offset from the local relationship. Three possible explanations are 1) systematic errors; 2) selection effects; 3) cosmic evolution. Systematic errors are unlikely to account for the offset, which is significantly larger than the overall systematic uncertainty ($\sim$ 0.2–0.3 dex). Selection effects could be present both in our sample (selected against low luminosity AGNs and thus small $M_\bullet$), and in the local sample (favoring more evolved systems), possibly resulting in the observed evolution of the $M_\bullet$–bulge property relation. Larger samples of AGNs with determined $M_\bullet$, σ, and host galaxy properties are needed both locally and at high-redshift to improve the understanding of selection effects. If cosmic evolution is the correct explanation, the observed offset would support earlier growths of supermassive BHs in galaxies with mass scales of $\langle\sigma\rangle$=170 km s^{-1}. This could be evidence for 'downsizing' in the BH-galaxy coevolution i.e. more massive galaxies arrive at the local relationship early in time. This scenario can be further investigated with a sample of AGN host galaxies with a range in mass at fixed redshifts.

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Deborah Dultzin-Hacyan: Some authors use the width of narrow lines such as [OIII] and [NII] lines as tracers of velocity dispersion. You have the data to check if this is correct.

Jong-Hak Woo: We find that depending on how [OIII] line is fitted (Gaussian fits, double-Gaussian, etc) σ_* derived from [OIII] show a systematic offset. Also, there is a large scatter between measured velocity dispersions and [OIII]-derived velocity dispersions as also other authors find.

Suzy Collin: Isn't there a contradiction with what we heard in a talk by Dr. Peng, namely, that there is evolution at $z \sim 4$ while you find no evolution below $z \sim 2$?

Jong-Hak Woo: I think the main reason for the difference between samples is the mass dependency. Peng's sample has more massive galaxies whereas our objects are about order of magnitude less massive. Perhaps by selecting more massive objects at low redshift would give similar results as the Peng's sample.