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CONSTRAINTS FROM GALAXY-AGN CLUSTERING ON THE CORRELATION BETWEEN GALAXY AND BLACK HOLE MASS AT REDSHIFT $2 \lesssim z \lesssim 3$[1]

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ABSTRACT

We use the clustering of galaxies around distant active galactic nuclei (AGNs) to derive an estimate of the relationship between galaxy and black hole mass that obtained during the ancient quasar epoch, at redshifts $2 \lesssim z \lesssim 3$, when giant black holes accreted much of their mass. Neither the mean relationship nor its scatter differs significantly from what is observed in the local universe, at least over the ranges of apparent magnitude ($16 \lesssim G_{AB} \lesssim 26$) and black hole mass ($10^6\ M_\odot \lesssim M_{BH} \lesssim 10^{10.5}\ M_\odot$) that we are able to probe.

Subject headings: galaxies: high-redshift — large-scale structure of universe — quasars: general

Online material: color figures

The study of black holes has been driven to the forefront of extragalactic research by the recent discovery of black holes as massive as a billion suns inside nearby bulge galaxies. Simple physical arguments (e.g., Silk & Rees 1998) suggest that these enormous objects should profoundly affect the process of galaxy formation, a belief that is strengthened by the tight observed correlation between the masses of local galaxies and their black holes (Gebhardt et al. 2000; Ferrarese & Merritt 2000). Various theoretical models attempt to explain the existence of the correlation with a wide range of physical processes. Since these models make discordant predictions for the evolution of the correlation over time, we decided to test them by measuring the relationship between galaxy and black hole mass in the distant past, at redshifts $2 < z < 3$.

A novel approach (see, e.g., Kauffmann & Haehnelt 2002) lets us use our existing surveys (Steidel et al. 2003, 2004) of ~1600 galaxies at redshifts $1.5 \lesssim z \lesssim 3$ to measure the dependence of galaxy mass M_h on black hole mass M_{BH} over a 5 decade baseline of black hole mass, reaching masses roughly 1000 times smaller than the limits of other surveys (e.g., Shields et al. 2003; Walter et al. 2004; Croom et al. 2005) at similar redshifts. After using the technique of Vestergaard (2002) to estimate the masses of the black holes that powered each of the 79 active galactic nuclei (AGNs) in our survey (see Fig. 1 and the Appendix), we estimated the typical halo mass for black holes in different mass ranges by measuring how strongly the other galaxies in our survey clustered around them.

Adelberger & Steidel (2005) describe our analysis in more detail. Briefly, we estimated the cross-correlation length r_0 from the number of galaxy-AGN pairs with angular separation $60'' < \theta < 300''$ and comoving radial separation $\Delta Z < 30\ h^{-1}$ Mpc with the approach of Adelberger (2005), and then used the GIF-LCDM numerical simulation (Kauffmann et al. 1999) of structure formation in a standard cosmological model[3] to estimate from r_0 the total (dark matter plus baryon) mean mass M_h of the galaxies associated with black holes in each mass range. The relationship between r_0 and M_h depends on the redshift and on the mass of the typical (nonactive) galaxies in our survey, but the resulting systematic errors in M_h are much smaller than the random errors (Fig. 2).

We found galaxy-AGN cross-correlation lengths of $r_0 = 5.27^{+1.59}_{-1.36}$ for the 38 AGNs with $10^{5.8}\ M_\odot < M_{BH} < 10^8\ M_\odot$ and $r_0 = 5.20^{+1.85}_{-1.16}$ for the 41 AGNs with $10^8\ M_\odot < M_{BH} < 10^{10.5}\ M_\odot$. The inferred relationship between $\log M_{BH}$ and $\langle \log M_h \rangle$ is shown in Figure 3.

If the predicted relationship between galaxy and black hole mass has the form $\log M_{BH} = f(\log M_h) + \epsilon$, with f a function to be specified and ϵ a random deviate, the expectation value of $\log M_h$ for a given value of $\log M_{BH}$ follows from the elementary relationship

$$E(l_h|l_{BH}) = \frac{\int_{-\infty}^{\infty} dl_h\, l_h P(l_h) P(l_{BH}|l_h)}{\int_{-\infty}^{\infty} dl_h\, P(l_h) P(l_{BH}|l_h)}, \quad (1)$$

where $l_h \equiv \log M_h$, $l_{BH} \equiv \log M_{BH}$, $P(l_h)$ is the distribution of $\log M_h$ measured in the GIF-LCDM simulation and extrapolated with the appropriate Press-Schechter (1974) formula, and $P(l_{BH}|l_h)$ is the distribution of $\log M_{BH}$ at fixed galaxy mass, which depends on f and on the characteristics of the random variable ϵ. Solving equation (1) numerically for different functions f under the assumption that ϵ has a normal distribution with rms σ_ϵ, we find the theoretical tracks shown in Figure 3.

The solid line is for a M_{BH}-M_h relationship identical to the one observed locally, $\log (M_{BH}/10^7\ M_\odot) = 1.65 \log (M_h/10^{12}\ M_\odot) + \epsilon$ (Ferrarese 2002). For this line we assumed $\sigma_\epsilon = 0.5$, roughly the expected error in our black hole masses (Vestergaard 2002). The line therefore assumes negligible intrinsic scatter in the correlation. It fits the data well.

The other lines show that alternative relationships in the literature generally provide a worse fit. The dashed line in Figure 3 results from scaling the ratio of black hole to galaxy mass by $(1 + z)^{5/2}$, as advocated by many semianalytic models (e.g., Haehnelt et al. 1998; Wyithe & Loeb 2002; Volonteri et al. 2003). The dash-dotted line shows the redshift $z = 3$ pre-

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[3] $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $\sigma_8 = 0.9$, $\Gamma = 0.21$.

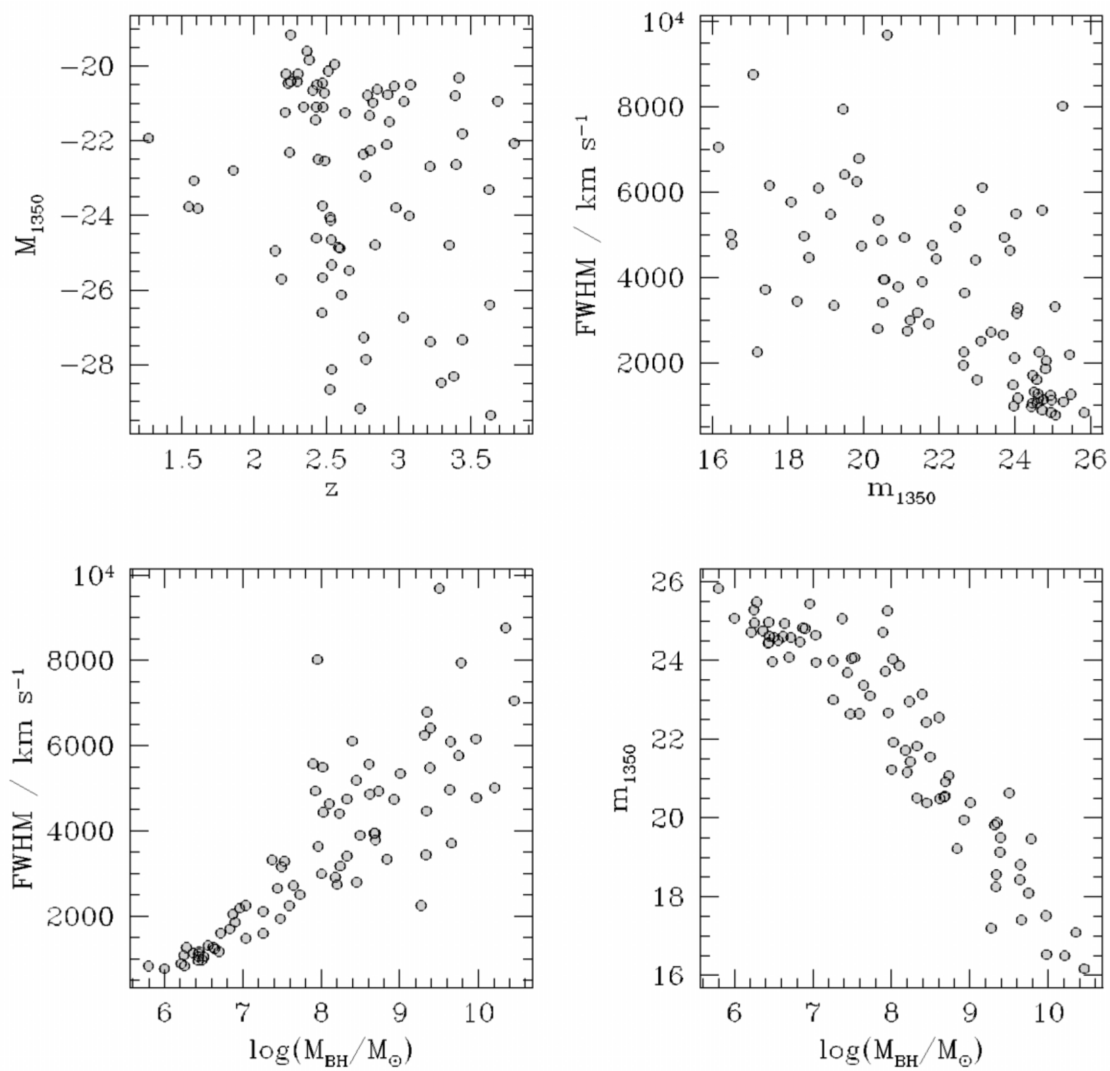

FIG. 1.—Overview of the characteristics of the AGNs in our sample. *Upper left:* Redshifts and absolute AB magnitude at rest frame 1350 Å. The uncertainty in the AB magnitude is $\lesssim 0.2$ mag for even our faintest objects (e.g., Steidel et al. 2003). *Upper right:* Relationship between C IV line width and apparent AB magnitude at rest frame 1350 Å. The uncertainty in line width ranges from 10% to 20% and is dominated by systematics (e.g., continuum placement) for the brightest AGNs. *Lower panels:* Relationship between C IV line width, m_{1350}, and the resulting estimate of black hole mass $M_{\rm BH}$. The selection bias is severe in our AGN sample, since (for example) we deliberately targeted AGNs that were bright and had broad emission lines. These panels show the characteristics of our sample as selected, not of a fair sample of high-redshift AGNs.

diction $M_{\rm BH}/M_\odot = 6.2 \times 10^7 (M_h/10^{12}\ M_\odot)^{1.033}$ of a model in which black holes accrete a fixed fraction of the total gas mass in each merger (Di Matteo et al. 2003). The dotted line assumes that the mean $M_{\rm BH}$-M_h relationship is the same as observed locally but that its intrinsic scatter has increased to 1.0 dex. Increasing the scatter decreases the typical mass of galaxies that contain black holes of a given mass. This is because galaxies with low masses are much more common than galaxies with high masses; when the scatter in the $M_{\rm BH}$-M_h relationship is big, the largest black holes are more likely to reside in low-mass galaxies with unusual ratios of $M_{\rm BH}$ to M_h than in high-mass galaxies with normal ratios. The clustering of galaxies around AGNs would therefore be far weaker than we observe if there were no relationship at all between $M_{\rm BH}$ and M_h.

A χ^2 test suggests that the three alternatives to the no-evolution model [$(1 + z)^{5/2}$ scaling, supply-limited accretion, large σ_ϵ] disagree with the observations at the 90%–95% level. They can therefore be considered marginally consistent with our present data, although the odds are against them. More extreme evolution from the local relationship (e.g., Haehnelt & Rees 1993) can be ruled out with high significance.

The apparent lack of evolution in the $M_{\rm BH}$-M_h correlation seems consistent with models in which the correlation results from active feedback from the black hole. In these models the black hole mass is pinned near the maximum allowed by its halo at all times. If this maximum is set by the escape velocity at a fixed proper radius from the black hole, it will not depend strongly on redshift. One might object that black holes are able to enter the quasar phase in these models only because their masses have temporarily fallen below the maximum allowed by their growing halos, and so the most luminous AGNs should never lie on the correlation. As long as the quasar phase occurs near the end of the accretion, however (e.g., Hopkins et al. 2005), the black hole should have nearly achieved its equilibrium mass. In any case, a slight decrease in $M_{\rm BH}$ at fixed M_h would make the predictions fit our data even better.

It is a pleasure to acknowledge several interesting conver-

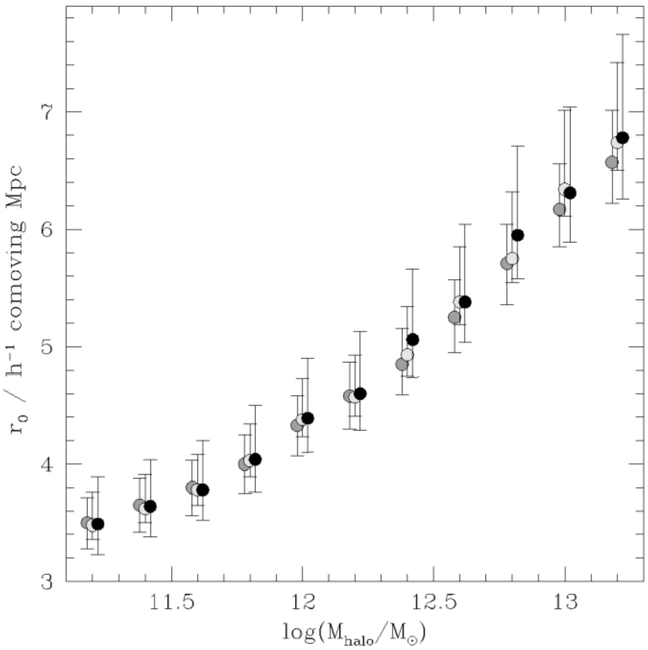

FIG. 2.—Relationship between cross-correlation length r_0 and implied mass of the black holes' galaxies at redshifts $2 \lesssim z \lesssim 3$. The black, light gray, and dark gray points show the dependence of r_0 on M_h in the GIF-LCDM simulation (Kauffmann et al. 1999) at redshifts $z = 2.97$, 2.74, and 2.32. Small offsets have been added to the abscissae for clarity. The relationship is somewhat uncertain because it depends on the assumed masses of the halos that contain nonactive galaxies. Error bars show the 1 σ uncertainty in the relationship that results from the uncertainty in the masses of the nonactive galaxies. [*See the electronic edition of the Journal for a color version of this figure.*]

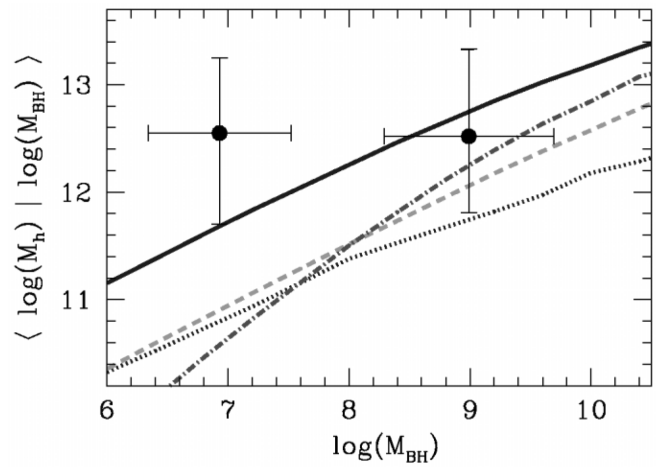

FIG. 3.—Observed and expected relationship between black hole and halo mass (in solar units) at redshift $z \sim 2.5$. The ordinate is $\langle \log M_h | \log M_{BH} \rangle$, the mean value of $\log M_h$ for a given value of $\log M_{BH}$. Points show our observations. Vertical error bars show the 1 σ random uncertainty. Horizontal error bars show the mean and rms value of $\log M_{BH}$ for the two groups of black holes. Lines show theoretical predictions. *Solid line:* No evolution in mean M_{BH}-M_h relationship, with negligible intrinsic scatter. We adopt eq. (6) of Ferrarese (2002) for the local relationship, but her two alternatives fit our observations comparably well. *Dotted line*: No evolution, with 1 dex of scatter in M_{BH} at fixed M_h. *Dashed line*: Local relationship scaled by $(1 + z)^{5/2}$. *Dash-dotted line*: Relationship at $z = 3$ in a supply-limited accretion model (Di Matteo et al. 2003). Observations at large M_{BH} agree with any of these scenarios, as has also been noted by Shields et al. (2003) and Walter et al. (2004). Our small-M_{BH} data help us to distinguish between them. [*See the electronic edition of the Journal for a color version of this figure.*]

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APPENDIX

TECHNICAL DETAILS

The general population of galaxies tends to cluster more strongly around individual galaxies with larger masses. We exploit this effect to estimate the masses of the galaxies that harbor black holes. After estimating the characteristic mass M_g of the general galaxy population from its measured correlation length (Adelberger et al. 2005), we use the GIF-LCDM simulation to calculate as a function of M_h how strongly galaxies of mass $M > M_g$ cluster around galaxies of mass $M > M_h$. We infer the masses of the galaxies that harbor various black holes by finding the value of M_h required to match the observed cross-correlation length r_0. Figure 2 shows the relationship we used to estimate from our measured cross-correlation length r_0 the typical mass of the galaxies containing the black holes (light gray points). Adopting other plausible relationships between r_0 and M_h would change the inferred masses by less than their random uncertainties. Percival et al. (2003) and Kauffmann & Haehnelt (2002) have shown that halos undergoing mergers have the same correlation length on large scales as other halos of the same mass, so our estimates of r_0 should provide reasonable estimates of the halos masses even if AGNs are fueled by mergers.

To estimate the random uncertainty in r_0, we took a Monte Carlo approach that exploited the similarity of the AGN-galaxy cross-correlation length to the galaxy-galaxy correlation length. We generated many alternate realizations of our data by treating randomly chosen galaxies in each field as that field's AGNs, rather than the true AGNs themselves, and recalculated r_0 for each simulated sample. Since the galaxies in our survey outnumber the AGNs by more than 20 to one, the simulated samples are nearly independent of each other and of the true sample. We took the rms spread in r_0 among them as the 1 σ uncertainty in our measured correlation length r_0^{obs}. The distribution of $\chi^2 \equiv \sum [(r_0^{obs} - r_0^{pred})/\sigma_{r_0}]^2$ for the predicted values of r_0 in Figure 3 should be roughly equal to the distribution of χ^2 in the simulated samples around the line $r_0^{pred} = \text{constant} = r_0^{gg}$, where r_0^{gg} is the galaxy-galaxy correlation length in our sample. We used this distribution to associate our measured values of χ^2 with a P-value.

Our conclusion depends on the assumption that the estimated black hole masses M_{BH} are not wildly inaccurate. We estimate

M_{BH} from an AGN's luminosity $l \equiv \lambda L_\lambda$ at $\lambda = 1350$ Å and C IV line width FWHM with the relationship that is observed in the local universe: $M_{BH}/M_\odot \simeq 10^{6.2}(l/10^{44}\ \mathrm{ergs\ s^{-1}})^{0.7}(\mathrm{FWHM}/1000\ \mathrm{km\ s^{-1}})^2$ (Vestergaard 2002). Correcting for a stellar contribution to the AGNs' luminosities (which we have not done) would decrease our lowest observed values M_{BH} even further, strengthening our conclusions. Our estimated black hole masses would be too low for some AGNs with small M_{BH} if their observed C IV emission line were produced in the narrow-line region rather than the broad-line region (as we assume). In this case the line widths would be roughly equal to the galaxies' stellar velocity dispersions (Nelson 2000), at least for radio-quiet AGNs, but in fact the galaxies' mean stellar velocity width ($\sim$200 km s^{-1}) is an order of magnitude smaller than the mean AGN line width for $M_{BH} < 10^8\ M_\odot$ (2100 km s^{-1}) or $M_{BH} > 10^8\ M_\odot$ (4900 km s^{-1}). It is far smaller than even the smallest observed AGN line width in our sample, 800 km s^{-1}. Radio-loud AGNs make up too small a fraction of our sample to affect our results if omitted. In any case, the observed range of M_{BH} is so large that our estimates of M_{BH} would have to be wrong by $\sim$1 order of magnitude to alter our results significantly. We cannot rule out the idea that the relationship between M_{BH}, luminosity, and line width was utterly different in the past, but it seems easier to believe that the relationship between M_{BH} and M_h has not changed at all.

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