CONSTRAINTS FROM GALAXY-AGN CLUSTERING ON THE CORRELATION BETWEEN GALAXY AND BLACK HOLE MASS AT REDSHIFT 2 ≤ z ≤ 3

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Received 2005 April 24; accepted 2005 May 25; published 2005 June 14

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 ≤ z ≤ 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 ≤ GAB ≤ 26) and black hole mass (10^6 M☉ ≤ MBH ≤ 10^{10.5} M☉) 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 existence of the correlation with a wide range of physical processes. Since these models make discordant predictions for the mass in the distant past, at redshifts .2

We found galaxy-AGN cross-correlation lengths of r0 = 5.27^{+1.59}_{-1.36} for the 38 AGNs with 10^{8} M☉ < MBH < 10^{9} M☉ and r0 = 5.20^{+1.16}_{-1.16} for the 41 AGNs with 10^{9} M☉ < MBH < 10^{10.5} M☉. The inferred relationship between log MBH and (log M*) is shown in Figure 3.

If the predicted relationship between galaxy and black hole mass has the form log MBH = f(log M*) + ε, with f a function to be specified and ε a random deviate, the expectation value of log M* for a given value of log MBH follows from the elementary relationship

\[ E(l_\text{p}|l_{\text{BH}}) = \frac{\int_{-\infty}^\infty dl_\text{p} P(l_\text{p})P(l_{\text{BH}}|l_\text{p})}{\int_{-\infty}^\infty dl_{\text{BH}} P(l_{\text{BH}})}, \quad (1) \]

where l_\text{p} = log M*, l_{\text{BH}} = log MBH, P(l_\text{p}) is the distribution of log M*, measured in the GIF-LCDM simulation and extrapolated with the appropriate Press-Schechter (1974) formula, and P(l_{\text{BH}}|l_\text{p}) is the distribution of log MBH 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, we find the theoretical tracks shown in Figure 3.

The solid line is for a MBH-M* relationship identical to the one observed locally, log (MBH/10^7 M☉) = 1.65 log (M*/10^7 M☉) + ε (Ferrarese 2002). For this line we assumed σ = 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)^{0.2}, 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-
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 ±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 \( M_{\text{BH}} \). 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.

\[
M_{\text{BH}} = 6.2 \times 10^7(M_* / 10^{12} M_\odot)^{0.03}
\]

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 \( M_{\text{BH}}^* - M_* \) 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 \( M_{\text{BH}}^* - M_* \) relationship is big, the largest black holes are more likely to reside in low-mass galaxies with unusual ratios of \( M_{\text{BH}}^* \) to \( M_* \) 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 \( M_{\text{BH}}^* \) and \( M_* \).

A \( \chi^2 \) test suggests that the three alternatives to the no-evolution model \([ (1 + z)^{3/2} \text{ scaling, supply-limited accretion, large } q_e ] \) 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 \( M_{\text{BH}}^* - M_* \) 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 \( M_{\text{BH}}^* \) at fixed \( M_* \) would make the predictions fit our data even better.

It is a pleasure to acknowledge several interesting conver-
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 $M_\star$ 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 $M_\star$ how strongly galaxies of mass $M > M_\star$ cluster around galaxies of mass $M > M_\star$. We infer the masses of the galaxies that harbor various black holes by finding the value of $M_\star$ 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 $M_\star$ 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 if that field’s AGNs, rather than the true AGNs themselves, and recalculated 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 1σ uncertainty in our measured correlation length $r_0^{\text{obs}}$. The distribution of $\chi^2 = \sum (r_0^{\text{obs}} - r_0^{\text{pred}})^2/\sigma_0^2$ for the predicted values of $r_0$ in Figure 3 should be roughly equal to the distribution of $\chi^2$ in the simulated samples around the line $r_0^{\text{pred}} = \text{constant} = r_0^{\text{ref}}$, where $r_0^{\text{ref}}$ is the galaxy-galaxy correlation length in our sample. We used this distribution to associate our measured values of $\chi^2$ with a P-value.

Our conclusion depends on the assumption that the estimated black hole masses $M_{\text{BH}}$ are not wildly inaccurate. We estimate supported by a fellowship from the Carnegie Institute of Washington; C. C. S. was supported by grant AST 03-07263 from the National Science Foundation and by a grant from the Packard Foundation. We are grateful that the people of Hawaii allow astronomers to build and operate telescopes on the summit of Mauna Kea.

**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 $M_\star$ 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 $M_\star$ how strongly galaxies of mass $M > M_\star$ cluster around galaxies of mass $M > M_\star$. We infer the masses of the galaxies that harbor various black holes by finding the value of $M_\star$ 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 $M_\star$ 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.

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$M_{\text{BH}}$ 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: $M_{\text{BH}}/M_\odot = 10^{4.2}(l/10^{44} \text{ ergs s}^{-1})^{0.7}(\text{FWHM/1000 km s}^{-1})^2$ (Vestergaard 2002). Correcting for a stellar contribution to the AGNs’ luminosities (which we have not done) would decrease our lowest observed values $M_{\text{BH}}$ even further, strengthening our conclusions. Our estimated black hole masses would be too low for some AGNs with small $M_{\text{BH}}$ 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 $M_{\text{BH}} < 10^8 M_\odot$ (2100 km s$^{-1}$) or $M_{\text{BH}} > 10^9 M_\odot$ (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 $M_{\text{BH}}$ is so large that our estimates of $M_{\text{BH}}$ 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 $M_{\text{BH}}$, luminosity, and line width was utterly different in the past, but it seems easier to believe that the relationship between $M_{\text{BH}}$ and $M_\star$ has not changed at all.

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