Evolution of the Black Hole – Bulge Relationship in QSOs

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Abstract

QSOs allow study of the evolution of the relationship between black holes in galactic nuclei and their host galaxies. The black hole mass $M_{\text{BH}}$ can be derived from the widths of the broad emission lines, and the stellar velocity dispersion $\sigma_*$ of the host galaxy can be inferred from the narrow emission lines. Results based on [O iii] and [O ii] line widths indicate that the $M_{\text{BH}} - \sigma_*$ relationship, at redshifts up to $z \approx 2$, is consistent with no evolution or an increase of up to $\sim 0.5$ dex in $M_{\text{BH}}$ at fixed $\sigma_*$. CO line widths offer an estimate of $\sigma_*$ for luminous QSOs at high redshifts. The available objects from $z \approx 4$ to 6 have very massive black holes, $M_{\text{BH}} \sim 10^{9.5} \, M_\odot$, but their CO line widths suggest much smaller host galaxies than would be expected by the local $M_{\text{BH}} - \sigma_*$ relationship. The most massive black holes must continue to reside in comparatively modest galaxies today, because their number density inferred from QSO statistics exceeds the present-day abundance of proportionally massive galaxies.

Key words: galaxies: active galactic nuclei, supermassive black holes

1. Introduction

The study of black hole demographics has added a new dimension to research involving active galactic nuclei (AGN). This is rooted in two developments of recent years. The first is the availability of measurements of supermassive black holes in nearby galaxies, involving observations of stellar and gaseous motions with HST along with other techniques (reviews by Kormendy & Gebhardt 2001; Ferrarese & Ford 2004; Combes 2005). This has led to the realization that $M_{\text{BH}}$ is closely correlated with the luminosity and especially the velocity dispersion of the bulge component of the host galaxy (Gebhardt et al. 2000; Ferrarese & Merritt 2000).

The local $M_{\text{BH}} - \sigma_*$ relationship is given by Tremaine et al. (2002) as

$$M_{\text{BH}} = (10^{8.13} \, M_\odot)(\sigma_*/200 \, \text{km s}^{-1})^{4.02}. \quad (1)$$

The rms dispersion of only $\sim 0.3$ in log $M_{\text{BH}}$ in this relationship suggests a fundamental connection between the evolution of supermassive black holes and their host galaxies. The formation and evolution of supermassive black holes has become a focus of theoretical study (review by Haiman & Quataert 2004; Croton 2005, and references therein).

The second development is the ability to estimate $M_{\text{BH}}$ in AGN based on evidence that the broad emission lines come from gas orbiting the black hole at a radius that can be estimated from the continuum luminosity (Kaspi et al. 2005, and references therein). Central black hole masses in AGN can easily be estimated in this fashion, al-
lowing demographic studies and providing insight into AGN physics. Results below assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. Black Holes in QSOs

Direct measurements of nuclear black holes, based on spatially resolved measurements of the velocities of stars and gas within the gravitational sphere of influence of the hole, are limited to nearby objects with negligible look-back times. QSOs afford an opportunity to study the $M_{BH} - \sigma_*$ relationship as a function of cosmic time. However, this requires a measurement of the luminosity or velocity dispersion of the host galaxy in addition to the black hole mass. The host galaxy luminosity and the stellar velocity dispersion are difficult to measure directly at high redshift, given the glare of the active nucleus. An alternative approach is to estimate $\sigma_*$ through the use of some surrogate involving emission lines of gas orbiting in the host galaxy.

Nelson & Whittle (1996) found that, on average, the width of [O iii] tracks the stellar velocity dispersion, $\sigma_{[O \text{ iii}]} \equiv \text{FWHM}([\text{O iii}])/2.35 \approx \sigma_*$. This is supported by the agreement of $M_{BH}$ and $\sigma_{[O \text{ iii}]}$ in nearby AGN with the local $M_{BH} - \sigma_*$ relationship (Nelson 2000). Further support comes from the study of Bonning et al. (2005), who found overall agreement between $\sigma_{[O \text{ iii}]}$ in low redshift QSOs and the value of $\sigma_*$ implied by the measured host galaxy luminosity and the Faber-Jackson relation. The rms scatter is $\sim 0.13$ in log $\sigma_{[O \text{ iii}]}$ at fixed host luminosity. This suggests that $\sigma_{[O \text{ iii}]}$ may be a useful proxy for $\sigma_*$ in statistical studies, although not for individual objects.

Shields et al. (2003) carried out such a program using the narrow [O iii] $\lambda 5007$ emission line of QSOs. They collected measurements of the widths of the broad H$\beta$ line and narrow [O iii] line in QSOs ranging in redshift from $z < 0.1$ to $z = 3.3$. Black hole masses were derived from the expression

$$M_{BH} = (10^{7.69} M_{\odot}) v_{3000}^2 L_{44}^{0.5}, \quad (2)$$

where $v_{3000} \equiv \text{FWHM}(H\beta)/3000$ km s$^{-1}$ and $L_{44} \equiv \nu L_\nu/\left(10^{44} \text{ erg s}^{-1}\right)$, the continuum luminosity at 5100 Å, based on Kaspi et al. (2000). They expressed their results in terms of the deviation of an object’s actual $M_{BH}$ from the value $M_\nu$ expected on the basis of Equation 1 using $\sigma_{[O \text{ iii}]}$. We follow their use of $\Delta \log M_{BH} \equiv \log M_{BH} - \log M_\nu$. Figure 1 shows the results for $\Delta \log M_{BH}$ as a function of redshift. There is considerable scatter, but overall the objects show little systematic offset from Equation 1 as a function of redshift. Shields et al. concluded that $M_{BH}$ at $z \sim 2$ differs by less than 0.5 dex from the present day value expected for a given $\sigma_*$. However, the high redshift objects have larger masses ($M_{BH} \approx 10^{9.6} M_{\odot}$) than the low redshift objects ($\sim 10^{8.3} M_{\odot}$), so the evolutionary comparison involves some disparity in mass.

Salviander et al. (2006; see also these proceedings) used these methods to assess the evolution of the $M_{BH} - \sigma_*$ relationship in the QSOs in Data.
Release 3 (DR3) of the Sloan Digital Sky Survey\(^1\) (SDSS; Abazajian et al. 2005). They used H\(\beta\) and [O\(\text{iii}\)] for redshifts up to 0.8, and the broad Mg\(\text{ii}\) \(\lambda2800\) and narrow [O\(\text{ii}\)] \(\lambda3727\) emission lines to reach redshifts up to 1.2. Their results, included in Figure 1, nominally show a rise of \(\sim 0.5\) in \(\Delta \log M_{\text{BH}}\) from \(z \sim 0.3\) to \(z \sim 1.0\). However, they show that two sources of bias contribute to this apparent evolution. (1) The scatter in the local \(M_{\text{BH}} - \sigma_*\) relationship causes some galaxies to harbor exceptionally large black holes. If these are fueled in proportion to their mass, their high luminosities cause them to be over-represented in the QSO sample. (2) There is a tendency in data of these, we have measured the CO line width from the broad Mg\(\text{ii}\) and [C\(\text{iv}\)] lines to assess the \(M_{\text{BH}} - \sigma_*\) relationship in QSOs up to \(z = 6.4\). They find large black holes \(\sim 10^{9.5} M_\odot\) that are at least an order of magnitude larger than expected for the CO line width (see Figure 1). These giant black holes in the early universe evidently reside in comparatively modest galaxies, as found for the case of SDSS J1148+5251 \((z = 6.4)\) by Walter et al. (2005).

Figure 1 summarizes a variety of measurements of \(\Delta \log M_{\text{BH}}\) as a function of redshift. Included are a number of \(z \sim 2\) QSOs from Netzer et al. (2004) and Shemmer et al. (2004), as selected by Bonning et al. (2005). The six radio-loud objects have a mean \(\Delta \log M_{\text{BH}}\) of \(-0.4\). Also shown are nine QSOs from the study of Sulentic et al. (2004). For these, we have measured the [O\(\text{iii}\)] width from the VLT spectra of Sulentic et al., kindly provided by P. Marziani (personal communication). We made a direct measurement of the FWHM of the \(\lambda5007\) line for those objects having adequate [O\(\text{iii}\)] intensity and not having excessive [Fe\(\text{ii}\)] emission, keeping nine of 17 objects. We measured the continuum flux at 5100 Å rest wavelength from the spectra, derived the luminosity (for our cosmology), and calculated \(M_{\text{BH}}\) from Equation 2 (see text). Absolute luminosity \(\nu L_\nu\) is given at rest wavelength \(\lambda 5100\) for our adopted cosmology.

### Table 1

| QSO     | \(z\) | \(\log \sigma_{\text{[O III]}\text{*}}\) | \(\log \nu L_\nu\) | \(\log M_{\text{BH}}\) | \(\Delta \log M_{\text{BH}}\) |
|---------|-------|-----------------|-------------------|-----------------|------------------|
| HE 0003 | 1.077 | 2.41            | 46.12             | 9.26            | 0.68             |
| HE 0005 | 1.412 | 2.73            | 46.25             | 9.40            | -0.45            |
| HE 0048 | 0.847 | 2.41            | 45.49             | 9.23            | 0.64             |
| HE 0248 | 1.536 | 2.76            | 47.49             | 9.73            | -0.25            |
| HE 0331 | 1.115 | 2.34            | 46.40             | 9.41            | 1.11             |
| HE 0454 | 0.853 | 2.18            | 45.83             | 8.71            | 1.06             |
| HE 2340 | 0.922 | 2.34            | 46.18             | 9.07            | 0.77             |
| HE 2349 | 1.604 | 2.83            | 46.36             | 9.35            | -0.91            |
| HE 2355 | 2.382 | 2.67            | 46.71             | 9.77            | 0.15             |
| Average | 1.305 | 2.52            | 46.31             | 9.33            | 0.31             |

### 3. Does [O\(\text{iii}\)] track \(\sigma_*\) in AGN?

We noted above some indications that \(\sigma_{\text{[O III]}\text{*}}\) may be a useful surrogate for \(\sigma_*\) in a statistical sense. Figure 2, based on Bonning et al. (2005), compares \(\sigma_{\text{[O III]}\text{*}}\) with \(\sigma_*\) in a wide variety of AGN. Because of the scatter in \(\sigma_{\text{[O III]}\text{*}}\) at fixed \(\sigma_*\), a wide dynamic range in \(\sigma_*\) is needed to clarify the overall trend. For lower luminosity AGN (Seyfert galaxies), direct measurements of \(\sigma_*\) are used. For QSOs, in which \(\sigma_*\) is difficult to measure, \(\sigma_*\) is inferred from \(M_{\text{BH}}\) and Equation 1. We include here the VLT results of Table 1 and, at very low \(\sigma_*\) the

\(^1\) The SDSS Web site is [http://www.sdss.org/](http://www.sdss.org/).
consistent with the idea that universe, and the implied values of $\sigma$ for details and references. This figure follows Bonning et al. (2004) and the VLT data from Table 1. See Bonning et al. for narrow-line Seyfert galaxies from SDSS. They find of several narrow emission lines in a sample of dwarf Seyfert galaxy POX 52 (Barth et al. 2004). There is a clear trend of increasing $\sigma_{\text{O III}}$ with $\sigma_*$, consistent with the idea that $\text{[O III]}$ is a valid, if noisy, surrogate.

Greene & Ho (2005) compare $\sigma_*$ with the widths of several narrow emission lines in a sample of narrow-line Seyfert galaxies from SDSS. They find that $\sigma_{\text{O II}}$ agrees in the mean with $\sigma_*$. However, $\sigma_{\text{O III}}$ exceeds $\sigma_*$ by $\sim 0.13$ dex unless a correction is made for the extended blue wing of the $\text{[O III]}$ profile. In contrast, Salviander et al. (2006) find that $\sigma_{\text{O III}}$ and $\sigma_{\text{O II}}$ agree within a few hundredths of a dex in their sample of SDSS QSOs, without any correction for the blue wing. It is important to clarify the effect of the blue wing on $\sigma_{\text{O III}}$ in various classes of AGN, and how best to correct for it.

4. Homelessness Amongst the Largest Black Holes

Several authors have noted that the largest black hole masses, inferred in the most luminous QSOs from broad line widths or the Eddington limit, exceed the largest values of $M_{\text{BH}}$ found in the local universe, and the implied values of $\sigma_*$ by Equation 1 exceed the largest $\sigma_*$ values in galaxies (Netzer 2003; Wyithe & Loeb 2003; Shields & Gebhardt 2004). If the black hole masses are correct, this implies a breakdown of the local $M_{\text{BH}} - \sigma_*$ relationship at high $M_{\text{BH}}$.

McLure & Dunlop (2004), in a study of SDSS QSOs, find values of $M_{\text{BH}}$ up to $\sim 10^{10}$ $M_{\odot}$, but they dismiss the largest values as resulting from the scatter in deriving $M_{\text{BH}}$ from expressions like Equation 2. Thus they conclude that black holes in QSOs are consistent with the maximum mass $M_{\text{BH}} \sim 10^{9.5}$ $M_{\odot}$ found in giant elliptical galaxies, such as M87 (Tremaine et al. 2003). There is indeed scatter in the BLR radius as a function of luminosity (Kaspi et al. 2000), which underlies Equation 1. However, we argue here that the large values of $M_{\text{BH}}$ in the most luminous quasars are likely real.

In the QSO sample of Shields et al. (2003), there are eight radio-quiet objects with $\log \nu L_\nu(5100) \geq 46.6$; and of these, five have $\log M_{\text{BH}} \geq 9.7$, substantially exceeding the largest $M_{\text{BH}}$ in local galaxies. Here we are dealing with a majority of the objects of a class selected by a criterion that does not involve the scatter in Equation 2. Thus, one cannot appeal to scatter to dismiss the large values. These six objects have an average $\log L/L_{\text{Ed}} \approx -0.1$, suggesting that $M_{\text{BH}}$ cannot be much less than derived from the H$\beta$ width.

What is the present-day density of these giant black holes? From the QSO luminosity function of Boyle et al. (2003), we estimate the space density of QSOs with $\log \nu L_\nu(5100) > 46.6$ to be $\sim 6$ Gpc$^{-3}$ (comoving) at $z = 2$. Since they are nearly at the Eddington limit, we take their lifetime to be the Salpeter e-folding time of 50 million years (efficiency $0.1 c^2$). Applying the above fraction of 5/8 and taking an effective QSO epoch of 3 billion years (Warren, Hewitt, & Osmer 1994), we find the density of relic black holes over 5 billion $M_{\odot}$ to be $\sim 10^{2.3}$ Gpc$^{-3}$.

By the local $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - M_{\text{bulge}}$ relationships (Kormendy & Gebhardt 2001), a black hole of 5 billion $M_{\odot}$ corresponds to $\sigma_* \approx 500$ km s$^{-1}$ and $M_{\text{bulge}} \approx 10^{12.6}$ $M_{\odot}$. The largest local giant ellipticals (e.g., M87) have $\sigma_* \approx 350$ km s$^{-1}$ (Faber et al. 1997), and the velocity dispersion function of SDSS galaxies ends at $\sim 400$ km s$^{-1}$ (Sheth et al. 2003). Bernardi et al. (2006) find only two or three candidate galax-
ies in SDSS with $\sigma_*> 500$ km s$^{-1}$ in a volume $\sim 0.5$ Gpc$^3$ among the objects for which they find the evidence for superposition to be weakest. The nearest black hole with mass $\geq 10^{9.7} M_\odot$ should be at a distance of $\sim 100$ Mpc and redshift of $\sim 7000$ km s$^{-1}$. Wyithe (2006) and Wyithe & Loeb (2003) reach a similar conclusion based on the assumption that the most luminous QSOs shine at the Eddington limit. This distance corresponds to the largest cD galaxies, such as NGC 6166 in Abell 2199 and NGC 7720 in Abell 2634. Such galaxies may be a logical place to look for a 5 billion solar mass hole. However, such a black hole in NGC 6166 or NGC 7720 would violate Equation 1, since these galaxies have central velocity dispersions $\sim 350$ km s$^{-1}$ (Tonry 1984).

The space density of galaxy clusters with $\sigma_*> 500$ km s$^{-1}$ (Bahcall et al. 2003) exceeds by an order of magnitude our derived density of black holes over 5 billion solar masses. Ample dark matter halos at this velocity dispersion exist in the modern universe, but not individual galaxies. Evidently, at this value of $\sigma_*$, the physics of baryon assembly is such that giant black holes can form in the early universe but the growth of their host galaxies is stunted. Perhaps this involves the disruptive effect of the QSO luminosity (Benson et al. 2003; Wyithe & Loeb 2003; di Matteo et al. 2005). The giant holes in the CO quasars discussed above appear destined to remain in galaxies of comparatively modest proportions.

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