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CO LINEWIDTHS AND THE BLACK HOLE - BULGE RELATIONSHIP FOR HIGH REDSHIFT QSOS

K. L. Menezes,[1] G. A. Shields,[1] C. A. Massart,[1] and P. Vanden Bout[2]

Supermassive black holes in galactic nuclei have masses $M_{\rm BH}$ closely related to the mass and velocity dispersion σ_* of the host galaxy. We examine the $M_{\rm BH} - \sigma_*$ relationship in high redshift QSOs, deriving $M_{\rm BH}$ from the broad emission-line widths and σ_* from the the radio CO lines. At redshifts z = 4 to 6, gigantic black holes appear to exist in relatively modest galaxies.

Supermassive black holes in galactic nuclei show a strong correlation between $M_{\rm BH}$ and σ_* for the host galaxy bulge (Gebhardt et al. 2000; Ferrarese & Merritt 2000; Kormendy & Gebhardt 2001). Tremaine et al. (2002) give this relationship as

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

Observational constraints on the evolution of this relationship may provide clues to its origin. Here we examine $M_{\rm BH} - \sigma_*$ in quasars up to $z = 6$ using CO emission-line widths as a surrogate for σ_* (see Shields et al. 2005 for details). We use $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.3$, and $\Omega_\Lambda = 0.7$.

Shields et al. (2003, "S03") used QSO emission lines to study the $M_{\rm BH} - \sigma_*$ relationship for large lookback times. The black hole "photoionization mass" (based on Kaspi et al. 2000) was derived from

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

where $v_{3000} \equiv$ FWHM(Hβ)/3000 km s^{-1} and $L_{44} \equiv \nu L_\nu/(10^{44}$ erg s$^{-1})$, the continuum luminosity at 5100 Å. Following Nelson (2000; see also Bonning et al. 2005, and references therein), σ_* was estimated as $\sigma_{\rm [O\ III]}$ = FWHM([O III])/2.35. S03 found little change in the $M_{\rm BH} - \sigma_*$ relationship from redshifts $z \approx 2$ to today.

Solomon & Vanden Bout (2005) list 36 "early universe molecular emission galaxies" (EMGs) at redshifts $z = 1.4$ to 6.4, including 15 QSOs with measured CO line widths. We found published spectra giving useful broad line widths (C IVλ1550 or Mg IIλ2800) for 9 of these. Previous work (McLure & Jarvis 2002; Vestergaard 2002) has shown that Mg II and C IV are useful alternatives to Hβ for measuring $M_{\rm BH}$ in AGN. We evaluate $\lambda L_\lambda(5100)$ from the observed flux at 1350 or 1450 Å, extrapolated to λ5100 as $F_\nu \propto \nu^{-0.5}$. We used FWHM(CO) $= 0.67\times$FWZI when FWZI was given. Figure 1 shows the resulting values of $M_{\rm BH}$ and $\sigma_{\rm CO} \equiv$ FWHM(CO)/2.35 for the CO objects along with the objects studied by SO3. The CO objects lie above and to the left of the line representing the $M_{\rm BH} - \sigma_*$ relationship for nearby galaxies (equation 1). The black holes are too large for $\sigma_{\rm CO}$, by as much as two orders of magnitude.

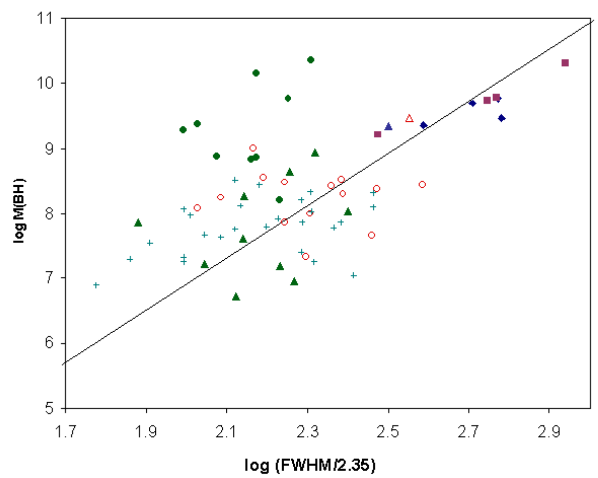

Fig. 1. The $M_{\rm BH} - \sigma_*$ relationship using $\sigma_{\rm [O\ III]}$ and $\sigma_{\rm CO}$ as surrogates for σ_*. Filled circles are the nine CO QSOs from this paper. The other points are from Figure 2 of SO3, based on $M_{\rm BH}$(Hβ) and $\sigma_{\rm [O\ III]}$ (see SO3 for legend and references). The solid line is equation 1.

Figure 2 shows the redshift dependence of Δlog$M_{\rm BH} \equiv$ log$M_{\rm BH}$ − log$M_{\rm BH*}$, where $M_{\rm BH*}$ is given by equation 1. There is a trend of increasing Δ log $M_{\rm BH}$ with redshift. The low and intermediate redshift objects of SO3, based on $\sigma_{\rm [O\ III]}$, scatter about Δlog$M_{\rm BH} = 0$. The four CO objects with z between 1.4 and 2.8 as a group ("group 1")have Δlog$M_{\rm BH} \approx 1$, and the five high redshift CO objects ("group 2") have Δlog$M_{\rm BH} \approx 2$. The increase in Δ log $M_{\rm BH}$ from group 1 to group 2 results from

[1]Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA (shields@astro.as.utexas.edu).
[2]National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville VA 22903.

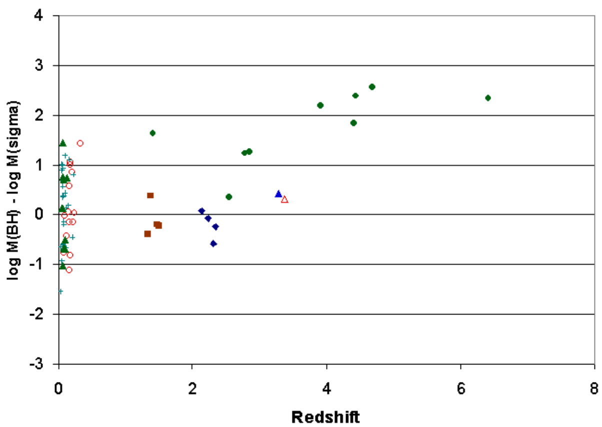

Fig. 2. Redshift dependence of Δ log $M_{\rm BH}$ for the high and low redshift samples. See SO3 for legend and references.

an increase in $M_{\rm BH}$ not accompanied by an increase in $\sigma_{\rm CO}$. Groups 1 and 2 have means log $M_{\rm BH}$ = 8.7, 9.8 and log FWHM(CO) = 2.16, 2.15. The two groups have log $L_{\rm bol}/L_{\rm Ed}$ = -0.5, -0.35, where $L_{\rm bol} \approx 9\lambda L_\lambda(5100)$ (Kaspi et al. 2000) and $L_{\rm Ed}$ is the Eddington limit, which suggests that the masses are not greatly overestimated.

Is $\sigma_{\rm CO}$ is a faithful indicator of σ_*? For the low redshift PG quasars observed in CO by Evans et al. (2001) and Scoville et al. (2003), we find log$\sigma_* \approx$ log$\sigma_{\rm CO}$+0.12 based on (1) $M_{\rm BH}$ derived from the Hβ line width using equation 2, (2) $\sigma_{\rm [O\ III]}$ as a surrogate for σ_*, and (3) σ_* estimated from the Faber-Jackson relation and the host galaxy luminosity (Bonning et al. 2005). This also roughly agrees with CO gas orbiting in a disk in the bulge potential, with $v_c = \sqrt{2}\sigma_*$, FWZI = $2v_c$, and random orientations given mean sin $i = 0.866$. This calibration corresponds to lowering Δ log $M_{\rm BH}$ by 0.5 for the CO objects in Figure 2 . This lessens the discrepancy between the optical and CO points at redshift 1 to 3. However, the high redshift points (group 2) still have Δ log $M_{\rm BH}$ around +1.5, larger by 1.0 dex than for the $z = 1$ to 3 CO objects. (We cannot rule out that the high redshift QSOs suffer a more severe selection for face on disks that the PG QSOs.)

Our conclusion agrees with a high resolution study of the host galaxy in the z = 6.42 quasar SDSS J1148 (Walter et al., 2004), who found a dynamical mass essentially equal to the sum of the black hole and the molecular gas, leaving no room for a galaxy obeying $M_{\rm BH} - \sigma_*$. The dynamical masses for our other CO QSOs, quoted by Solomon & Vanden Bout (2005) or estimated by us for $r_{\rm CO} \approx 1$ kpc, give an average $M_{\rm dyn} \sin^2 i \approx 10^{10.5}$ M$_\odot$, compared with $M_{\rm gas} \approx 10^{10.9}$ and $M_{\rm BH} \approx 10^{9.3}$. These values fall far short of the bulge mass $M_{\rm bulge} \approx 700 M_{\rm BH} \approx 10^{12.2}$ prescribed by the local $M_{\rm BH} - \sigma_*$ relationship (Kormendy & Gebhardt 2001). Our perspective of $\sigma_{\rm CO}$ as a measure of σ_* addresses the host galaxy in its entirety rather than only the mass within the CO radius. Several of our CO QSOs may be mergers in progress, but this should only increase the CO line width.

Do the giant black holes observed at high redshift acquire commensurate host galaxies through later mergers, gas accretion, and star formation? The local galaxy luminosity function does not afford a sufficient number of giant galaxies to host the largest black holes observed in QSOs (Shields et al. 2004; see also Netzer 2003). Some of these black holes evidently remain to this day in comparatively modest galaxies.

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