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QSO Narrow [OIII] Line Width and Host Galaxy Luminosity

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ABSTRACT

Galaxy bulge luminosity L, black hole mass $M_{\rm BH}$, and stellar velocity dispersion σ_* increase together in a way suggesting a close evolutionary relationship. Measurements of the $M_{\rm BH} - \sigma_*$ relationship as a function of cosmic time may shed light on the origin of this relationship. Direct measurements of σ_* at high redshift are difficult, and the width of the narrow emission lines of AGN has been proposed as a surrogate for σ_*. We investigate the utility of using $\sigma_{\rm [O\ III]}$ for σ_* by examining host galaxy magnitudes and [O III] line widths for low redshift QSOs. For radio-quiet QSOs, $\sigma_{\rm [O\ III]}$ is consistent in the mean with the value of σ_* predicted by the Faber-Jackson relation. For our limited range of $L_{\rm host}$, scatter obscures the expected increase of $\sigma_{\rm [O\ III]}$ with $L_{\rm host}$. However, for a sample of AGN covering a wide range of measured or inferred σ_* , there is a clear increase of $\sigma_{\rm [O\ III]}$ with σ_* . Radio-loud QSOs on average have $\sigma_{\rm [O\ III]}$ smaller by 0.1 dex than radio-quiet QSOs of similar $L_{\rm host}$, at least for luminosities typical of PG QSOs. Star formation rates in our low redshift QSOs are smaller than required to maintain the typical observed ratio of bulge mass to black hole mass.

Subject headings: galaxies: active — quasars: general — black hole physics

1. INTRODUCTION

The relationship between a galaxy's central black hole and the evolutionary history of its host galaxy is unclear. Probing the correlations between galaxy luminosity, stellar velocity,

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gas velocity, and black hole mass may reveal the connections between a galaxy's central black hole and its formation history.

Galaxy magnitudes are closely related to the mass of the central black hole ($M_{\rm BH}$). Kormendy & Richstone (1995) and Magorrian et al. (1998) showed that the central black hole mass correlates with the bulge mass and luminosity. Laor (1998) showed that quasar host galaxy luminosity is similarly correlated with the black hole mass deduced from the broad Hβ lines. The stellar velocity dispersion (σ_*) in the galactic bulge also correlates with the mass of the central black hole. Gebhardt et al. (2000a) and Ferrarese & Merritt (2000) found that the correlation between $M_{\rm BH}$ and σ_* is strong, suggesting a link between the formation of the bulge and the black hole. Theoretical interpretations of this correlation (e.g. Silk & Rees 1998; Adams, Graff, & Richstone 2001; Burkert & Silk 2001; Ostriker 2000; Balberg & Shapiro 2002; Haehnelt & Kauffmann 2000; Murray, Quataert, & Thompson 2004) differ as to whether the black hole forms before, during, or after the bulge. Measurements of the $M_{\rm BH} - \sigma_*$ relationship at high redshift may help to resolve this question (Shields et al. 2003).

Derivation of $M_{\rm BH}$ from AGN broad line widths and continuum luminosity is now well established (see Kaspi et al. 2000; McLure & Dunlop 2004, and references therein). In contrast, measurements of σ_* are difficult for distant QSOs, given the faintness of the galaxy and the relative brightness of the nucleus. However, it may be possible to infer σ_* from the widths of the narrow emission lines. Nelson & Whittle (1996) made a comparison of bulge magnitudes, [O III] $\lambda\lambda5007, 4959$ line widths and stellar velocity dispersions in Seyfert galaxies, taking $\sigma_{\rm [O\ III]} \equiv$ FWHM[O III]/2.35 as appropriate for a Gaussian line profile. They found on average good agreement between $\sigma_{\rm [O\ III]}$ and σ_*, although $\sigma_{\rm [O\ III]}$ shows more scatter than σ_* on a Faber-Jackson plot. This supports the idea that the NLR gas is largely in orbital motion in the gravitational potential of the bulge and can be effectively used as a substitute where stellar velocities cannot be measured. Further supporting the use of $\sigma_{\rm [O\ III]}$ for σ_* is the work of Nelson (2000), who shows that the $M_{\rm BH} - \sigma_*$ relation for normal galaxies and AGN (Gebhardt et al. 2000a, 2000b) is preserved when $\sigma_{\rm [O\ III]}$ is used in place of σ_*.

Shields et al. (2003) examined the $M_{\rm BH} - \sigma_{\rm [O\ III]}$ relationship in QSOs with redshifts up to $z = 3$, finding little evolution with cosmic time. This result suggests that supermassive black holes and their host galaxies grow together, or that both have largely completed their growth by $z \approx 2$. Such a conclusion would provide valuable guidance to theories of the evolution of galaxies and their black holes. However, the use of $\sigma_{\rm [O\ III]}$ for σ_* is controversial. [O III] line profiles often have substantial asymmetry and a non-Gaussian profile. This may arise from outflow combined with extinction of the far side of the NLR (e.g., Wilson & Heckman 1985; Nelson & Whittle 1995). Objects with strong iron emission can obscure the

[O III] emission due to the Fe II features lying close to the [O III]$\lambda\lambda 4959, 5007$ line. These complications and no doubt others contribute to the large scatter shown by [O III] emission in comparison to σ_*. This underscores the importance of quantifying the correspondance of σ_* with $\sigma_{[\mathrm{O\ III}]}$ at QSO luminosities.

Direct comparisons of $\sigma_{[\mathrm{O\ III}]}$ with σ_* have generally been limited to lower luminosity AGN (Smith, Heckman, & Illingworth 1990; Nelson & Whittle 1996; Onken et al. 2004). Indirect comparisons using the $M_{\mathrm{BH}} - \sigma_*$ relationship (Shields et al. 2003; Boroson 2003) rely on the derivation of M_{BH} from the broad line widths. Therefore it is important to evaluate the substitution of σ_* for $\sigma_{[\mathrm{O\ III}]}$ as directly as possible for QSO luminosities that more closely approach the luminosities of observed high redshift QSOs. In normal galaxies, σ_* is related to bulge luminosity by the Faber-Jackson relation (Forbes & Ponman 1999; Kormendy & Illingworth 1983). This relation is particularly true for early-type galaxies, which comprise the majority of the hosts of luminous quasars with $M_R < -24$ (Dunlop et al. 2003; Schade, Boyle, & Letawsky 2000). Additionally, Woo et al. (2004) have shown that the host galaxies of BL Lac objects and radio galaxies up to redshift $z \sim 0.34$ lie on the normal galaxy fundamental plane. This allows an indirect determination of σ_* for comparison with $\sigma_{[\mathrm{O\ III}]}$, as done for Seyfert galaxies by Nelson & Whittle (1996). In this paper, we test the use of [O III] line widths as a surrogate for σ_* by studying the $M_{\mathrm{HOST}} - \sigma_{[O\ III]}$ relationship in a sample of quasars for which the host galaxy luminosity has been measured. In § 2 we describe the host galaxy luminosities used here and our measurements of the [O III] line widths. In § 3 we show that $\sigma_{[\mathrm{O\ III}]}$ agree closely with σ_* in the mean, examine the scatter in this agreement, and show that $\sigma_{[\mathrm{O\ III}]}$ does indeed track σ_* over a broad range of QSO luminosities. We assume a cosmology with $H_0 = 70$ km s^{-1} Mpc$^{-1}, \Omega_{\mathrm{M}} = 0.3, \Omega_\Lambda = 0.7$. All values of luminosity used are corrected to these cosmological parameters.

2. DATA

2.1. Host Galaxy Magnitudes

Host galaxy magnitudes for ellipticals, and bulge magnitudes for spiral hosts were taken from the literature, including McLure & Dunlop (2002), Percival et al. (2001), Floyd et al. (2004), McLure, Percival, & Dunlop (2004) and Hamilton, Casertano, & Turnshek (2002). The host galaxy measurements in the first four papers (i.e., excepting Hamilton et al.) were performed using the same method for fitting and subtracting the nucleus, modeling the host galaxy, integrating host galaxy light, and performing K-corrections, evolution corrections, and correction for Galactic extinction (described in McLure, Dunlop, & Kukula 2000). The measurements done by Hamilton et al. (2002) differed in these respects. As a result, when comparing the set of objects for which both sudies report a host galaxy magnitude, there is an average offset. We converted the V-band magnitudes of Hamilton et al. to the Cousins R-band in which McLure & Dunlop report their results by using colors $V - R_c = 0.61$ for elliptical galaxies and $V - R_c = 0.54$ for spiral galaxies (Fukugita, Shimasaku, & Ichikawa 1995), taking the morphologies as given in Hamilton et al. The resulting magnitudes are, on average, brighter than those of McLure & Dunlop (2002) by about 0.25 mag. We therefore adjusted all magnitudes measured by Hamilton et al. by this amount in order to correct for average measurement difference between the two methods.

2.2. [O III] Line Widths

The [O III] line widths in this paper were measured directly from spectra publicly available from Marziani et al. (2003) and the spectra presented by McLure & Dunlop (2001). Line widths were corrected by subtracting in quadrature the instrumental FWHM, which ranged from 3 - 7 Å. Iron emission was subtracted from the spectra using the Boroson & Green (1992) Fe II template so as to eliminate the emission bands around $\lambda4500$ and $\lambda5200$. Objects for which Fe II emission obscured the [O III] line were discarded. For the McLure & Dunlop sample, this led to the exclusion of one out of 13 radio-loud QSOs (RLQ) and 2 out of 17 radio-quiet QSOs (RQQ). Of the 7 objects from McLure, Percival, & Dunlop, all RLQ, one was rejected. Of the three in the Floyd et al. sample that had spectra from Marziani et al., one was rejected leaving 1 RQQ and 1 RLQ. Of the objects from Hamilton et al. with available spectra, four duplicated objects already in the foregoing sources, and one was rejected, leaving 3 RLQ and 8 RQQ.

We made a direct measurement of the FWHM using the IRAF [1] routine SPLOT, in preference to using a fit to the line profile. Typical errors in FWHM([O III]) are about 10%, coming largely from uncertainy in continuum placement. Objects with W(Fe II) > 50 Å have FWHM [O III] about 0.1 dex wider than in objects with weaker Fe II (Salviander, Shields, & Gebhardt 2005, in preparation). This has the potential to bias our sample towards objects with narrow [O III] since we must discard objects in which the [O III] is obscured by strong Fe II emission. However, we only discard about one in ten objects, giving a negligible 0.01 dex effect on the mean values. FWHM [O III] are converted to velocity dispersion as $\sigma_{[\rm O\ III]}$ by $\sigma_{[\rm O\ III]} \equiv \rm FWHM[O\ III]/2.35$ following Nelson (2000) and others.

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2.3. Black Hole Masses

Below we compare host galaxy magnitudes and [O III] widths with black hole masses for our objects. Black hole masses were derived from the FWHM of the broad component of the Hβ emission line and the continuum luminosity at 5100 Å, using equation A7 of McLure & Dunlop (2004, see references therein for details and background). Objects from McLure & Dunlop (2002) had Hβ width and continuum luminosity given in McLure & Dunlop (2001). For the other objects, Hβ width and the continuum luminosity at λ5007 were taken from Marziani et al., with the λ5007 scaled to a λ5100 value using a typical continuum slope $F_\lambda \propto \lambda^{-1.5}$. Two objects (0204+292 and 2247+140) were rejected because of weak or asymmetrical Hβ , a strong narrow component of Hβ , and noise; and 0100+020 was omitted because Marziani et al. do not give an absolute flux. The black hole masses here are typically several tenths dex smaller than those tabulated by McLure & Dunlop (2001) because of differences in the adopted cosmology and mass formula.

Table 1: Below are the objects for which we were able to obtain both host magnitudes and reliable [O III] line widths. Host galaxies are given in the Cousins R-Band and adjusted for the adopted cosmology, and $\sigma_{[\mathrm{O\ III}]}$ = FWHM[O III]/2.35. Magnitude sources: (1) McLure & Dunlop (2002, see references therein); (2) Hamilton et al. (2002); (3) Floyd et al. (2004); (4) Percival et al. (2001) (5) McLure et al. (2004) [O III] sources: (a) McLure & Dunlop (2001); (b) Marziani et al. (2003).

Name	Redshift	M_{R_c}(host)	$\log(\sigma_{[O\ III]})$ (km/s)	Magnitude Source	[O III] source
			Radio-Quiet Quasars		
0052+251	0.154	-22.44	2.44	(1)	(a)
0054+144	0.171	-23.11	2.59	(1)	(a)
0100+020	0.393	-22.11	2.14	(2)	(b)
0137-010	0.335	-21.66	2.25	(4)	(b)
0157+001	0.164	-23.76	2.45	(1)	(a)
0204+292	0.109	-22.81	2.36	(1)	(a)
0205+024	0.155	-20.83	2.54	(1)	(b)
0244+194	0.176	-22.45	2.31	(1)	(a)
0923+201	0.190	-22.76	2.57	(1)	(a)
0953+414	0.239	-22.32	2.41	(1)	(a)
1012+008	0.185	-23.26	2.67	(1)	(b)
1029-140	0.086	-22.15	2.40	(1)	(b)
1116+215	0.177	-23.17	2.73	(1)	(b)
1202+281	0.165	-22.21	2.28	(1)	(b)
1216+069	0.331	-22.21	2.16	(2)	(b)
1219+755	0.071	-22.11	2.14	(2)	(b)
1307+085	0.155	-21.97	2.34	(1)	(b)
1309+355	0.184	-22.94	2.48	(1)	(b)
1416-129	0.129	-21.32	2.42	(2)	(b)
1635+119	0.146	-22.55	1.95	(1)	(b)
1821+643	0.297	-24.47	2.43	(3)	(b)

Name	Redshift	M_{R_c}(host)	$\log(\sigma_{[O\ III]})$	Magnitude Source	[O III] Source
		Radio-Loud Quasars			
0133+207	0.425	-23.04	2.28	(2)	(b)
0137+012	0.258	-23.55	2.29	(1)	(a)
0202-765	0.389	-22.79	2.26	(2)	(b)
0837-120	0.198	-22.73	2.38	(2)	(b)
1004+130	0.240	-23.63	2.39	(1)	(a)
1020-103	0.197	-22.87	2.46	(1)	(a)
1150+497	0.334	-23.45	2.19	(3)	(b)
1217+023	0.240	-23.19	2.20	(1)	(b)
1226+023	0.158	-23.79	2.71	(1)	(b)
1302-102	0.286	-23.48	2.39	(1)	(b)
1425+267	0.366	-23.19	2.20	(5)	(b)
1512+370	0.371	-23.69	2.30	(5)	(b)
1545+210	0.266	-23.12	2.33	(1)	(b)
1704+608	0.371	-23.36	2.24	(5)	(b)
2135-147	0.200	-22.90	2.35	(1)	(b)
2141+175	0.213	-23.13	2.54	(1)	(b)
2247+140	0.237	-23.36	2.33	(1)	(a)
2251+113	0.323	-22.70	2.41	(5)	(b)
2308+098	0.432	-22.92	2.32	(5)	(b)
2349-014	0.173	-23.77	2.24	(1)	(b)
2355-082	0.210	-23.12	2.30	(1)	(a)

3. RESULTS

3.1. The $M_{\rm HOST} - \sigma_{[O\ III]}$ relationship

Our results for $M_{\rm HOST} - \sigma_{[O\ III]}$ are plotted in Figure 1. The Faber-Jackson relation is shown as taken from Bernardi et al. (2003a, 2003b) with $L \sim \sigma^{3.91}$. Bernardi et al. note that their measurements of σ_* are 0.05 dex smaller than those previously published. We also indicate the relation with the changed zero point in Figure 1. As can be seen, the data for the QSOs given agree in the mean with the Faber-Jackson relation, using $\sigma_{\rm [O\ III]}$ in lieu of σ_*. However, the scatter is large, about 0.16 in log $\sigma_{\rm [O\ III]}$, for the full sample or 0.11 dex for the radio-quiet objects excluding the extreme outlier (1635+119) at low $\sigma_{\rm [O\ III]}$. Given the limited range of luminosities available to us this scatter obscures any increase of $\sigma_{\rm [O\ III]}$ with $M_{\rm HOST}$ as expected by the Faber-Jackson relation.

Scatter inherent in the Faber-Jackson relation for normal galaxies contributes very little to the scatter seen in Figure 1. Bernardi et al. (2003a, 2003b), in a sample of 9000 early-type galaxies, find the rms scatter in σ_* in the R-band to be around .075 dex in log σ at constant luminosity (see Figure 4 in Bernardi et al. 2003b). Another source of uncertainty comes from the inability to measure FWHM [O III] with high accuracy. Plausible displacements in location of the continuum level can lead to a ΔFWHM([O III]) of about ± 50 km/s, or a scatter of ~ 0.04 dex in log $\sigma_{\rm [O\ III]}$. Measurement error of ~ 0.5 mag. in $M_{\rm HOST}$ corresponds to 0.05 in log $\sigma_{\rm [O\ III]}$. Taken together with the standard deviation in log $\sigma_{\rm [O\ III]}$ of ~ 0.16, one is left with an intrinsic scatter in [O III] of

$$(\log \sigma_{\rm [O\ III]})^2 \sim (0.16)^2_{OBS} - (0.075)^2_{FJ} - (0.04)^2_{FWHM} - (0.05)^2_{M_{HOST}} = (0.13)^2 \qquad (1)$$

Clearly, the geometry and kinematics of the NLR cause the $\sigma_{\rm [O\ III]}$ to differ substantially from σ_* in individual objects. However, some mix of processes evidently increases or decreases $\sigma_{\rm [O\ III]}$ with respect to σ_* with roughly equal probability, so that $\sigma_{\rm [O\ III]}$ and σ_* agree in the mean. This agrees with Boroson (2003), who in effect uses $M_{\rm BH}$ to infer σ_* in a sample of low-redshift radio-quiet QSOs and Seyfert 1 galaxies in the Sloan Digital Sky Survey (SDSS). [2] The limited range of $M_{\rm HOST}$ in our sample implies a limited range of σ_*, and the expected increase in $\sigma_{\rm [O\ III]}$ with σ_* is obscured. Boroson (2003) likewise found that the scatter in $\sigma_{\rm [O\ III]}$ artificially flattened the slope of the $M_{\rm BH} - \sigma_{\rm [O\ III]}$ relationship in his QSO sample.

[2]The SDSS Web site is http://www.sdss.org/.

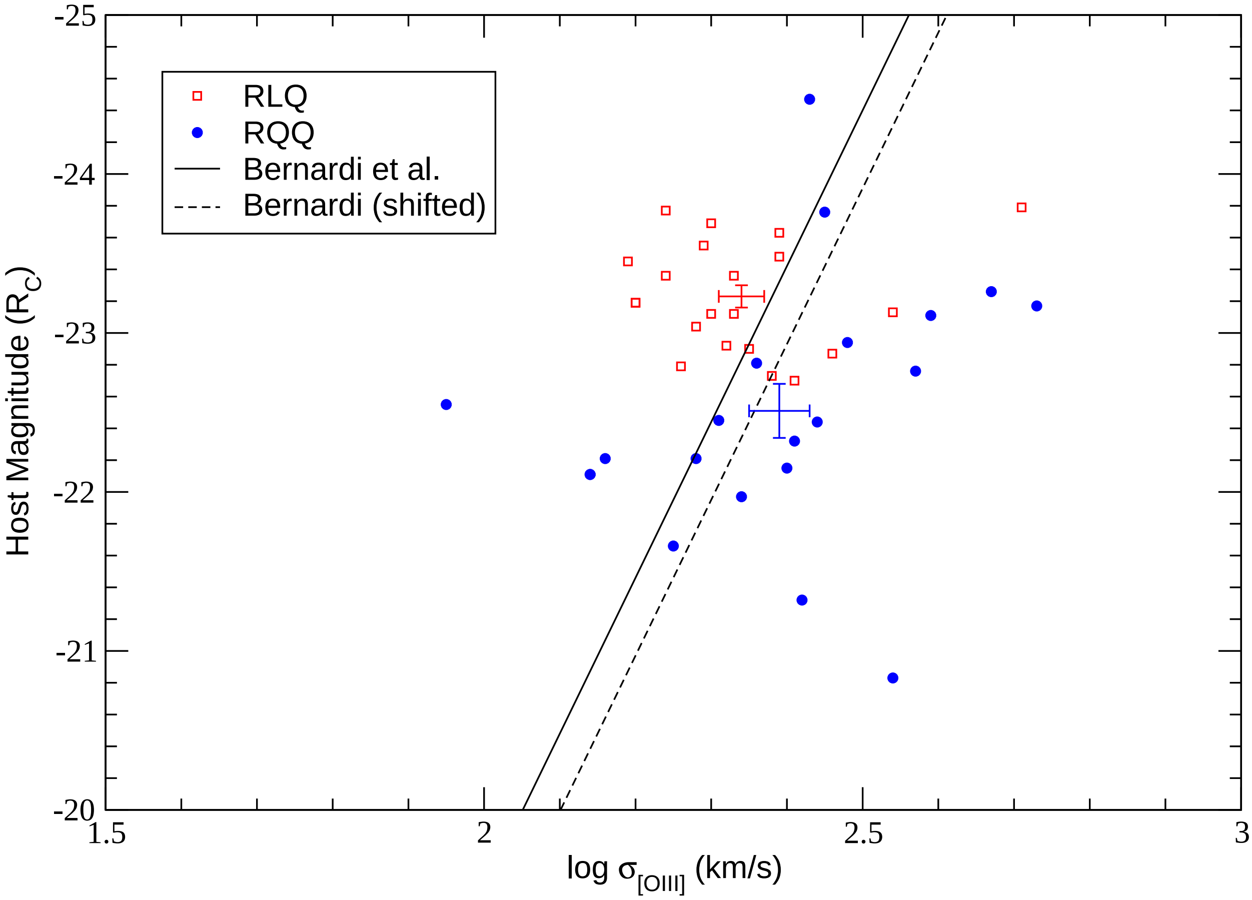

Fig. 1.— The above plot shows the sample of quasars for which we have host galaxy bulge magnitudes and reliable [O III] FWHM. The objects were classified as radio-loud or quiet according to the papers from which bulge magnitudes were taken. The straight line is the Faber-Jackson relation measured by Bernardi et al. (2003a, 2003b); it is not a fit to the data. The dashed line is the same relation with log σ displaced by 0.05 to account for the remark by Bernardi et al. (2003b, p.1854) that their meausured σ_* is smaller than the results of other authors by this amount. The crosses indicate the mean values and errors of the mean for host luminosity and $\sigma_{[\mathrm{O\ III}]}$ for RL and RQ objects, the RL being above and to the left of the RQ mean.

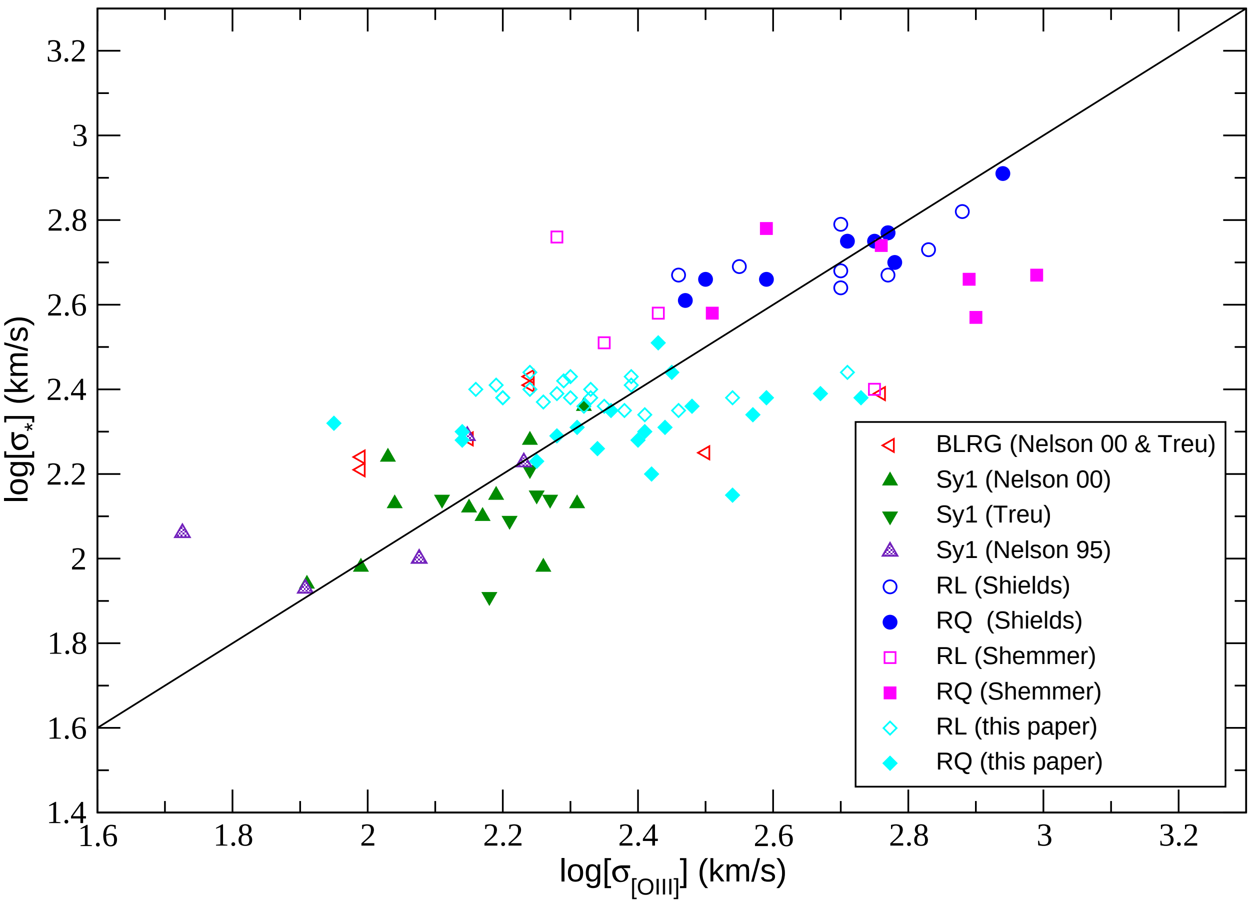

Fig. 2.— $\sigma_{[\mathrm{O\ III}]}$ v σ_* (or a surrogate) for our data sample and others. The broad line radio galaxies (BLRG) and Seyferts are given with measured σ_* . The QSOs from Shields et al. and Shemmer et al. have σ_* calculated from M_{BH} . QSOs from this paper have σ_* calculated from their host galaxy luminosity. Details of the data sets are given in the text.

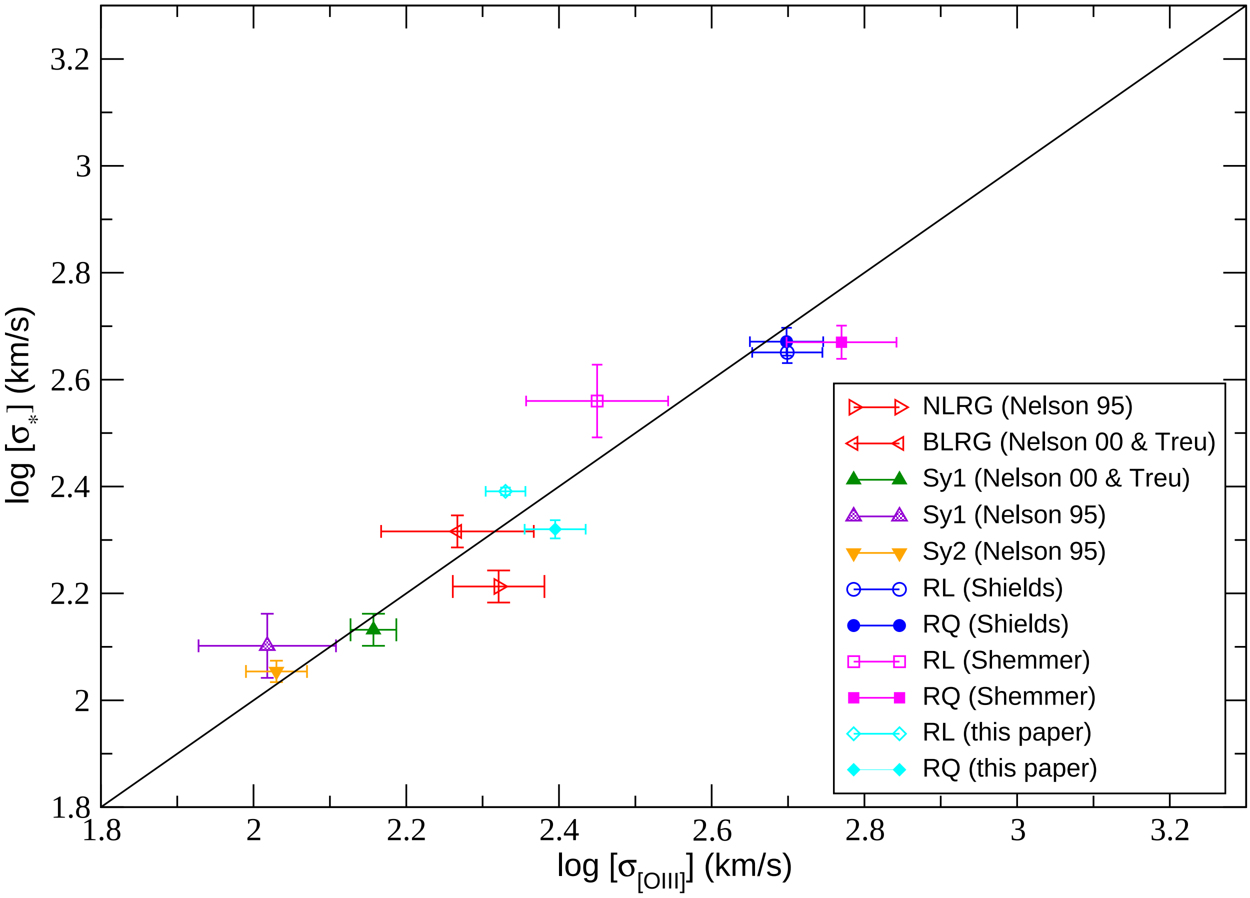

Fig. 3.— The means of each data set with error bars indicating the standard deviation of the mean. Also included are narrow line radio galaxies (NLRG) and Seyfert 2 objects from Nelson & Whittle (1995).

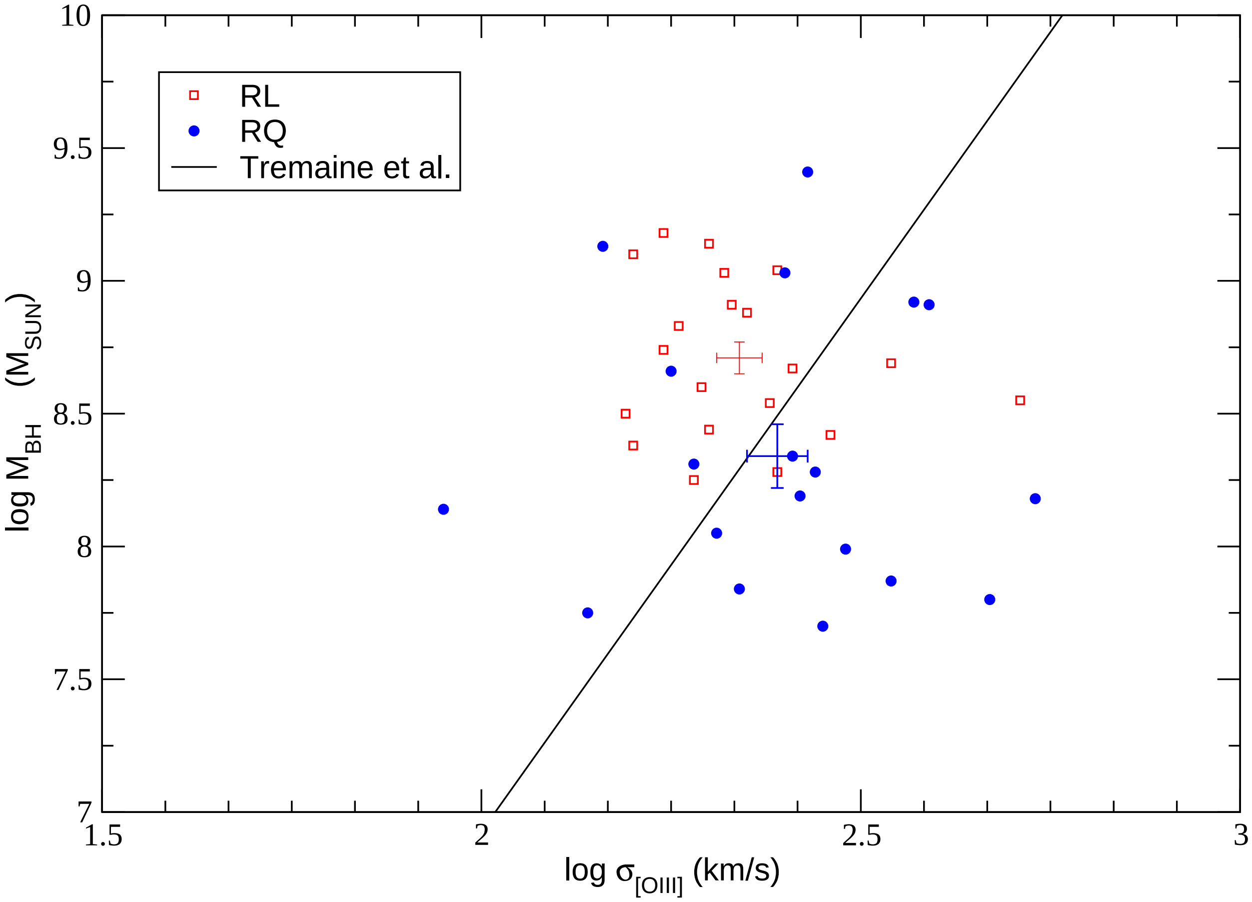

Fig. 4.— $M_{\rm BH}$ versus $\sigma_{\rm [O\ III]}$ for objects in Table 1 with exceptions described in the text, and expressed in log $M/{\rm M}_{\odot}$. The $\sigma_{\rm [O\ III]}$ values are taken from Table 1. The RL objects are offset from the Tremaine et al. (2002) relation similarly to the RL-RQ offset in Figure 1

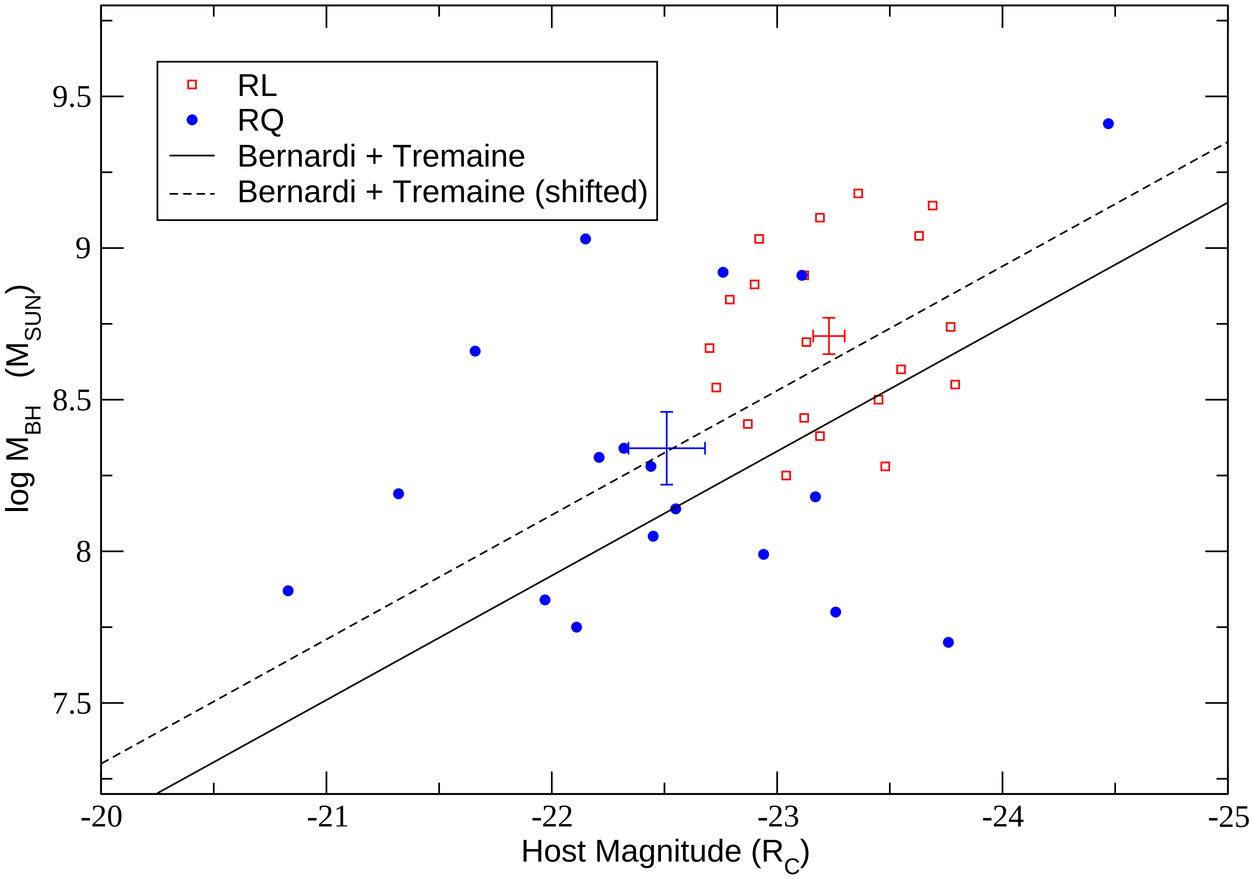

Fig. 5.— $M_{\rm BH}$ versus $M_{\rm HOST}$ for the same objects as Figure 4, along with the relation described in the text. This figure is similar to Figure 2 of McLure & Dunlop (2001), where it can be seen that the RL objects are not offset from the RQ objects in relation to the normal $M_{\rm BH}$ - $M_{\rm HOST}$ trend.

One possible systematic error in the values of $M_{\rm HOST}$ would be the presence of a young stellar population associated with the AGN episode and any triggering galactic merger. Nelson et al. (2004) find their sample of Seyfert 1 galaxies to be 0.4 magnitude brighter than expected for the normal Faber-Jackson relation. A similar offset was found by Nelson & Whittle (1996). In contrast, McLure & Dunlop (2001) find no offset. Nolan et al. (2001) examined the ages of QSO host galaxies with the aid of off-nuclear spectra. Their sample includes 6 RQQ and 8 RLQ in common with this paper. They find a predominantly old stellar population with any young population limited to less than 1% of the old, or less than ∼0.3% if the fits include nuclear continuum. The stellar population synthesis models of Charlot & Bruzual (1991) give an absolute magnitude per solar mass of $M_R = 3.3, 7.1$ for an age $10^8, 10^{10}$ yr, respectively. For a young population of age $\sim 10^8$ yr with 0.3% of the mass of the old population, the brightening is $\sim$ 0.1 magnitude. Even if the brightening were as large as the 0.4 magnitude found by Nelson et al., the difference in expected $\sigma_{\rm [O\ III]}$ would be only 0.04 dex, not enough to seriously alter Figure 1.

3.2. Does $\sigma_{\rm [O\ III]}$ track σ_* ?

Given the large scatter observed in $\sigma_{\rm [O\ III]}$ the question arises if $\sigma_{\rm [O\ III]}$ does indeed track σ_* . Results for Seyfert and radio galaxies do show an overall increase of $\sigma_{\rm [O\ III]}$ with σ_* or host luminosity of the expected magnitude (Nelson & Whittle 1995, 1996). We examine the increase in $\sigma_{\rm [O\ III]}$ with σ_* over a wide range of AGN luminosity, deriving σ_* by various means in different ranges of luminosity, extending the results of Nelson & Whittle by using an inferred σ_* . Figure 2 shows $\sigma_{\rm [O\ III]}$ versus σ_* deduced from a variety of sources. For high luminosity QSOs, we calculate σ_* from the $M_{\rm BH} - \sigma_*$ relation (Tremaine et al. 2002):

$$M_{\rm BH} = (10^{8.13}\ {\rm M_\odot}) \left(\frac{\sigma_*}{200\ {\rm km\ s^{-1}}}\right)^{4.02} . \tag{2}$$

High luminosity objects are included from Shields et al. (2003), using their three highest redshift data sets, and near IR spectra from Shemmer et al. (2004) and Netzer et al. (2004). We include those objects from the sample of Netzer et al. and Shemmer et al. for which their "fit" and "direct" measurements of the [O III] FWHM agree within 20% of each other in order to exclude those objects which do not have well measured [O III] widths. For our data in Table 1, we convert host galaxy magnitude to σ_* via the Faber-Jackson relation. The effect of recent star formation on the expected σ_* is discussed above; this applies only to the σ_* values derived from host galaxy luminosity (this paper). For Seyfert and radio galaxies, direct measurement of σ_* are available in the literature. Nelson & Whittle (1995) give values of σ_* and $\sigma_{\rm [O\ III]}$ for a number of Seyfert galaxies, noted as 'Nelson 95' in Figures 2 and

3. Figure 2 shows only broad line objects, but in Figure 3 we include mean values for the Nelson & Whittle Seyfert 2 galaxies, noting as narrow line radio galaxies (NLRG) Seyfert 2s with radio luminosity $L_{1415} > 22.5$, following Nelson & Whittle. All broad line radio galaxies in Nelson and Whittle are included in Figure 2 from the later sources. Figure 5 of Nelson & Whittle (1996) shows that the Seyfert 1 and 2 galaxies occupy a similar location in a $\sigma_{[\mathrm{O\ III}]} - \sigma_*$ diagram. In addition to objects from Nelson & Whittle, we have taken values for σ_* from Nelson et al. (2004), Onken et al. (2004), Treu, Malkan, & Blandford (2004) and Bettoni et al. (2001). FWHM of [O III] were obtained from Nelson (2000), and Heckman et al. (1981). For objects in Nelson & Whittle (1995) also contained in Nelson et al. (2004) or Onken et al. (2004), we used the latter sources. [O III] was measured directly from SDSS spectra for the Seyfert galaxies in Treu et al. Figure 3 shows the means of each data set, both for RL and RQ objects. It is clear that, though considerable scatter is present, in the mean, [O III] tracks σ_* over a wide range of object luminosity. A possible shift in σ_* of less than 0.1 dex due to, e.g. brightening from young stellar populations, is again not large enough to seriously alter Figure 3.

3.3. Is [O III] narrow in Radio-Loud Quasars?

There is some evidence that FWHM [O III] in radio-loud objects tends to be narrower than in radio-quiet objects at a given host luminosity. Figure 1 shows that the radio-loud objects in our sample have, on average, narrower FWHM [O III] for a given host luminosity. We find average values of log $\sigma_{[\mathrm{O\ III}]}$, M_{HOST} ($2.34 \pm 0.03, -23.23 \pm 0.07$) for radio-loud objects, and ($2.37 \pm 0.04, -22.47 \pm 0.15$) in radio-quiet objects. (Errors are standard deviations of the mean). In our sample, the RL hosts are 0.76 magnitudes brighter, on average, than the RQ hosts. Therefore, they should have log $\sigma_{[\mathrm{O\ III}]}$ about 0.08 larger. In fact, we find them to have log $\sigma_{[\mathrm{O\ III}]}$ smaller by 0.04, giving a total discrepancy of 0.12 ± 0.05 in log $\sigma_{[\mathrm{O\ III}]}$ with respect to the Faber-Jackson relation.

Shields et al. (2003) found radio-loud objects to have, on average, narrower FWHM [O III] than radio-quiet objects for a given black hole mass. Bian & Zhao considered the $M_{\mathrm{BH}} - \sigma$ relationship, taking M_{BH} from the velocity of the broad line region (BLR) and the BLR size - luminosity relation of Kaspi et al. (2000), and using published FWHM [O III] measurements from Marziani et al. and Shields et al. They find M_{BH} to be larger than expected from FWHM([O III]) in radio-loud objects. Table 3 of Bian & Zhao gives the magnitude of this offset as Δ log M_{BH} = 0.51, -0.36 for RL, RQ objects in Marziani et al., respectively, and 0.59, 0.17 for Shields et al., where Δ log M_{BH} = log (M_{BH} /$M_{[\mathrm{O\ III}]}$) and $M_{[\mathrm{O\ III}]}$ is the black hole mass as implied by the $M_{\mathrm{BH}} - \sigma$ relation given in § 3.2. This gives an average Δ log $M_{\rm BH}$ (RL-RQ) of 0.65. Using $M_{\rm BH} \propto \sigma^4$ (Tremaine et al. 2002), we may restate this as Δ log $\sigma_{\rm [O\ III]}$ (RL-RQ) = 0.16, close to our value of 0.12. QSOs in the SDSS Data Release 1 have [O III] systematically narrower for RLQ than for RQQ at fixed $M_{\rm BH}$ by $\sim$ 0.08 dex (Salviander et al. 2004). Thus there is some evidence for a RL–RQ offset at moderate QSO luminosities. However, in Figures 2 and 3, high luminosity QSOs of Shields et al. and the low luminosity Seyfert and radio galaxies show no significant RL-RQ offset. Further complicating the picture, Nelson & Whittle have found that AGN with powerful, linear radio sources sometimes have FWHM([O III]) larger than expected for the value of σ_* .

Bian & Zhao (2004) consider whether the RL-RQ offset seen in the $M_{\rm BH}$ - $\sigma_{\rm [O\ III]}$ relation might be due to the measurements of $M_{\rm BH}$ or $\sigma_{\rm [O\ III]}$. Geometrical effects in RLQ might affect the observed width of the broad Hβ line or the optical continuum luminosity, either of which would affect the derived $M_{\rm BH}$. Alternatively, the RL-RQ offset could be due to narrower [O III] lines in RL objects. Figure 4 shows an $M_{\rm BH}$ -$\sigma_{\rm [O\ III]}$ plot for our objects, where $M_{\rm BH}$ is derived as described above. The RL-RQ offset is similar to that in the $M_{\rm HOST}$ -log $\sigma_{\rm [O\ III]}$ plot. Figure 5 shows an $M_{\rm BH}$ -$M_{\rm HOST}$ plot along with the relationship predicted by combining the Faber-Jackson relationship in Figure 4 of Bernardi et al. (2003b) with the $M_{\rm BH}$ -σ_* relationship of Tremaine et al. (2002). The F-J relation was adjusted from r^* to R_C using Fukugita et al. (1995). Figure 5 shows no significant RL-RQ offset relative to the expected slope. These results suggest that narrower $\sigma_{\rm [O\ III]}$ for RL objects is responsible for the RL-RQ offset in the $M_{\rm BH}$ -$\sigma_{\rm [O\ III]}$ relationship, and not any systematic effect involving $M_{\rm BH}$. The cause of this offset is unknown.

3.4. Do PG Quasars Have Star Formation Commensurate with Black Hole Growth?

The proportionality of black hole mass and bulge mass, $M_{\rm BH} \approx 0.0013 M_{bulge}$ (Kormendy & Gebhardt 2001) raises the question of whether black hole growth and bulge growth occur simultaneously. Massive amounts of star formation are observed in some luminous AGN (Sanders & Mirabel 1996). Does the black hole growth resulting from the accretion that powers the PG QSOs of our sample (Table 1) correspond to a young stellar population consistent with $\Delta M_{\rm BH} \approx 0.0013\ \Delta M_{bulge}$? Our RQQ have an average bolometric luminosity $L \approx 10^{45.7}$ erg s^{-1} for a bolometric luminosity estimated as $L \approx 9\ \nu\ L_\nu(5100\ \text{Å})$ (Kaspi et al. 2000). This corresponds to an accretion rate $\dot{M} \approx 1\ M_\odot\,{\rm yr}^{-1}$ for an efficiency $L \approx 0.1 \dot{M} c^2$. The corresponding star formation rate is $\sim$ 700 $M_\odot {\rm yr}^{-1}$ to maintain the $M_{\rm BH} - M_{\rm bulge}$ relationship. Rates of this magnitude are observed in some ULIRGs but not in these PG

QSOs. Thus the instantaneous star formation rate is insufficient to build bulge in proportion to black hole. However, one may ask if a period of star formation over the recent past may have augmented the bulge in the correct proportion to the the growth of the black hole expected during the current QSO outburst. As discussed above, Nolan et al. (2001) find that any young stellar component is not more than about 0.3% of the old bulge stellar component. QSOs in our sample have $L/L_{\rm Ed} \approx 0.2$, for $M_{\rm BH}$ and L as described above. For $L = 0.1\dot{M}c^2$, this gives a black hole growth time of $10^{8.4}$ yr. Dunlop et al (2003) find an activation fraction for low redshift RQQ of $\sim 10^{-3}$, implying a minimum QSO lifetime of $\sim 10^7$ yr. This would entail black hole growth by at least $\sim 4\%$, much larger than the fractional addition of bulge stars allowed by Nolan et al. Star formation in PQ quasars seems to be far less than required to maintain detailed balance between bulge and black hole mass; however, the main growth of the black hole at higher redshifts may involve more nearly simultaneous star formation and bulge growth.

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