ON QUASAR MASSES AND QUASAR HOST GALAXIES

Ari Laor
Physics Department, Technion, Haifa 32000, Israel
laor@physics.technion.ac.il

ABSTRACT

The mass of massive black holes in quasar cores can be deduced using the typical velocities of Hβ-emitting clouds in the Broad Line Region (BLR) and the size of this region. However, this estimate depends on various assumptions and is susceptible to large systematic errors. The Hβ-deduced black hole mass in a sample of 14 bright quasars is found here to correlate with the quasar host galaxy luminosity, as determined with the Hubble Space Telescope (HST). This correlation is similar to the black hole mass vs. bulge luminosity correlation found by Magorrian et al. in a sample of 32 nearby normal galaxies. The similarity of the two correlations is remarkable since the two samples involve apparently different types of objects and since the black hole mass estimates in quasars and in nearby galaxies are based on very different methods.

This similarity provides a "calibration" of the Hβ-deduced black hole mass estimate, suggesting it is accurate to ±0.5 on log scale. The similarity of the two correlations also suggests that quasars reside in otherwise normal galaxies, and that the luminosity of quasar hosts can be estimated to ±0.5 mag based on the quasar continuum luminosity and the Hβ line width. Future imaging observations of additional broad-line active galaxies with the HST are required in order to explore the extent, slope, and scatter of the black hole mass vs. host bulge luminosity correlation in active galaxies.

Subject headings: galaxies: nuclei-quasars: general
1. INTRODUCTION

Indirect evidence for the existence of massive black holes (MBHs) in Active Galactic Nuclei (AGNs) has been growing over the years (e.g. Rees 1984). However, the most conclusive evidence for the existence of massive black holes has been recently obtained in the Milky Way (e.g. Genzel et al. 1997), and in NGC 4258 (Miyoshi et al. 1995), a weakly-active galaxy. This new evidence is based on high spatial resolution observations of stellar and gas kinematics. Similar estimates could not be employed in quasars and bright Seyfert galaxies as the stellar kinematics close to the black hole is hopelessly lost behind the glare of the active nucleus. A rough estimate of the black hole mass in AGNs can be obtained based on the size and the typical velocities in the Broad Line Region (BLR, e.g. Dibai 1981; Wandel & Yahil 1985; Joly et al. 1985; Padovani & Rafanelli 1988; Koratkar & Gaskell 1991). However, this method is susceptible to various systematic errors, and there is currently no independent way to estimate its accuracy.

Compact massive dark objects, most likely MBHs, were inferred in the cores of many nearby normal galaxies based on stellar kinematics and the observed light distribution (see review by Kormendy & Richstone 1995). In a recent comprehensive study of the stellar dynamics of a large sample of nearby galaxies based on stellar kinematics and the observed light distribution (see review by Kormendy & Richstone 1995). In a recent comprehensive study of the stellar dynamics of a large sample of nearby galaxies (Faber et al. 1997) one can instead test if quasars follow the MBH versus L_{bulge} correlation found for normal galaxies.

Rather accurate determinations of quasar host galaxy luminosities were recently obtained by Bahcall et al. (1997) for a representative sample of 20 bright low redshift quasars using the Hubble Space Telescope (HST). In this Letter I show that the quasar host galaxy luminosity appears to be significantly correlated with the Hβ-deduced black hole mass, \( M_{BH}(\beta) \), and that this correlation is very similar to the \( L_{bulge} \) versus \( M_{BH} \) relation determined by Magorrian et al. for nearby normal galaxies. This similarity provides a “calibration” for the \( M_{BH} \) estimates in AGNs. The \( M_{BH}(\beta) \) estimation method, its application to the Bahcall et al. sample, and the correlation analysis results are given in §2, and the implications are discussed in §3, together with some predictions of host luminosities which can be tested with HST in the near future.

2. The \( M_{BH}(\beta) \) versus \( L_{host} \) Correlation

2.1. \( M_{BH}(\beta) \)

The black hole mass can be estimated using the velocity dispersion of the Hβ emitting clouds in the BLR and the size of this region, together with the assumption that the clouds’ motion are virialized, i.e.,

\[
M_{BH}(\beta) = R_{BLR}(\beta)v_{BLR}^2/G
\]

where \( R_{BLR}(\beta) \) is the size of the Hβ-emitting region in the BLR and \( v_{BLR} \) is the observed Hβ velocity dispersion.

Kaspi et al. (1996) find \( R_{BLR}(\beta) = 0.014L_{44}^{1/2} \) pc, where \( L_{44} \) is the 0.1 – 1µm luminosity in units of \( 10^{44} \text{erg s}^{-1} \), assuming \( \Omega_0 = 1.0, H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \). This relation is equivalent to

\[
R_{BLR}(\beta) = 0.086L_{46}^{1/2} \text{ pc,}
\]

where \( L_{46} \) is the Bolometric luminosity in units of \( 10^{46} \text{erg s}^{-1} \) (using \( L_{bol} = 3L_{0.1-1\mu m} \), e.g. Fig.7 in Laor & Draine 1993), and \( \Omega_0 = 1.0, H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1} \) which is used throughout the paper. The \( R_{BLR} \propto L^{1/2} \) scaling is also indicated by the weak luminosity dependence of AGN emission line spectra, and is also expected based on dust sublimation which occurs at \( R_{dust} \simeq 0.2L_{46}^{1/2} \) pc (Laor & Draine 1993; Netzer & Laor 1993).

Thus, just based on \( v_{BLR} \), taken here as the observed Hβ FWHM, and \( L_{46} \), one obtains the following estimate for the black hole mass from Eqs.1& 2,

\[
m_9 = 0.18\Delta v_{3000}L_{46}^{1/2},
\]

where \( m_9 \equiv M_{BH}(\beta)/10^9M_\odot \), and \( \Delta v_{3000} \equiv \text{H β FWHM}/3000 \text{ km}^{-1} \).

2.2. \( L_{host} \)

Quasar hosts have been studied extensively from the ground (e.g. McLeod & Rieke 1994a, 1994b; Dunlop et al. 1993). However, separating out the quasar
host galaxy clearly requires a high angular resolution, and thus measurements with the HST can provide the most accurate determination of quasar host properties.

I use the sample of 20 luminous low redshift (z < 0.3) quasars studied by Bahcall et al. with the HST Wide Field/Planetary Camera-2 (WFPC2). This sample is likely to represent the properties of nearby bright quasars. In addition, the large sample size, the uniform and detailed reduction, and the detection of all quasar hosts, make this sample the best one available for exploring the $M_{BH}$ versus $L_{host}$ relation in quasars.

Some of the host galaxies morphologies were identified by Bahcall et al. as elliptical, and for these galaxies $L_{bulge} \equiv L_{host}$ (taken from the best fit 2-D model in their Table 5). Other hosts were identified as spirals, or interacting, and the value of $L_{bulge}$ for these objects, required for a direct comparison with the Magorrian et al. results, is not available. An estimate of $L_{bulge}$ for the objects which are best fit by an exponential disk is obtained by subtracting the $7.5 \leq r \leq 15$ kpc annular magnitude (their Table 8) from the total magnitude (their Table 5), yielding $M_V$ (inner host). The mean $\Delta M_V$ (host–inner host) is 0.5 mag, which is smaller than $\langle \Delta M_B(\text{total}–\text{bulge}) \rangle \sim 1–2$ mag for early type spiral galaxies (Simien & de Vaucouleurs 1986), suggesting that $M_V$ (inner host) overestimates $L_{bulge}$. Although, $M_V$ (host) may be underestimated, since the fit does not included a bulge component.

2.3. The correlations

Table 1 lists the Bahcall et al. quasars used for the correlation analysis together with their $z$, $M_V$ (bulge) for objects with a de Vaucouleurs fit, or $M_V$ (inner host) for objects with an exponential disk fit, Hβ FWHM, bolometric luminosity, $M_{BH}$ (Hβ) as deduced from Equation 3, and the host morphology from Bahcall et al. The Hβ FWHM is obtained from Boroson & Green (1992) which provide high quality and uniformly reduced spectra of all 87 $z \leq 0.5$ PG quasars (Schmidt & Green 1983), of which 14 overlap with the Bahcall et al. sample. Continuum fluxes are available for all of these 14 PG quasars in Neugebauer et al. (1987), which provides accurate and uniformly reduced continuum spectrophotometry for most PG quasars. The luminosity at 3000Å is converted to $L_{Bol}$ using $L_{Bol} = 8.3 \times \nu L_{\nu}(3000\text{Å})$ (see Fig. 7 in Laor & Draine).

There is no uniform data set with the continuum flux and Hβ FWHM for 5 additional quasars from the Bahcall et al. sample. Different papers quote parameters that can differ by $>50\%$ for a given object. These objects were therefore not included in the analysis as they may be subject to significant systematic deviations.

The upper panel in Figure 1 shows $M_V(bulge/inner host$) [hereafter $M_V(b/ih)$] versus $M_{BH}$ for the 19 Bahcall et al. quasars. Only the 14 quasars marked with filled squares were used in the analysis. The Spearman rank order correlation coefficient is $-0.70$ which has a probability of 0.005 to occur for unrelated parameters. A simple least squares fit to the data gives

$$M_V(b/ih) = -21.76 \pm 0.24 - (1.41 \pm 0.38) \log m_9, \quad (4)$$

Three quasars which are best fit by an exponential disk, PKS 1302-102, PG 1307+085, and PG 1444+407 (Bahcall et al. Table 5), may have an elliptical morphology (Table 1). A least squares fit for the 14 quasars using the three quasars de Vaucouleurs fit $M_V(bulge)$ yields the coefficients $-21.85 \pm 0.28$ and $-1.18 \pm 0.44$.

The middle panel in Fig. 1 shows the $M_V(bulge)$ vs. $M_{BH}$ relation for nearby normal galaxies from Magorrian et al. (1998). The dashed line represents the relation

$$M_V(bulge) = -21.40 - (2.21 \pm 0.28) \log m_9, \quad (5)$$
as deduced from the

$$\log(M_{BH}/M_\odot) = -1.79 + (0.96 \pm 0.12) \log(M_{bulge}/M_\odot), \quad (6)$$

and

$$\log(M_{bulge}/M_\odot) = -1.11 + (1.18 \pm 0.03) \log(L_{bulge}/L_\odot) \quad (7)$$

relations found by Magorrian et al., and the standard relation $M_V(bulge) = 4.83 - 2.5 \log(L_{bulge}/L_\odot)$.

The quasar correlation is flatter than the Magorrian et al. correlation ($-1.41$ vs. $-2.21$). This may be partly due to the fact that all the quasar hosts at $\log m_9 < -0.7$ are disk galaxies, where $M_V$ (inner host) may overestimate $M_V(bulge)$ ($\S 2.2$).

The lower panel in Figure 1 compares directly the distributions of the 32 Magorrian et al. galaxies and of the 19 quasars in the $M_{BH}$ versus $M_V(b/ih)$ plane. The two distributions overlap surprisingly well.
3. DISCUSSION

The overlap of the distributions of quasars and of normal galaxies in the $M_{\text{BH}}$ versus $M_V(b/ih)$ plane is the main result of this paper. This overlap is remarkable as bright quasars and nearby galaxies are apparently different types of objects, and since the $M_{\text{BH}}$ estimates in quasars and in nearby galaxies are based on very different methods (the BLR versus stellar dynamics). The overlap is also surprising given the crudeness of the $M_{\text{BH}}$ estimates for both populations. As stressed by Magorrian et al., their data are fit with a simplified, axisymmetric, stellar dynamics model, and a more general model may yield $M_{\text{BH}}$ which could be off by an order of magnitude, or may even not require a “massive dark object” at all. The $M_{\text{BH}}$ estimates available in the Galaxy and in NGC 4258, where $\log m_9 = -2.59$; $-1.44$ (Miyoshi et al. 1995; Genzel et al. 1997) and $M_V(\text{bulge}) = -18.4$; $-19.13$ (Bahcall & Soneira 1980; RC2 catalogue + Simien & de Vaucouleurs 1986). These galaxies follow the quasar relation significantly better than the Magorrian relation (see Fig.1). Thus, the data in the range $-2.59 \leq \log m_9 \leq 1.2$ appears to agree better with the steeper quasar relation. The quasar relation is also interestingly close to the Haehnelt, Natarajan & Rees (1998) prediction of $M_{\text{BH}} \propto M_{\text{halo}}^{5/3}$.

There are some objects, such as M 32, which appear to agree better with the nearby galaxies relation (Fig.1). A number of Seyfert 1 galaxies with $M_{\text{BH}} \sim 10^8 - 10^9 M_\odot$, as deduced by reverberation mappings (Peterson et al. 1998), are 1-2 mag brighter than expected based on the quasar relation (Ho 1998). Subtraction of the AGN light from the host light would bring them closer to the quasar relation.

The distribution of quasars in the absolute quasar $B$ band magnitude $M_B(\text{quasar})$ versus the absolute host $H$ band magnitude $M_H(\text{host})$ plane appears to be bounded such that $M_B(\text{quasar}) < M_H(\text{host})$ (e.g. McLeod & Rieke 1995; fig. 6). McLeod (1998) suggested that the reason for this bound is that objects where $M_B(\text{quasar}) = M_H(\text{host})$ “have a maximum allowed black hole mass for their galaxy mass and that the black hole is accreting at the Eddington rate.” This idea is broadly consistent with the correlation found here. For example, a quasar with $M_H(\text{host}) = -25$ mag typically has $M_V(b/ih) \simeq -21.3$ mag (using $(V - H) = 3.7$ mag for our 14 PG quasar hosts, with $M_H(\text{host})$ from McLeod & Rieke 1994b). Equation 4 then gives $\log m_9 \simeq -0.33$ (or $-0.47$). A magnitude of $M_B(\text{quasar}) = M_H(\text{host}) = -25$ mag translates to log $\nu L_\nu(4400\AA) = 45.55$, and log $L_{\text{bol}} \simeq 46.5$, which corresponds to 0.44 or 0.75 of $L_{\text{Eddington}}$. The above estimates are rather rough since the $M_H(\text{host})$ versus $M_V(b/ih)$ correlation has a significant scatter.

How can the analysis presented here be improved? The crude “inner host” estimate for the bulge luminosity, used here for disk galaxies, can be improved by fitting a disk+bulge model to the $HST$ images. This

relation has a relatively large uncertainty due to the small range in $M_{\text{BH}}$ available ($-1.16 \leq \log m_9 \leq 0.17$), but it is interesting to note that at the high mass end ($\log m_9 > 0.2$) the Magorrian et al. galaxies appear to follow the quasar relation quite well (see Fig.1). At the low black hole mass end one has the two best $M_{\text{BH}}$ estimates available, in the Galaxy and in NGC 4258, where $\log m_9 = -2.59$; $-1.44$ (Miyoshi et al. 1995; Genzel et al. 1997) and $M_V(\text{bulge}) = -18.4$; $-19.13$ (Bahcall & Soneira 1980; RC2 catalogue + Simien & de Vaucouleurs 1986). These galaxies follow the quasar relation significantly better than the Magorrian relation (see Fig.1). Thus, the data in the range $-2.59 \leq \log m_9 \leq 1.2$ appears to agree better with the steeper quasar relation. The quasar relation is also interestingly close to the Haehnelt, Natarajan & Rees (1998) prediction of $M_{\text{BH}} \propto M_{\text{halo}}^{5/3}$.
may be feasible for early type spiral hosts where the typical effective radius of the bulge is \( r_e \approx 1.4 \text{ kpc} \) (Simien & de Vaucouleurs), or \( \sim 0'.5 \) for the Bahcall et al. \( z \sim 0.2 \) quasars. However, it will not be feasible for late type spiral hosts, where \( r_e \approx 0.3 \text{ kpc} \), and a sample of lower \( z \) AGNs will be required. One also needs to measure the H\( \beta \) FWHM and luminosity simultaneously to guard against variability, and to obtain a more accurate estimate of the ionizing luminosity to use in the \( R_{\text{BLR}}(\text{H}\beta) \) relation (Eq.2). Obscuration effects are well established in AGNs, and these may increase the scatter, if not accounted for.

In particular, objects with a very narrow H\( \beta \) line may have their BLR partly obscured, or may be strongly dominated by emission from the narrow line region. Using the variable H\( \beta \) component profile can overcome such biases.

Future observations with \textit{HST} can address the following questions: 1. Does the black hole mass vs. host bulge luminosity correlation extends to quasars with higher and lower black hole masses? 2. Can the scatter in the correlation be reduced with a more careful analysis, or is it intrinsically large, as suggested for galaxies? and 3. Does \( M_{\text{BH}} \propto M_{\text{bulge}}^{1.5-1.8} \), as suggested here, or is \( M_{\text{BH}} \propto M_{\text{bulge}} \) as suggested by Magorrian et al.?

The PG quasars sample may be particularly useful for such future explorations with \textit{HST} since a high S/N homogeneous spectroscopic data base is already available from Neugebauer et al. and Boroson & Green. Using this data set and Eqs.3 \& 4 one can predict that of the 87 \( z < 0.5 \) PG quasars, some of the lowest luminosity hosts should be found in PG 1244+026, PG 1404+226, and PG 1448+273 (predicted \( M_V(b/i)=−18.4 \) to \(-19.3 \)), while some of the highest luminosity hosts should be found in PG 1704+608, PG 1425+267, and PG 2308+098 \((−22.0 \) to \(-22.3 \)). One can also predict that the hosts of PG 2304+042 and PG 2209+184 should be 2-3 magnitudes brighter than the hosts of PG 1244+026 and PG 1448+273 respectively, although the former and later quasars have, respectively, similar luminosities.

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| Object        | $z$  | $M_V$ | $H\beta$ | $L_{bol}$ | $M_{BH}$ | $T$  |
|--------------|------|-------|----------|----------|----------|------|
| PG 0052+251  | 0.155| 20.89 | 5.20     | 46.02    | 8.74     | Sb   |
| PHL 909      | 0.171| 21.48 | 11.0     | 46.37    | 9.57     | E4   |
| NAB 0205+02f | 0.155| 19.33 | 1.05     | 46.41    | 7.55     | S0?  |
| PH 0923+201  | 0.190| 21.48 | 7.61     | 46.06    | 9.09     | E1   |
| PG 0953+414  | 0.239| 20.29 | 3.13     | 46.39    | 8.49     | ?    |
| PKS 1004+130 | 0.240| 22.48 | 6.30     | 46.39    | 9.10     | E2   |
| PG 1012+008  | 0.185| 19.91 | 2.64     | 45.85    | 8.07     | Int. |
| HE 1029−140f | 0.086| 20.98 | 7.50     | 46.49    | 9.30     | E1   |
| PG 1116+215  | 0.177| 21.88 | 2.92     | 46.38    | 8.42     | E2   |
| PG 1202+281  | 0.165| 20.98 | 5.05     | 45.51    | 8.46     | E1   |
| 3C 273       | 0.158| 22.58 | 3.52     | 46.96    | 8.87     | E4   |
| PKS 1302−102 | 0.286| 21.15 | 3.40     | 46.77    | 8.75     | E4?  |
| PG 1307+085  | 0.155| 20.51 | 2.36     | 45.99    | 8.04     | E1?  |
| PG 1309+355  | 0.184| 21.23 | 2.94     | 45.83    | 8.15     | Sab  |
| PG 1402+261  | 0.164| 19.95 | 1.91     | 45.96    | 7.84     | SBb  |
| PG 1444+407  | 0.267| 20.49 | 2.48     | 46.13    | 8.16     | E1?  |
| 3C 323.1     | 0.266| 21.48 | 7.03     | 46.34    | 9.17     | E3?  |
| PKS 2135−147f| 0.200| 21.58 | 5.50     | 46.61    | 9.09     | E1   |
| PKS 2349−044f| 0.173| 22.58 | 5.50     | 46.57    | 9.07     | Int. |

*a* Host absolute magnitude from Bahcall et al. (1997, Table 5), calculated for $\Omega_0 = 1.0, H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

*b* $H\beta$ FWHM in units of 1000 km s$^{-1}$ from Boroson & Green (1992).

*c* Log Bolometric luminosity in erg s$^{-1}$, based on $f_\nu$ at rest frame 3000Å from Neugebauer et al. (1987).

*d* Log of black hole mass in units of $M_\odot$ (see Eq.3).

*e* Host morphology from Bahcall et al.

*f* Object not included in the correlation analysis (see text).
Fig. 1.— Comparison of the correlations for quasars and for nearby galaxies. Upper panel: the $M_V$ (bulge/inner host) versus $M_{\text{BH}}$ correlation for quasars. The solid line is a least squares fit. Open squares represent objects which were not included in the fit (see text). Middle panel: the $M_V$ (bulge) versus $M_{\text{BH}}$ relation obtained by Magorrian et al. for nearby normal galaxies. Lower panel: the two data sets overlaid. The two distributions overlap surprisingly well. The quasar relation is also consistent with the nearby galaxies distribution at log $m_9 > 0.2$, and the positions of the Milky Way and NGC 4258.