The Black Hole to Bulge Mass Relation in Active Galactic Nuclei

A. Wandel

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

ABSTRACT

The masses of the central black holes in Active Galactic Nuclei (AGNs) can be estimated using the broad emission-lines as a probe of the virial mass inside the BLR. Using reverberation mapping to determine the size of the Broad Line Region (BLR) and the width of the variable component of the line profile Hβ line it is possible to find quite accurate virial mass estimates for AGN with adequate data. Compiling a sample of AGN with reliable central masses and bulge magnitudes we find an average black hole to bulge mass ratio of 0.0003, a factor of 20 less than the value found for normal galaxies and for bright quasars. This lower ratio is more consistent with the black hole mass density predicted from quasar light, and agrees with the value found for our Galaxy. We argue that the black hole to bulge mass ratio actually has a significantly larger range than indicated by MBHs detected in normal galaxies (using stellar dynamics) and in bright quasars, which may be biased towards larger black holes, and derive a scenario of black hole growth that explains the observed distribution.

Subject headings: Galaxy: center — galaxies: active — galaxies: nuclei — galaxies: Seyfert — black holes — quasars: emission-lines — dark matter

1. Introduction

Massive black holes (MBHs) have been postulated in quasars and active galaxies (Lynden-Bell 1969, Rees 1984). Evidence for the existence of MBHs has recently been found in the center of our Galaxy (Ghez et al. 1998, Genzel et al. 1997) and in the weakly active
galaxy NGC 4258 (Miyoshi et al. 1995). Compact dark masses, probably MBHs, have been detected in the cores of many normal galaxies using stellar dynamics (Kormendy and Richstone 1995). The MBH mass appears to correlate with the galactic bulge luminosity, with the MBH being about one percent of the mass of the spheroidal bulge (Magorrian et al. 1998, Richstone et al. 1998).

The question whether AGN follow a similar black hole-bulge relation as normal galaxies is a very interesting one, as it may shed light on the connection between the host galaxy and the active nucleus. Wandel & Mushotzky (1986) have found an excellent correlation between the virial mass included within the narrow line region (of order of tens to hundreds pc from the center) and the black hole mass estimated from X-ray variability in a sample of Seyfert 1 galaxies. A black hole-bulge relation similar to that of normal galaxies has been reported between MBH of bright quasars and the bulge of their host galaxies (Laor 1998), but the black hole and bulge mass estimates have large uncertainties (section 3.2).

Seyfert 1 galaxies provide an opportunity to obtain more reliable black hole-to-bulge mass ratios (BBRs): because of their lower nuclear brightness, their bulge magnitudes can be measured directly. Also the black hole mass estimates (Wandel 1998) are much more reliable for AGN with reverberation data, which are more readily obtained for low luminosity AGN. The relation between the bulge and the nonstellar central source has been studied for many Seyfert galaxies (Whittle 1992; Nelson & Whittle 1996). These works find a tight correlation between the stellar velocity dispersion and the O[III] line and radio luminosity.

Reliable BLR size measurements are now possible through reverberation mapping techniques (Blandford & McKee 1982, recently reviewed by Netzer & Peterson 1997). High quality reverberation data and virial masses are presently available for about twenty AGN, most of them Seyfert 1s (Wandel, Peterson and Malkan 1999, hereafter WPM). We combine the reverberation masses (section 2) with Whittle’s bulge estimates in order to study the BBR in low-luminosity AGN and compare it to MBHs in normal galaxies and quasars (section 3). In section 4 we derive a MBH-evolution theory that can explain our results.

2. BLR reverberation as a probe of black hole masses in AGN

Broad emission lines probably provide the best probe of black holes in AGN. Assuming the line-emitting matter is gravitationally bound, and hence has a near-Keplerian velocity dispersion (indicated by the line width), it is possible to estimate the virial central mass:
\[ M \approx G^{-1}rv^2. \] This remains true for many models where the line emitting gas is not in Keplerian motion, such as radiation-driven motions and disk-wind models (e.g. Murray et al. 1998): in a diverging outflow the density (and hence the emissivity) decreases outwards, the emission is dominated by the gas close to the base of the flow, where the velocity is close to the escape velocity. (Note that if the velocity is actually larger than Keplerian, the virial mass is an upper limit and the result that the Seyfert galaxies in our sample have smaller black hole masses than MBHs detected in normal galaxies becomes even stronger).

The main problem in estimating the virial mass from the emission-linedata is to obtain a reliable estimate of the size of the BLR, and to correctly identify the line width with the velocity dispersion in the gas. WPM use the continuum/emission-line cross-correlation function to measure the responsibility-weighted radius \( c\tau \) of the BLR (Koratkar & Gaskell 1991), and the variable (rms) component of the spectrum to measure the velocity dispersion in the same part of the gas which is used to calculate the BLR size, automatically excluding constant features such as narrow emission lines and Galactic absorption. The line width and the BLR size yield the virial "reverberation" mass estimate \( M_{\text{rev}} \approx (1.45 \times 10^5 M_\odot) c\tau \text{days} v_3^2 \) where \( v_3 \) is the rms FWHM in units of \( 10^3 \text{km s}^{-1} \).

The virial assumption \( v \propto r^{-1/2} \) has been directly tested using data for NGC 5548 (Krolik et al. 1991; Peterson & Wandel 1999). The latter authors find that when the BLR reverberation size is combined with the rms line width in multi-year data for NGC 5548, the virial masses derived from different emission lines and epochs are all consistent with a single value ((6.3 \pm 2) \times 10^7 M_\odot) which demonstrates the case for a Keplerian velocity dispersion in the line-width/time-delay data.

3. The Black-Hole - Bulge Relation

3.1. Seyfert 1 galaxies

We use the WPM sample with the virial mass derived from the H\( \beta \) line by the reverberation-rms method (table 1). For 13 of the objects in the WPM sample we obtain the bulge magnitudes from the compilation of Whittle et al. (1992), who calculate the bulge magnitude from the total blue magnitude, using the empirical formula of Simien & deVaucolours (1986), relating the galaxy type to the bulge/total fraction. The bulge magnitudes are corrected for the nonstellar emission using the correlation between H\( \beta \) and the nonstellar continuum luminosity (Shuder 1981).

Mkn 110 and Mkn 335 have no estimated bulge magnitude in Whittle’s compilation, because they do not have well defined Hubble types. For these objects we adopt a canonical
Hubble type of Sa, which has a bulge correction \((m_{\text{bulge}} - m_{\text{gal}})\) of 1.02 mag. For Mkn 335 there is already a fairly large (and therefore uncertain) correction for the active nucleus (1.17 mags). For 3C120 the bulge magnitude is taken from Nelson & Whittle (1995) who find a bulge magnitude of -22.12. The uncertainties in the bulge magnitude were estimated from Whittle’s (1992) quality indicators. These indicators estimate the error in the subtraction of the nonstellar luminosity and some other factors, which for most galaxies amount to an uncertainty in the range 0.2-0.6 magnitudes. To the galaxies with an uncertain Hubble type we assign an uncertainty of 1.2 mag.

We relate the bulge luminosity to the magnitude by the standard expression
\[
\log(L_{\text{bulge}}/L_\odot) = 0.4(-M_v + 4.83).
\]
The bulge mass is then calculated using the mass-to-light relation for normal galaxies,
\[
\frac{M/M_\odot}{L/L_\odot} \approx 5(L/10^{10}L_\odot)^{0.15} \quad \text{(see Faber et al. 1997).}
\]

Fig. 1 shows the black hole mass as a function of the bulge mass. All the objects in our sample have BBRs lower than 0.006, the average value found for normal galaxies (Magorrian et al. 1998, represented by a dashed line), and the sample average is 
\[
< M_{\text{BH}} > = 3 \times 10^{-4} < M_{\text{bulge}} >.
\]
Also shown is NGC 1068 (a Seyfert 2), with the MBH mass estimated by maser dynamics. The narrow-line Seyfert galaxy NGC 4051, which has by far the lowest BBR in our sample, may indicate that narrow-line Seyfert 1 galaxies have smaller black holes than ordinary Seyfert 1 galaxies (Wandel and Boller 1998).
Table 1: AGN Central Masses derived from BLR data, Compared with Host Bulge magnitudes and corresponding mass. Column (2) – FWHM of (H\(\beta\)), rms profile, in \(10^3\)km/s. (3) - log(lag) – corresponding to the BLR size light days, (4) – absolute blue bulge magnitude from Whittle et al. (1992), (5) – log of the galactic bulge mass \((M_{bul})\) in \(M_\odot\), (6) – black hole mass (from WPM), (7) – BH to bulge mass ratio, (8) – the Eddinton ratio of the ionizing luminosity.

<table>
<thead>
<tr>
<th>Name</th>
<th>FWHM (1)</th>
<th>log((\tau)) (3)</th>
<th>(-M_B) (4)</th>
<th>log((M_{bul})) (5)</th>
<th>(\log\left(\frac{M_{bh}}{10^7 M_\odot}\right)) (6)</th>
<th>(\log\left(\frac{M_{bh}}{M_{bul}}\right)) (7)</th>
<th>(\log\left(\frac{L_{ion}}{L_E}\right)) (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 120*</td>
<td>2.2</td>
<td>1.64</td>
<td>20.3± 1.2</td>
<td>10.77± 0.5</td>
<td>3.1_{-0.5}^{+2.0}</td>
<td>-3.28</td>
<td>-0.57</td>
</tr>
<tr>
<td>3C 390.3</td>
<td>10.5</td>
<td>1.38</td>
<td>22.12±0.4</td>
<td>11.0±0.15</td>
<td>39.1_{-14.8}^{+12.4}</td>
<td>-2.41</td>
<td>-2.19</td>
</tr>
<tr>
<td>Akn 120</td>
<td>5.85</td>
<td>1.59</td>
<td>21.06±0.8</td>
<td>11.12±0.3</td>
<td>19.4_{-4.6}^{+4.1}</td>
<td>-2.83</td>
<td>-1.48</td>
</tr>
<tr>
<td>F9</td>
<td>5.9</td>
<td>1.23</td>
<td>22.25±0.6</td>
<td>11.67±0.25</td>
<td>8.7_{-4.5}^{+2.6}</td>
<td>-3.73</td>
<td>-1.84</td>
</tr>
<tr>
<td>IC 4329A</td>
<td>5.96</td>
<td>0.15</td>
<td>19.93±0.8</td>
<td>10.60±0.3</td>
<td>&lt; 0.73</td>
<td>&lt; −3.73</td>
<td>&gt; −2.94</td>
</tr>
<tr>
<td>Mrk 79</td>
<td>6.28</td>
<td>1.26</td>
<td>20.19±0.2</td>
<td>10.72±0.1</td>
<td>10.4_{-5.7}^{+4.0}</td>
<td>-2.70</td>
<td>-1.87</td>
</tr>
<tr>
<td>Mrk 110*</td>
<td>1.67</td>
<td>1.29</td>
<td>20.76±1.0</td>
<td>10.98±0.4</td>
<td>0.80_{-0.39}^{+0.29}</td>
<td>-4.07</td>
<td>-0.69</td>
</tr>
<tr>
<td>Mrk 335*</td>
<td>1.26</td>
<td>1.23</td>
<td>20.02±1.0</td>
<td>10.64±0.4</td>
<td>0.39_{-0.11}^{+0.14}</td>
<td>-4.06</td>
<td>-0.49</td>
</tr>
<tr>
<td>Mrk 509</td>
<td>2.86</td>
<td>1.90</td>
<td>21.75±0.6</td>
<td>11.44±0.25</td>
<td>9.5_{-1.1}^{+1.1}</td>
<td>-3.46</td>
<td>-0.54</td>
</tr>
<tr>
<td>Mrk 590</td>
<td>2.17</td>
<td>1.31</td>
<td>21.26±0.2</td>
<td>11.21±0.1</td>
<td>1.4_{-0.3}^{+0.3}</td>
<td>-4.06</td>
<td>-0.89</td>
</tr>
<tr>
<td>Mrk 817</td>
<td>4.01</td>
<td>1.19</td>
<td>21.17±0.4</td>
<td>11.17±0.15</td>
<td>3.7_{-0.9}^{+1.1}</td>
<td>-3.61</td>
<td>-1.54</td>
</tr>
<tr>
<td>NGC 3227</td>
<td>5.53</td>
<td>1.04</td>
<td>20.46±0.4</td>
<td>10.84±0.25</td>
<td>4.9_{-1.9}^{+2.7}</td>
<td>-3.15</td>
<td>-1.98</td>
</tr>
<tr>
<td>NGC 3783</td>
<td>4.1</td>
<td>0.65</td>
<td>20.07±0.2</td>
<td>10.66±0.1</td>
<td>1.1_{-1.0}^{+1.1}</td>
<td>-3.62</td>
<td>-2.10</td>
</tr>
<tr>
<td>NGC 4051</td>
<td>1.23</td>
<td>0.81</td>
<td>19.70±0.2</td>
<td>10.62±0.1</td>
<td>0.14_{-0.09}^{+0.15}</td>
<td>-4.42</td>
<td>-0.86</td>
</tr>
<tr>
<td>NGC 4151</td>
<td>5.23</td>
<td>0.48</td>
<td>19.98±0.4</td>
<td>11.04±0.15</td>
<td>1.3_{-0.7}^{+0.8}</td>
<td>-3.54</td>
<td>-2.49</td>
</tr>
<tr>
<td>NGC 5548</td>
<td>5.50</td>
<td>1.26</td>
<td>20.89±0.2</td>
<td>11.05±0.1</td>
<td>6.8_{-1.0}^{+1.5}</td>
<td>-3.06</td>
<td>-1.83</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>3.2</td>
<td>0.70</td>
<td>20.90±0.2</td>
<td>11.05±0.1</td>
<td>0.76_{-0.76}^{+0.75}</td>
<td>-4.15</td>
<td>-1.85</td>
</tr>
<tr>
<td>PG 0953+414</td>
<td>3.14</td>
<td>2.03</td>
<td>20.29±1.0(^b)</td>
<td>11.49±0.4</td>
<td>15.5_{-9.1}^{+10.8}</td>
<td>-2.57</td>
<td>-0.49</td>
</tr>
</tbody>
</table>

\(^a\)Unknown Hubble type, bulge correction estimated assuming Sa

\(^b\)From Bahcall et al. (1997)
Figure 1. The virial black hole mass calculated by the reverberation BLR method (from Wandel, Peterson & Malkan 1999) vs. the bulge magnitude (from Whittle 1992) for the Seyfert 1 galaxies in our sample (diamond), the masing Seyfert 2 galaxy NGC 1068 (square) and PG0953+414 (triangle). Open diamonds indicate an unknown Hubble type (and therefore a large uncertainty in the bulge magnitude). The dashed diagonal lines are the average BBRs for normal galaxies (Magorrian et al. 1998) and Seyfert 1s (this work).
3.2. Quasars

Laor (1998) has studied the black hole-host bulge relation for a sample of 15 bright PG quasars. Estimating the bulge masses from the Bahcall et al. (1997) study of quasar host galaxies he admits the uncertainty in estimating bulge luminosity, dominated by the much brighter nonstellar source.

Laor estimates the black hole mass using the H$\beta$ line width and the empirical relation $r_{BLR} = 15L_{44}^{1/2}$ light − days (Kaspi et al. 1997), where $L_{44} = L(0.1 - 1 \mu m)$ in units of $10^{44}$ erg s$^{-1}$.

As this relation has been derived for less than a dozen low- and medium luminosity objects (mainly Seyferts) with measured reverberation sizes, it is not obvious that it may be extrapolated to more luminous quasars. The BLR size is also dependent on the ionizing and soft X-ray continua (Wandel 1997). The WPM sample (which includes Kaspi’s sample) indicates that the slope of the BLR-size luminosity relation may flatter than 0.5; WPM find $r \sim 17L_{44}^{0.36 \pm 0.09}$ – d. If this result is correct, extrapolating the $r \sim L^{1/2}$ relation over two orders of magnitude (the difference between the average luminosity of the PG quasars used by Laor and Kaspi’s sample average) overestimates the black hole mass. Indeed, for the only object common to the Laor and WPM samples - the quasar PG 0953+414 - Laor finds $3 \times 10^8 M_\odot$, while the reverberation -rms method gives $(1.5^{+1.1}_{-0.9}) \times 10^8 M_\odot$.

3.3. Comparing Normal Galaxies, Seyferts and Quasars

Fig. 2 shows the three groups in the plane of black hole mass vs. bulge luminosity. The best fits and the corresponding standard deviations to the data in the three groups are ($M_8 = M_{BH}/10^8 M_\odot$ and $L_{10} = L_{bulge}/10^{10} L_\odot$):

1. Normal galaxies (Magorrian et al. 1998, table 2, excluding upper limits) - $M_8 = 2.9L_{10}^{1.26}$, $\sigma = 0.47$

2. PG quasars (Laor 1998, all objects in his table 1) - $M_8 = 1.6L_{10}^{1.10}$, $\sigma = 0.38$

3. Seyfert 1s (this work, excluding NGC 4051) $M_8 = 0.2L_{10}^{0.83}$, $\sigma = 0.43$
Figure 2. Mass estimates of MBHs plotted against the luminosity of the bulge of the host galaxy. Squares: MBH candidates from Magorrian et al. (1998), open squares - MBHs detected by maser dynamics triangles - PG quasars from Laor (1998), diamonds - Seyfert 1 galaxies (this work). MW denotes our Galaxy. Also given are the best linear fits for each class (see text). The dashed long line is the estimate of dead black holes from integrated AGN light.
As a group Seyfert 1 galaxies have a significantly lower BBR than normal galaxies and bright quasars. This lower value agrees with the remnant black hole density derived from integrating the emission from quasars (Chokshi and Turner 1992):

$$\rho_{BH} = \int \int \frac{L}{\epsilon c^2} \Phi(L, t) dL dt = 2 \times 10^5 (\epsilon/0.1) M_{\odot} \text{Mpc}^{-1},$$

(\Phi is the quasar luminosity function and \(\epsilon\) is the efficiency), which compared to the density of starlight in galaxies \(\rho_{gl}\) gives \(\rho_{BH}/\rho_{gl} = 2 \times 10^{-3} (0.1/\epsilon)(M_{\odot}/L_{\odot})\) (shown as a dashed line in Fig. 2).

**4. Black hole Evolution and the Black Hole - Bulge ratio**

**4.1. Demography**

While Seyfert 1 galaxies seem to have a lower BBR than bright quasars and the galaxies with detected MBHs in the Magorrian et al. (1998) sample, they are in good agreement with the BBRs of the upper limits and of our Galaxy, and with remnant quasar black holes. It is plausible therefore that the Seyfert galaxies in our sample represent a larger population of galaxies with low BBRs, which is under-represented in the Magorrian et al. sample. This hypothesis is supported by the distribution of black hole masses in Fig. 2: the only MBHs under \(2 \times 10^8 M_{\odot}\) detected by stellar dynamical methods are in the Milky Way, in Andromeda and its satellite M32, and in NGC 3377 (the latter being nearly \(10^8 M_{\odot}\)). These galaxies, as well as NGC1068 and at least two of the three upper limit in Magorrian’s sample do have low BBRs, comparable to our Seyfert 1 average. Actually for angular-resolution limited methods, the MBH detection limit is correlated with bulge luminosity: for more luminous bulges the detection limit is higher, because the stellar velocity dispersion is higher (the Faber-Jackson relation). In order to detect the dynamic effect of a MBH it is necessary to observe closer to the center, while the most luminous galaxies tend to be at larger distances, so for a given angular resolution, the MBH detection limit is higher.

This may imply that Magorrian et al. ’s sample is biased towards larger MBHs, as present stellar-dynamical methods are ineffective for detecting MBHs below \(\sim 10^8 M_{\odot}\) (except in the nearest galaxies). The BLR method is not subject to this constraint, making Seyfert 1 galaxies good candidates for detecting low-mass MBHs. (Note however that by the same token the WPM sample may be biased towards Seyferts with low black hole masses, which tend to vary on shorter timescales and hence are more likely to be chosen for reverberation studies).
4.2. Black Hole Growth by Accretion

Fig. 2 shows that Seyfert 1 galaxies have relatively small MBHs compared to MBHs in normal galaxies and to quasars, yet they have comparable bulges. Below we suggest a possible explanation.

Consider MBH growth by accretion from the host galaxy. Since the accretion radius, \( R_{\text{acc}} \approx 0.3M_6v_2^{-2}\text{pc} \) (where \( M_6 = M_{BH}/10^6M_\odot \) and \( v_2 = v_\ast/100\text{km s}^{-1} \) is the stellar velocity dispersion) is small compared with the size of the bulge, we may assume the mass supply to the black hole is given by the spherical accretion rate, \( \dot{M} = 4\pi\lambda R_{\text{acc}}v_\ast^2\rho_\ast = (1.4\times10^{-16}\text{yr})v_\ast^2\rho_\ast M_8^{-3}\dot{\rho}_\ast \), where \( \rho_\ast \) is the stellar (or gas) mass density in units of \( M_\odot\text{pc}^{-3} \) (corresponding to 4.4 g/cm\(^3\)) and \( \lambda < 1 \) is the Bondi parameter combined with a possible reduction factor due to angular momentum. Integrating we find the time required for growing from a mass \( M_i \) to \( M_f \) by accretion of gas or stars,

\[
 t_{\text{acc}} \approx (10^{16}\text{yr})v_\ast^2\rho_\ast^{-1}\lambda^{-1}(M_\odot/M_i - M_\odot/M_f) \approx (10^8\text{yr})M_8^{-1}v_\ast^2\rho_\ast^{-1} \]

For masses \( < 10^6\dot{\rho}_\ast^{-1}M_\odot \) this is larger than the Hubble time, so seed MBHs must grow by black hole coalescence which, even for dense clusters, is of the order of the Hubble time (Lee, 1993; Quinlan & Shapiro 1987). For densities as high as in the central parsec of the Milky Way (few \( \times 10^7M_\odot\text{pc}^{-3} \); Genzel et al. 1997) or for NGC 4256 (Miyoshi et al. 1995) accretion-dominated growth becomes feasible for masses as low as 100-1000\( M_\odot \).

While the accretion rate is growing as \( M^2 \) and the growth time decreases as \( M^{-1} \), the MBH eventually becomes large enough for accretion-dominated growth time \( t_g = t_{\text{acc}} \). This phase may be applicable for the Seyfert population. Since the luminosity is \( L \propto \dot{M} \propto M^2 \), the Eddington ratio increases as \( L/L_{\text{Edd}} \propto M \propto L^{1/2} \). The black hole growth slows down when the Eddington ratio approaches unity, \( t_g \) being bound by the Eddington time,

\[
 t_g \sim t_E = M/M_\text{E} = 4.5 \times 10^7(\epsilon/0.1)^{-1}\text{yr} \]

where \( M_\text{E} \) is the accretion rate that would produce an Eddington luminosity. Equating \( t_E \) to \( t_{\text{acc}} \) we find that the growth rate flattens at a BH mass of \( M_t \approx (2 \times 10^8M_\odot)v_\ast^2\rho_\ast^{-1}(\epsilon/0.1\lambda) \). In the Eddington-limited era, which may correspond to quasars, the growth rate is exponential, depleting the available matter in the bulge on the relatively short time scale \( t_{\text{Edd}} \). This leads to an asymptotic BBR, which is likely to be similar for luminous quasars and their largest remnant MBHs in normal galaxies.

This scenario predicts that on average quasars should have higher Eddington ratios (near unity) than Seyferts, and larger BBRs. We can test the prediction from the data at hand. Estimating the bolometric luminosity of AGN with reverberation data from the lag (WPM), and of PG quasars from the relation \( L_{\text{bol}} \approx 8\nu L_\nu(3000\text{A}) \) (Laor 1998), we find a correlation between the Eddington ratio and the BBR, with Seyferts having Eddington ratios in the \( 10^{-3} - 0.1 \) range and a low BBR, and quasars with Eddington ratios
close to unity and higher BBRs. From the Eddington ratio we can also infer the actual growth time, $t_g \approx t_E L / L_E$. For most objects in our sample $t_g$ is in the range $10^8 \text{--} \text{few} \times 10^9 \text{yr}$.

I acknowledge valuable discussions with Mark Whittle Gary Kriss, Geremy Goodman, Doug Richstone and Mark Morris and the hospitality of the Astronomy Department at UCLA.

REFERENCES


