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Relations between Massive Black Holes in AGN and their Host Galaxies

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Abstract

Massive black holes detected in the centers of many nearby galaxies are linearly correlated with the luminosity of the host bulge, the black hole mass being about 0.1% of the bulge mass. An even stronger relation exists between the BH mass (Mbh) and the stellar velocity dispersion in the host bulge. We show that massive BHs of AGNs (measured by reverberation mapping) and their bulge luminosity (measured by using a bulge/disk decomposition) follow the same relations as ordinary (inactive) galaxies, with the exeption of narrow line AGN which apparently have significantly lower BH/bulge ratios. Narrow line AGNs seem to be outstanding also in the Mbh-velocity dispersion relation: the small number of Seyfert galaxies with measured velocity dispersion indicate that narrow line Seyfert 1 galaxies have a smaller BH mass/velocity dispersion than quiescent galaxies and broad line Syferts. Estimating the velocity dispersion for from the bulge luminosity with the Faber-Jackson relation more than doubles the sample and supports these results.

1.1 Introduction

Over the past decade there has been a dramatic confirmation of the basic paradigm in which AGN are energized by the accretion of matter onto massive black holes (MBHs). Massive Black Holes (MBHs) detected in the centers of many nearby non-active galaxies (Kormendy and Richstone 1995, Kormendy & Gebhardt (2002)) show an approximately linear relation with the luminosity of the host bulge, inferring the black hole mass is 0.001-0.002 of the bulge. In addition to the MBHs detected by techniques of stellar and gas kinematics, the masses of about three dozen MBHs in AGNs have been estimated by reverberation mapping of the broad emission-line region. High quality reverberation data and virial BH mass estimates are presently available for 20 Seyfert 1 nuclei (Wandel, Peterson and Malkan 1999, hereafter WPM) and 17 PG quasars (Kaspi et al. 2000). The virial estimate has been shown to be consistent with the real BH mass (Peterson & Wandel 1999; 2000). Previous work suggested that MBHs of active galactic nuclei (Seyfert galaxies and quasars) follow a similar relation (Laor 1998; Ho 1999; Wandel 1999). New and updated data for AGN confirm that AGN and quiescent galaxies have the same BH-bulge mass relation (Wandel 2002; McLure & Dunlop 2002). A strong and tight relation was found between the BH mass and the central stellar velocity dispersion in the host galaxy: Ferrarese and Merritt (2000) and Gebhardt et al. (2000a) have found that MBHs of inactive galaxies is better correlated with the stellar velocity dispersion in the bulge than with the bulge luminosity.

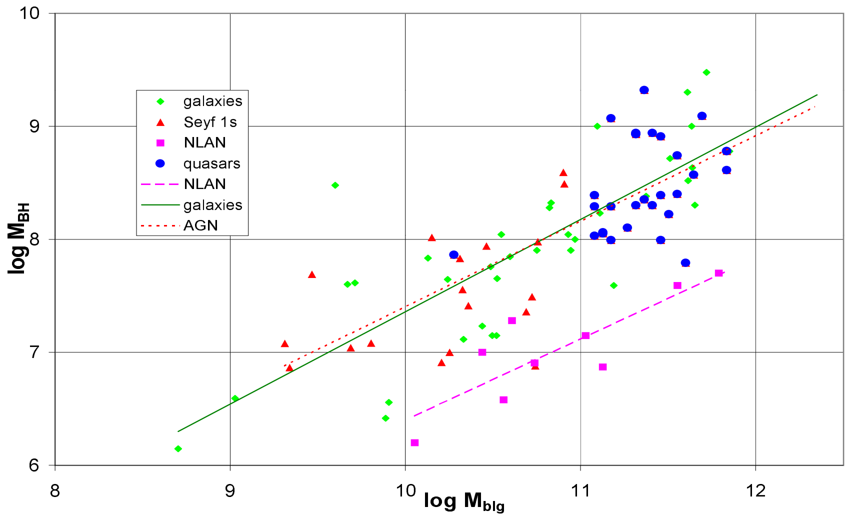

Fig. 1.1. Black hole mass vs. bulge mass. Green diamonds represent quiescent galaxies, red triangles and blue circles are broad line Seyferts and quasars, respectively, pink squares are narrow line AGNs

Apparently this relation holds also for AGNs: the few Seyfert galaxies with stellar velocity data and reverberation BH mass estimates seem to be consistent with the BH-velocity dispersion relation of inactive galaxies (Gebhardt et al. 2000b), a conclusion strengthened by recent observations of the velocity dispersion in reverberation mapped Seyfert galaxies (Ferrarese et al. 2001).

1.2 Results

We combine new and updated data to yield a data base of 55 AGNs (28 quasars, 18 Seyfert 1 galaxies and 9 narrow line Seyfert 1 galaxies and quasars). Most of these objects have reverberation mapping masses and almost all of them have the bulge luminosity measured directly by using bulge/disk decomposition (McLure & Dunlop 2000). Our results (Figure 1.1) indicate that broad-line AGNs(Wandel 2002) follow the same BH-bulge relation as ordinary (inactive) galaxies (Kormendy and Gebhardt 2002), while narrow line AGNs have significantly lower BH/bulge mass ratios. We find that broad line AGNs have an average black hole/bulge mass fraction of ~ 0.0015 with a strong correlation ($M_{\rm BH} \propto L_{\rm bulge}^{0.95\pm 0.16}$). This BH-bulge relation is consistent with the BH-bulge relation of quiescent galaxies and tighter than previous results. Narrow line AGNs (Narrow Line Seyfert 1s and quasars, defined by permitted lines narrower than 2000km/s) appear to have a lower BH/bulge ratio, $M_{\rm BH}/M_{\rm bulge} \sim 10^{-4} - 10^{-3}$. The lower BH/bulge ratio of narrow line AGNs does not reflect in the $\sigma - M_{BH}$ relation: the narrow line Seyfert 1 galaxies with measured stellar velocity

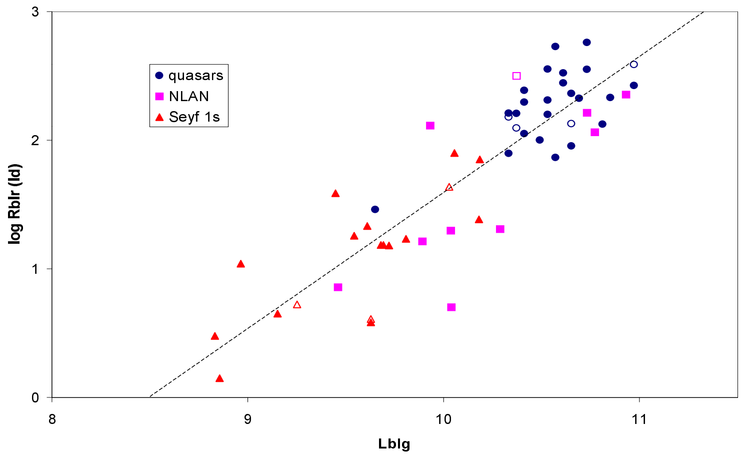

Fig. 1.2. Size of broad emission-line region (BLR) vs. bulge luminosity. Triangles and circles are broad line Seyferts and quasars, respectively, squares are narrow line AGNs

dispersion have the same $\sigma - M_{BH}$ relation as broad line AGNs and quiescent galaxies. We use the Faber-Jackson relation to predict the velocity dispersion of AGNs and combine it with the measured reverberation BH masses to give the $\sigma - M_{BH}$ relation for over 50 AGNs.

1.3 Dependence on the Broad Emission-Line Width

The lower BH/bulge ratios of narrow-line AGN seems to be part of a continous trend: we find that the $M_{\rm BH}/L_{\rm bulge}$ ratio in AGN is strongly correlated with the emission-line width, $M_{\rm BH}/L_{\rm bulge} \sim FWHM(H\beta)^2$

This tight correlation is not surprising - it is probably reflecting the virial relation $M_{\rm BH} = 1.46 \times 10^5 M_\odot \left(\frac{R_{blr}}{\rm lt\text{-}days}\right)\left(\frac{v_{FWHM}}{10^3 \rm km\ s^{-1}}\right)^2$. Combining the two relations and cancelling out the dependence on the line width (velocity) on both sides of the equation we find a new, independent relation:

$$R_{BLR} \approx 27 \left(\frac{L_{\rm bulge}}{10^{10} L_\odot}\right) \quad \rm lt-days.$$

a very tight correlation between bulge luminosity and BLR size (fig.1.2) The best fit to all 55 AGNs in our sample is $R = 13.5 L_{10}^{1.05}$ $\;$ lt $-$ days with a correlation coefficient of 0.91.

This is a non trivial correlation, as it relates two independent observables: on the one hand the bulge luminosity, a global galactic property on a scale of kpc, and on the other hand the distance of the line-emitting ionized gas from the central continuum source - the broad line region (BLR) size measured by reverberation mapping - on a scale of few light days. The correlation may be caused by the BLR radius scaling with the AGN luminosity via the Eddington ratio, but it is much stronger than the BH-bulge relation which supports the

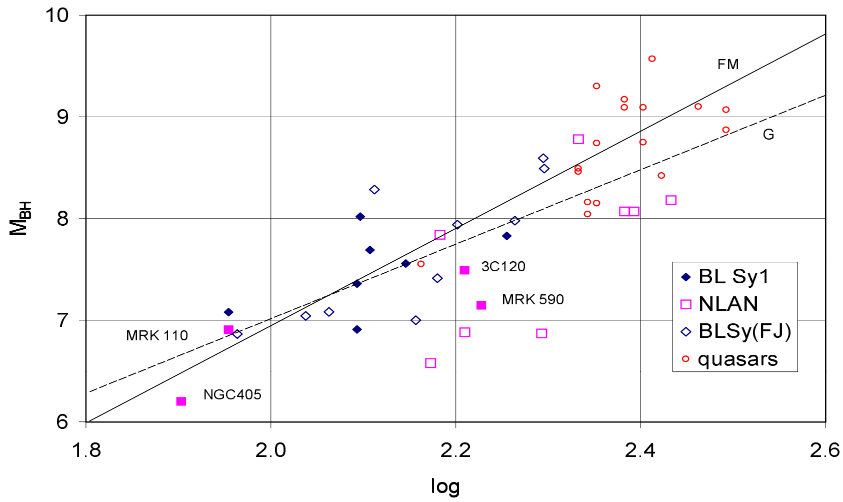

Fig. 1.3. Black hole mass of AGNs plotted against the stellar velocity dispersion ($v^* = \sigma$). Blue triangles are broad line Seyferts, pink squares denote NLS1s and red circles denote quasars. Solid symbols dennote Seyferts with measured σ, open ones denote Seyferts for which σ has been estimated from the Faber-Jackson relation (see text). The dashed and solid lines show the $\sigma - M_{\rm BH}$ relation of galaxies (Gebhardt et al. 2000a and Ferrarese & Merritt 2000, respectively).

possibility of this new relation being more fundamental. Interestingly, Narrow line AGNs are not different from broad line AGNs in this new relation.

1.4 The BH Mass - Velocity Dispersion Relation in AGN

We find that in AGNs with "narrow" boad lines (e.g. Hβ the black hole /bulge ratio seems to be significantly smaller than in broad line AGNs and in normal galaxies. Yet, in earlier works Seyfert galaxies seem to be consistent with the $\sigma - M_{\rm BH}$ relation of inactive galaxies (Gebhardt et al. 2000b; Merritt & Ferrarese 2001b). The question whether NLANs have smaller BH masses can therefore be approached by looking more carefully at their location in the $\sigma - M_{\rm BH}$ plane. The bulge velocity dispersion is measured only for 11 Seyfert 1 galaxies. Of these 4 can be classified as having narrow lines (Mrk 110, Mrk 590, 3C120 and NGC 4051) and 8 broad-line Seyferts. (We define narrow line AGNs as having FWHM(H$\beta < 2200$km s^{-1}).

In Figure 1.3 the BH mass is plotted against the stellar velocity dispersion. We see that broad line AGNs are consistent with the $M_{\rm BH} - \sigma$ relation of inactive galaxies ($M_{\rm BH} \propto \sigma^{\alpha}$, with $\alpha = 3.5 - 5$; Gebhardt et al. (2000a) find α =3.65 and Merritt and Ferrarese (2001a) give

4.72). This result is in agreement with previous results of smaller AGN samples (Gebhardt 2000b, Merritt & Ferrarese 2001b) .

We can now determine whether narrow line AGNs follow the same $M_{\rm BH}-\sigma$ relation (which would be in odds to their lower $M_{bh}-L_{blg}$ ratios) or they lie below the broad line AGNs in the $M_{\rm BH}-\sigma$ relation as well. If we look carefully at the locations of the NLS1s in Figure 1.3 (modifiied version of fig 7 in Wandel 2002) we see that out of the four narrow line Seyfert 1s with measured σ denoted by solid pink squares in Figure 1.3), three (MRK 590, 3C120 and NGC 4051) do have lower Mbh than the $M_{\rm BH}-\sigma$ relation of quiescent galaxies and broad line Seyferts. These NLS1s (and particularely 4th, MRK 110) have larger bulge luminosity than the average " $\sigma-L_{blg}$ relation" defined by all the Seyfert galaxies with measured bulge luminosity and velocity dispersion (fig. 6 of Wandel 2002). Therefore, part of the reason for the smaller $M_{\rm BH}-L_{blg}$ ratios of NLANs could be their relatively larger bulges.

1.5 Enhancing the Sample with the F-J Relation

For AGNs without a direct velocity dispersion measurement the relation between the narrow line width and the velocity dispersion (Nelson 2000) may be used to estimate the velocity dispersion in the bulge. Interestingly, a tight linear relation seems to exist between virial mass given by the narrow [OIII] line and the BH mass in Seyfert galaxies (Wandel and Mushotzky 1986).

Here we use the Faber-Jackson (F-J) relation to estimate the velocity dispersion of other AGN with measured or estimated bulge luminosity. This is useful to locate those AGNs (mainly quasars) which do not have a measured stellar velocity dispersion. Although the F-J estimates of the velocity dispersion are less certain since the F-J relation has a large scatter, it is encouraging that they lie reasonably well within the same relation as the measured AGNs.

The standard F-J relation is $L = L_o\sigma_2^4$, where $\sigma_2 = \sigma/100{\rm km\ s}^{-1}$ and L_o is a luminosity coefficient determined by a linear fit with a slope of 4 to the observed Seyfert Galaxies with measured stellar velocity dispersion. Using this relation one may enlarge the sample and increase the dynamical range by including also quasars, for a better estimate of the $\sigma-M_{\rm BH}$ relation for AGN. We note that the NLS1s with measured σ have a significantly larger luminosity coefficient than broad line ones (fig 6 of Wandel 2002): while for broad line Seyfert 1 galaxies $L_o = 10^9{\rm erg\ s}^{-1}$, for NLS1s galaxies $L_o = 6\times10^9{\rm erg\ s}^{-1}$. We thus use the best linear fit with imposed slope of 4, $L_o = 1.6\times10^9{\rm erg\ s}^{-1}$.

Doing this we see that all narrow line AGNs added in this manner (open pink squares in fig. 1.3) have lower BH masses than the value expected from the $\sigma-M_{\rm BH}$ relation. In Wandel (2002) a different conclusion is obtained because a larger L_o is used for narrow line AGNs.

1.6 Conclusion

We conclude that the lower $M_{\rm BH}/L_{bulge}$ relation of NLS1s and narrow line quasars is a result of a lower reverberation BH mass (relatively to the broad line AGNs) - which is reflected also in a lower M_{bh}/σ^4 ratio. Part of the effect may be due to a relatively larger L_{bulge}/σ^4 ratio (relative to broad line Seyferts).

Six out of the eight NLANs with estimated σ from the F-J relation (open pink squares in fig. 1.3) lie below the $M_{\rm BH}-\sigma$ relation (smaller BH masses). The lower reverberation BH mass of NLANs may be intrinsic or apparent, e.g. if the emission lines of NLANs seem narrower as a result of inclination, if the BLR has a flattened geometry and is viewed nearly edge on.

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