ON BLACK HOLE MASSES AND RADIO LOUDNESS IN AGN

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ABSTRACT

The distribution of radio to optical fluxes in AGN is bimodal. The physical origin for this bimodality is not understood. In this Letter I describe observational evidence, based on the Boroson & Green PG quasar sample, that the radio loudness bimodality is strongly related to the black hole mass ($M_{\text{BH}}$). Nearly all PG quasars with $M_{\text{BH}} > 10^9 M_\odot$ are radio loud, while quasars with $M_{\text{BH}} < 3 \times 10^8 M_\odot$ are practically all radio quiet. This result is consistent with the dependence of quasar host galaxy morphology on radio loudness. There is no simple physical explanation for this result, but it may provide a clue on how jets are formed near massive black holes. The radio loudness–black hole mass relationship suggests that the properties of various types of AGN may be largely set by three basic parameters, $M_{\text{BH}}$, $L/L_{\text{Eddington}}$, and inclination angle.

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

The radio to optical flux distribution in AGN is bimodal. This is demonstrated most clearly in the recent large compilation of Xu, Livio, & Baum (1999), which shows that radio loud AGN are about $10^4$ times brighter in the radio than radio quiet AGN with the same [O III] luminosity (which provides a measure of the ionizing continuum luminosity). The reason for this bimodality is one of the basic unsolved problems in AGN physics (e.g. Krolik 1999, Ch.15).

The radio emission is produced by relativistic electrons which are powered by a jet, both in radio loud AGN (e.g. Begelman, Blandford, & Rees 1984), and apparently also in radio quiet AGN (Blundell & Beasley 1998). What then controls the jet power, and why is the relative (i.e. radio to bolometric) power distribution bimodal? An ion torus may be required to collimate the jet, a spinning black hole may be required to accelerate the jet, and a low density environment may be required to allow it to propagate (e.g. Blandford & Znajek 1977; Blandford & Levinson 1995; Fabian & Rees 1995; Moderski, Sikora, & Lasota 1998; Rees et al. 1982; Wilson & Colbert 1995). However, no strong observational evidence is currently available to support these, or any other scenarios.

Hubble Space Telescope (HST) observations over the past few years established that radio loud quasars always reside in bright elliptical (or sometimes interacting) hosts, and that all quasars with spiral hosts are radio quiet (e.g. Bahcall et al. 1997; McLure et al. 1999). This relation is puzzling, how does the inner mpc of a galaxy, where the jet originates, knows about the type of host it resides in?

Some recent observations, and the new evidence described in this paper, provide a clue for one of the basic parameters which appears to control the formation of powerful jets, as further described below (see Laor 2000 for a short account).

2. EXISTING EVIDENCE

Xu, Livio, & Baum (1999) noted that radio loud AGN extend to higher [O III] luminosity than radio quiet AGN, and suggested that this may imply that the distribution of black hole masses in radio loud AGN extends to higher masses. Corbin (1997) made a similar suggestion based on the tendency of radio loud AGN to have broader H\(\beta\) lines.

A number of studies over the past few years established a few correlations which point more directly towards a relation between radio loudness and black hole mass, as further described below.

Compact non-thermal radio emission is commonly detected in the nuclei of normal elliptical galaxies (e.g. Sadler, Jenkins & Kotanyi 1989), and also in some spiral galaxies (Sadler et al. 1995). Similar emission is common in Seyfert galaxies (e.g. Nelson & Whittle 1996), and obviously in radio galaxies as well, where it is correlated with the nuclear H\(\alpha\) emission (e.g. Zirbel & Baum 1995). Ho (1999a) has shown that the nuclear radio power \(L_R\) vs. H\(\alpha\) luminosity correlation extends down to the lowest powers observed in nearby ellipticals, suggesting that their radio emission originates in a scaled down AGN.

Nelson & Whittle (1996) explored relations between the bulge properties and the AGN properties in a large sample of Seyfert galaxies. They found a correlation between \(L_R\) and the bulge luminosity and velocity dispersion, which implies a correlation between \(L_R\) and the bulge mass (as suggested by Heckman 1983).

Magorrian et al. (1998), studied the demography of massive black holes in nearby galaxies, and found that possibly all bulge galaxies have a massive black hole with a mass which correlates with the bulge mass, as first suspected by Kormendy (1993). This correlation is further supported by the recent studies of Gebhardt et al. (2000) and Ferrarese & Merritt (2000).

If the radio power is correlated with the bulge mass, and the bulge mass is correlated with the black hole mass (in both active and non active galaxies), then the radio power may be directly linked with the black hole mass. Indeed, Franceschini, Vercellone & Fabian (1998) found a surprisingly tight relation between black hole mass and radio power in a small sample of nearby mostly non active galaxies. McLure et al. measured the host properties of a sample of AGN, made an indirect estimate of their \(M_{BH}\) using the Magorrian et al. relation, and found their objects follow the \(M_{BH} vs. L_R\) relation of Franceschini et al.

Thus, it is interesting to explore whether there is a direct relation between \(M_{BH}\) and \(L_R\) in AGN as found for nearby galaxies, and also whether the radio loudness bimodality is related in any way to \(M_{BH}\).
3. THE NEW EVIDENCE

In order to explore the $M_{\text{BH}}$ vs. $L_R$ relation directly in AGN ones needs a direct way to estimate $M_{\text{BH}}$. A long known method to deduce $M_{\text{BH}}$ is to use the broad emission line width, and the distance of the Broad Line Region (BLR) from the center, together with the assumption of Keplerian motion (e.g. Dibai 1980). This method was subject to unknown, but potentially large errors, due to unestablished assumptions concerning the BLR radius, dynamics, and kinematics. Significant progress in reverberation mapping over the past few years established the radius luminosity relation for the BLR (Kaspi et al. 2000), and strongly suggests Keplerian dynamics in a few well explored cases (e.g. Peterson & Wandel 2000). However, possible anisotropy of the ionizing continuum, and of the cloud kinematics, still leaves a room for potentially significant systematic errors.

The Hβ line width and continuum luminosity were used by Laor (1998) to derive $M_{\text{BH}}(\text{Hβ})$ for a sample of Palomar Green (PG) quasars (Schmidt & Green 1983) observed by Bahcall et al. with the HST. This study revealed that $M_{\text{BH}}(\text{Hβ})$ is correlated with the bulge luminosity, and that this correlation overlaps remarkably well the Magorrian et al. correlation. This overlap provides an indirect check for the accuracy of the $M_{\text{BH}}(\text{Hβ})$ estimate, and indicates that any remaining systematic errors are less than a factor of 2–3 (Laor 1998). This check is particularly important for the radio loud AGN, where the generally large width of Hβ could otherwise be attributed to jet interactions with the BLR, as was suggested by Whittle (1992) for the forbidden lines of radio loud AGN.

To explore the $M_{\text{BH}}$ vs. $L_R$ relation in quasars I use the Boroson & Green (1992) sample of all 87 $z < 0.5$ PG quasars, where they provide Hβ FWHM values based on their high quality optical spectra. 1 The optical continuum luminosity is taken from Nuegebauer et al. (1987). These parameters are combined, as in Laor (1998), to yield $m_\beta = 0.18 \Delta v_{3000}^2 L_{46}^{1/2}$, where $m_\beta = M_{\text{BH}}(\text{Hβ})/10^9 M_\odot$, $\Delta v_{3000} \equiv \text{Hβ FWHM}/3000$ km s$^{-1}$, and $L_{46} = L_{\text{bol}}/10^{46}$ erg s$^{-1}$, where the bolometric luminosity is $L_{\text{bol}} = 8.3 \times \nu L_{\nu}(3000 \text{Å})$. Kaspi et al. suggest a somewhat steeper radius luminosity relation for the BLR than assumed above, but this has a small effect (< 50%) on the mass estimates of most objects. The radio luminosity $L_R \equiv \nu L_{\nu}(5 \text{ GHz})$ is obtained from Kellermann et al. (1989), modified for $H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $\Omega_0 = 1$ adopted here.

Franceschini et al. found a tight relationship between $M_{\text{BH}}$ and $L_R$ based on a compilation of these parameters for 13 nearby weakly or non active galaxies. A larger sample of 29 nearby galaxies is obtained here by combining all $M_{\text{BH}}$ values from Magorrian et al., and Gebhardt et al. (which supersedes some of the Magorrian et al. values), with all single dish 5 GHz $L_R$ values from Fabbiano, Gioia & Trinchieri (1989), and Becker, White, & Edwards (1991).

Figure 1 shows the $M_{\text{BH}}$ vs. $L_R$ relation for the 87 PG quasars, and the 29 nearby galaxies, together with the linear relation found by Franceschini et al. The scatter is very large. Nearby galaxies display a range of typically $10^4$ in $L_R$ at a given $M_{\text{BH}}$, and this range increases to $10^6$, or more, when active galaxies are included.

There is certainly a trend of $L_R$ increasing with $M_{\text{BH}}$, but the tight relation suggested by Franceschini et al. is not supported by our data. This trend is more apparent for the quasars. In particular, there appears to be a rather sharply defined ”zone of avoidance”, where the maximum radio luminosity $L_{R, \text{max}}$, at a given $M_{\text{BH}}$, increases with $M_{\text{BH}}$. The increase in $L_{R, \text{max}}$ is highly nonlinear, going up from $\sim 5 \times 10^{38}$ erg s$^{-1}$ for $10^7 M_\odot$, to $\sim 5 \times 10^{40}$ erg s$^{-1}$ for $10^8 M_\odot$, to $> 10^{44}$ erg s$^{-1}$ for $10^9 M_\odot$.

The very large range of $L_R$ at a given $M_{\text{BH}}$ is not surprising, it may simply be due to different levels of overall continuum luminosity of different AGN with the same black hole mass. However, how is the fraction of the bolometric luminosity emitted in the radio dependent on $M_{\text{BH}}$?

Figure 2 shows the relation between $M_{\text{BH}}$ and the radio loudness parameter $R \equiv f_\nu(5 \text{ GHz})/f_\nu(4400 \text{ Å})$ for the Boroson & Green sample, as taken from Kellermann et al. The distribution of $R$ values is bimodal, with a minimum at $R = 10$, commonly used to define radio loud vs. radio quiet quasars. The distribution of $M_{\text{BH}}$ for the radio loud and radio quiet PG quasars is remarkably different. Most quasars (10/11) with $M_{\text{BH}} > 10^9 M_\odot$ are radio loud, and essentially all quasars with $M_{\text{BH}} < 3 \times 10^8 M_\odot$ are radio quiet. The probability that the radio loud and radio quiet PG quasars are drawn from the same mass distribution is $4 \times 10^{-7}$ according to the KS test (using the KSTWO

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1 with the following corrections: PG 1307+085 FWHM=5320 km s$^{-1}$, PG 2304+042 FWHM=6500 km s$^{-1}$.
routine of Press et al. 1992). Interestingly, despite the highly significant difference in mass distribution, the difference in the distribution of \(L/L_{\text{Eddington}}\) values (\(\propto L_{\text{bol}}/m_{9}\)) is much less significant (4.4 \times 10^{-2}).

4. DISCUSSION

The tight relation between radio luminosity and black hole mass suggested by Franceschini et al. is not supported by our larger sample of 29 nearby galaxies. The scatter becomes even larger when active galaxies are included. For example, at \(M_{\text{BH}} = 3 \times 10^{8} M_{\odot}\) the radio power ranges from \(< 10^{35} \text{ erg s}^{-1}\) to \(10^{42} \text{ erg s}^{-1}\) (Fig.1). The non-thermal emission associated with a massive black hole is high when the system is active, but it can be very weak to non-detectable when the system is generally inactive.

However, the radio/optical luminosity ratio, or equivalently the relative jet power, in active galaxies is strongly related to the black hole mass (Fig.2). A high mass black hole, \(M_{\text{BH}} > 3 \times 10^{8} M_{\odot}\), is necessary for a relatively powerful jet, and is sufficient if \(M_{\text{BH}} > 10^{9} M_{\odot}\). Conversely, relatively powerful jets are impossible if \(M_{\text{BH}} < 3 \times 10^{8} M_{\odot}\). *Why should the relative jet power be so critically dependent on \(M_{\text{BH}}\)?*

None of the models for the formation of powerful jets (mentioned in \S1) predicts such a strong dependence on \(M_{\text{BH}}\). Some of these models suggest that radio loud AGN should have a low \(L/L_{\text{Eddington}}\) (e.g. Rees et al.), but as mentioned in \S3, the observed dependence on \(M_{\text{BH}}\) is much stronger than the dependence on \(L/L_{\text{Eddington}}\).

One physical process which is directly linked to \(M_{\text{BH}}\) is tidal disruption of main sequence stars outside the event horizon, which ceases for \(M_{\text{BH}} > 2 \times 10^{8} M_{\odot}\) for a rotating black hole (e.g. Rees 1988). However, tidal disruption is likely to be rather intermittent (< \(10^{-1}\) yr\(^{-1}\), Rees), and it is not clear why its effects (e.g. the disruption of a jet maintaining B field configuration) should be so long lasting, compared to the local dynamic timescale (<day). Alternatively, if jets are powered by the black hole spin, then the above correlation may result from a tight relation between black hole mass and spin.

Falcke, Sherwood, & Patnaik (1996) cautioned that since radio quiet quasars may also be powered by jets, some of the apparently radio loud quasars in the PG sample could be intrinsically radio quiet quasars which are beamed at us. These Radio Intermediate Quasars (RIQ) can be identified through their flat radio spectra (\(\alpha > -0.5\), indicating core dominance), yet relatively low \(R\) values (\(< 250\)) compared to flat spectrum radio selected quasars. There are four RIQ in the Boroson & Green sample, PG 0007+106, PG 1302–102, PG 1309+355, and PG 2209+184. VLBI observations of three of these confirmed their highly compact sizes (mas), as expected under the beaming hypothesis (Falcke, Patnaik, & Sherwood 1996), and also revealed superluminal motion in one (PG 0007+106, Brunthaler et al. 2000). These four RIQ are marked in Fig.2. It is interesting that these four objects all fall at the lowest \(M_{\text{BH}}\) values of the radio loud quasars. If these quasars are indeed all intrinsically radio quiet, then radio loud and radio quiet AGN may overlap only in the range \(5 \times 10^{8} M_{\odot} < M_{\text{BH}} < 10^{9} M_{\odot}\), and given the likely uncertainty in the \(M_{\text{BH}}\) estimate, may not overlap at all.

The \(M_{\text{BH}}\) vs. bulge mass relation, together with the \(R-M_{\text{BH}}\) relationship, provides a phenomenological understanding of the relation between radio loudness and host properties. Spiral galaxies have small bulges, these bulges have low mass black holes, and these cannot produce radio loud AGN. A radio loud quasar requires a massive black hole, and this is found only in bright ellipticals. Elliptical galaxies can have a low luminosity, thus a black hole mass below \(10^{9} M_{\odot}\), and thus host radio quiet AGN, as observed. Similarly, BL Lac objects, which are always radio loud, are essentially always found in luminous elliptical hosts (e.g. Urry et al. 2000).

Lacy, Ridgway & Trentham (2000) have noted that the Magorrian et al. relation, together with the fact that radio loud AGN reside in bright ellipticals, “strongly suggests a link between radio loudness and black hole mass”, and further proposed this can explain the increase in the fraction of radio loud quasars with luminosity, from < \(10\%\) at \(M_{B} > -24\) to ~ \(50\%\) at \(M_{B} = -28\) seen in some surveys (Hooper et al. 1996; Goldschmidt et al. 1999). This rise is consistent with the \(R-M_{\text{BH}}\) relationship since a magnitude of \(M_{B} = -28\) corresponds to \(\nu L_{\nu}(4400\text{Å}) \sim 5 \times 10^{46} \text{ erg s}^{-1}\), or \(L_{\text{bol}} \sim 5 \times 10^{47} \text{ erg s}^{-1}\), and thus if the Eddington limit applies, then \(M_{\text{BH}} > 4 \times 10^{9} M_{\odot}\). However, Stern et al. (2000) find the fraction of \(z > 4\) radio loud quasars to be constant up to \(M_{B} = -28\). Thus, the validity of the \(R-M_{\text{BH}}\) relationship at high redshifts remains an open question.

The \(R-M_{\text{BH}}\) relationship may help explain the low fraction of radio loud AGN at \(M_{B} > -24\) in some quasar surveys (e.g. Hooper et al.). Radio loud AGN
necessarily reside in bright hosts, and if the AGN is weak the object will be classified as a “radio galaxy”, and may be rejected from optical quasar surveys due to color or morphology criteria. Radio quiet AGN can reside in fainter hosts, and thus be easier to detect in quasar surveys down to lower luminosity.

How far down in luminosity is the $R$–$M_{\text{BH}}$ relationship maintained? The relation between bulge luminosity and $L_R$ presented by Nelson & Whittle (1996) suggests (through the $M_{\text{BH}}$ vs. $M_{\text{bulge}}$ relation) that the $R$–$M_{\text{BH}}$ relationship holds down to the Seyfert luminosity level. Further down, at the very weakly active galaxies level little data is currently available. Ho (1999b) provides a rough spectral energy distribution for seven very weak AGN ($L_{\text{bol}} \sim 10^{41} - 10^{42}$ erg s$^{-1}$) with measured $M_{\text{BH}}$. The standard $R$ parameter may not be a useful indicator of the relative jet power in these AGN since the optical emission carries a very small fraction of $L_{\text{bol}}$. I therefore use $L_R/L_{\text{bol}}$ instead of $R$ for the relative jet power, where $L_R$ is obtained from single dish broad beam (rather than VLB1) radio fluxes, to roughly match the spatial scales measured for the PG quasars. The two AGN in the sample of Ho with $M_{\text{BH}} = 4 \times 10^6 M_\odot$ have $\langle \log L_R/L_{\text{bol}} \rangle = -4.1$, while the other five AGN with $M_{\text{BH}} \geq 5 \times 10^8 M_\odot$ have $\langle \log L_R/L_{\text{bol}} \rangle = -2.2$. This suggests that the $R$–$M_{\text{BH}}$ relationship extends down to very low AGN activity levels. Interestingly, the jets in the Galactic microquasars, which most likely harbor $\sim 10 M_\odot$ black holes, are also “radio quiet” (e.g. Mirabel & Rodriguez 1998, Log $L_R/L_{\text{bol}}$ $\sim -7$).

How sharp is the transition in $R$ with $M_{\text{BH}}$? The $R$–$M_{\text{BH}}$ relationship is established here only for $z \leq 0.5$ optically selected bright AGN. It is important to study this relationship in a similarly complete, well defined, and deep sample of radio selected AGN, such as the FIRST Bright Quasar Survey sample (although this sample includes relatively few “proper” radio quiet AGN). Optical spectroscopy of a relatively large and heterogeneous sample of radio selected quasars is presented by Brotherton (1996). The lack of accurate spectrophotometry, non uniform spectroscopy, and sample inhomogeneity do not allow one to draw robust conclusions on the $R$–$M_{\text{BH}}$ relationship. However, at the order of magnitude level, one finds that all the newly measured quasars in this sample (except one, 3C 232) appear to have $M_{\text{BH}} \geq 10^8 M_\odot$, and $\sim 2/3$ appear to have $M_{\text{BH}} > 3 \times 10^8 M_\odot$.

If radio loudness is indeed set by $M_{\text{BH}}$, then it may be possible to relate the various types of AGN to various combinations of just three basic parameters, $M_{\text{BH}}$, $L/L_{\text{Edd}}$, and the inclination angle $\theta$. Figure 3 provides a rough sketch of the likely positions of the various types of AGN in the $M_{\text{BH}}$, $L/L_{\text{Edd}}$, $\theta$ cube. All radio loud AGN are located on the high $M_{\text{BH}}$ side, and all AGN where the bulge light is significant, or dominant, are necessarily on the low $L/L_{\text{Edd}}$ side. The position along the $\theta$ axis is derived from inclination based unification schemes which are now quite well established (Antonucci 1993; Urry & Padovani 1995; Wills 1999).

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REFERENCES

Fig. 1.— The dependence of radio luminosity on black hole mass. Nearby normal galaxies are marked as filled squares, and the PG quasars as empty triangles. Points with downward arrows indicate upper limits. The tight relation found by Franceschini et al. for a smaller sample of nearby galaxies is indicated by the solid line. Note the very large scatter in this relation for both active and non active galaxies.
Most quasars with $M_{\text{BH}} > 10^9 M_\odot$ are radio loud ($\log R > 1$), and essentially all quasars with $M_{\text{BH}} < 3 \times 10^8 M_\odot$ are radio quiet. The objects surrounded by a circle were proposed by Falcke et al. to be beamed intrinsically radio quiet quasars (see text), if true then radio loud and radio quiet quasars may not overlap in $M_{\text{BH}}$. 

Fig. 2.— The radio loudness versus black hole mass for the Boroson & Green sample of 87 $z \leq 0.5$ PG quasars.
Fig. 3.— A schematic representation of an $M_{\text{BH}}, L/L_{\text{Edd}}, \theta$ unification scheme. All objects at high $M_{\text{BH}}$ are radio loud. All objects at low $L/L_{\text{Edd}}$ have a low AGN/bulge luminosity ratio. All objects at $\theta \sim 90^\circ$ have an obscured core (the standard AGN unification scheme).