ON BLACK HOLE MASSES AND RADIO LOUDNESS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

The distribution of radio to optical fluxes in active galactic nuclei (AGNs) is bimodal. The physical origin for this bimodality is not understood. In this Letter I describe observational evidence, based on the Boroson & Green Palomar-Green 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 as to 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: $M_{\text{BH}}$, $L/L_{\text{Edd}}$, and inclination angle.

Subject headings: galaxies: nuclei — quasars: general

1. INTRODUCTION

The radio-to-optical flux distribution in active galactic nuclei (AGNs) is bimodal. This is demonstrated most clearly in the recent large compilation of Xu, Livio, & Baum (1999), which shows that radio-loud AGNs are about 10$^4$ times brighter in the radio than radio-quiet AGNs 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, chap. 15).

The radio emission is produced by relativistic electrons that are powered by a jet, both in radio-loud AGNs (e.g., Begelman, Blandford, & Rees 1984) and apparently also in radio-quiet AGNs (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 milliparsec of a galaxy, where the jet originates, know about the type of host it resides in?

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

2. EXISTING EVIDENCE

Xu et al. (1999) noted that radio-loud AGNs extend to higher [O iii] luminosity than radio-quiet AGNs and suggested that this may imply that the distribution of black hole masses in radio-loud AGNs extends to higher masses. Corbin (1997) made a similar suggestion based on the tendency of radio-loud AGNs to have broader H$\beta$ lines. A number of studies over the past few years established a few correlations that point more directly toward a relation between radio loudness and black hole mass, as further described below.

Compact nonthermal 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 $L_r$ versus H$\alpha$ luminosity correlation extends down to the lowest powers observed in nearby elliptical galaxies, 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 that 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 nonactive 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 nonactive galaxies. McLure et al. (1999) measured the host properties of a sample of AGNs, made an indirect estimate of their $M_{\text{BH}}$ ’s using the Magorrian et al. (1998) relation, and found their objects follow the $M_{\text{BH}}-L_r$ relation of Franceschini et al. Thus, it is interesting to explore whether there is a direct relation between $M_{\text{BH}}$ and $L_r$ in AGNs as found for nearby galaxies and also whether the radio loudness bimodality is related in any way to $M_{\text{BH}}$.

3. THE NEW EVIDENCE

In order to explore the $M_{\text{BH}}-L_r$ relation directly in AGNs, one 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 mappings 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 room for potentially significant systematic errors.

The Hβ line width and continuum luminosity were used by Laor (1998) to derive $M_{\text{BLR}}(H\beta)$ for a sample of Palomar-Green (PG) quasars (Schmidt & Green 1983) observed by Bahcall et al. (1997) with HST. This study revealed that $M_{\text{BLR}}(H\beta)$ is correlated with the bulge luminosity and that this correlation overlaps remarkably well the Magorrian et al. (1998) correlation. This overlap provides an indirect check for the accuracy of the $M_{\text{BLR}}(H\beta)$ 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 AGNs, 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 AGNs.

To explore the $M_{\text{BLR}}-L_\beta$ 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. The optical continuum luminosity is taken from Neugebauer et al. (1987). These parameters are combined, as in Laor (1998), to yield $m_\beta = 0.18\Delta v_{3000} L_{\text{bol}}^{1/4}$, where $m_\beta \equiv M_{\text{BLR}}(H\beta)/10^9 M_\odot$, $\Delta v_{3000} \equiv H\beta$ FWHM/3000 km s$^{-1}$, and $L_{\text{bol}} = L_{\text{bol}}/10^{46}$ ergs s$^{-1}$, where the bolometric luminosity is $L_{\text{bol}} = 8.3\nu L_\nu(3000 \AA)$. Kaspi et al. (2000) 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 $L_\beta \equiv n L_\nu (5 \text{ GHz})$ is obtained from Kellermann et al. (1989), modified for $H_\circ = 80$ km s$^{-1}$ Mpc$^{-1}$ and $Q_\circ = 1$ adopted here.

Franceschini et al. (1998) found a tight relationship between $M_{\text{BLR}}$ and $L_\beta$ based on a compilation of these parameters for 13 nearby weakly active or nonactive galaxies. A larger sample of 29 nearby galaxies is obtained here by combining all $M_{\text{BLR}}$ values from Magorrian et al. (1998) and Gebhardt et al. (2000); which supersedes some of the Magorrian et al. values, with all single-dish 5 GHz $L_\beta$-values from Fabbian, Gioia, & Trinchieri (1989), and Becker, White, & Edwards (1991).

Figure 1 shows the $M_{\text{BLR}}-L_\beta$ relation for the 87 PG quasars and the 29 nearby galaxies, together with the linear relation found by Franceschini et al. (1998). The scatter is very large. Nearby galaxies display a range typically of 10$^4$ in $L_\beta$ at a given $M_{\text{BLR}}$, and this range increases to 10$^5$ or more when active galaxies are included.

There is certainly a trend of $L_\beta$ increasing with $M_{\text{BLR}}$, but the tight relation suggested by Franceschini et al. (1998) 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 $L_{\text{max}}$ at a given $M_{\text{BLR}}$ increases with $M_{\text{BLR}}$. The increase in $L_{\text{max}}$ is highly nonlinear, going up from $\sim 5 \times 10^{44}$ ergs s$^{-1}$ for 10$^4 M_\odot$ to more than 10$^{44}$ ergs s$^{-1}$ for 10$^9 M_\odot$.

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

Figure 2 shows the relation between $M_{\text{BLR}}$ and the radio loudness parameter $R \equiv f_\nu (5 \text{ GHz})/f_\nu (4400 \AA)$ for the Boroson & Green (1992) sample, as taken from Kellermann et al. (1989). The distribution of $R$-values is bimodal, with a minimum at $R = 10$, commonly used to define radio-loud versus radio-quiet quasars. The distribution of $M_{\text{BLR}}$ for the radio-loud and radio-quiet PG quasars is remarkably different. Most quasars (10/11) with $M_{\text{BLR}} > 10^5 M_\odot$ are radio-loud, and essentially all quasars with $M_{\text{BLR}} < 3 \times 10^5 M_\odot$ 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 Kolmogorov-Smirnov test (using the KSTWO routine of Press et al. 1992). Interestingly, despite the highly significant difference in mass distribution, the difference in the

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Footnote:

1 With the following corrections: PG 1307+085, FWHM = 5320 km s$^{-1}$; PG 2304+042, FWHM = 6500 km s$^{-1}$.

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Fig. 1.—Dependence of radio luminosity on black hole mass. Nearby normal galaxies are marked as filled squares and the PG quasars as open triangles. Symbols with arrows indicate upper limits. The tight relation found by Franceschini et al. (1998) 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 nonactive galaxies.

Fig. 2.—Radio loudness vs. black hole mass for the Boroson & Green (1992) sample of 87 $z < 0.5$ PG quasars. Most quasars with $M_{\text{BLR}} > 10^6 M_\odot$ are radio-loud ($R > 1$), and essentially all quasars with $M_{\text{BLR}} < 3 \times 10^5 M_\odot$ are radio-quiet. The circled squares were proposed by Falcke et al. (1996a, 1996b) to be beamed intrinsically radio-quiet quasars (see text); if true, radio-loud and radio-quiet quasars may not overlap in $M_{\text{BLR}}$. 

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distribution of $L/L_{\text{Edd}}$ values ($\propto L_{\text{bol}}/m_\gamma$) is much less significant ($4.4 \times 10^{-8}$).

4. DISCUSSION

The tight relation between radio luminosity and black hole mass suggested by Franceschini et al. (1998) is not supported by our larger sample of 29 nearby galaxies. The scatter becomes even larger when active galaxies are included. For example, at $M_{\text{BH}} = 3 \times 10^6 M_\odot$, the radio power ranges from less than $10^{38}$ to $10^{40}$ ergs s$^{-1}$ (Fig. 1). The nonthermal emission associated with a massive black hole is high when the system is active, but it can be very weak to nondetectable 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, $M_{\text{BH}} > 3 \times 10^6 M_\odot$, 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 $M_{\text{BH}} < 3 \times 10^6 M_\odot$. 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 § 1) predicts such a strong dependence on $M_{\text{BH}}$. Some of these models suggest that radio-loud AGNs should have a low $L/L_{\text{Edd}}$ (e.g., Rees et al. 1982), but as mentioned in § 3, the observed dependence on $M_{\text{BH}}$ is much stronger than the dependence on $L/L_{\text{Edd}}$.

One physical process that is directly linked to $M_{\text{BH}}$ is tidal disruption of main-sequence stars outside the event horizon, which ceases for a rotating black hole (e.g., Rees 1988). However, tidal disruption is likely to be rather intermittent ($<10^{-1}$ yr$^{-1}$; Rees 1988), and it is not clear why its effects (e.g., the disruption of a jet maintaining field configuration) should be so long-lasting compared to the local dynamic timescale (less than a 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 (1996b) 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 that are beamed at us. These radio-intermediate quasars (RIQs) can be identified through their flat radio spectra ($\alpha < -0.5$, indicating core dominance), yet relatively low $R$-values ($\leq 250$) compared to flat spectrum radio-selected quasars. There are four RIQs in the Boroson & Green (1992) 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 (milliarcseconds), as expected under the beaming hypothesis (Falcke, Patnaik, & Sherwood 1996a), and also revealed superluminal motion in one (PG 0007+106; Brunthaler et al. 2000). These four RIQs are marked in Figure 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 AGNs may overlap only in the range $5 \times 10^5$ to $10^9 M_\odot$ and, given the likely uncertainty in the $M_{\text{BH}}$ estimate, may not overlap at all.

The $M_{\text{BH}}$ versus bulge mass relation, together with the $M_{\text{BH}}$-relation, 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 cannot produce radio-loud AGNs. A radio-loud quasar requires a massive black hole, and this is found only in bright elliptical galaxies. Elliptical galaxies can have a low luminosity, thus a black hole mass below $10^6 M_\odot$, and thus host radio-quiet AGNs, 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. (1998) relation, together with the fact that radio-loud AGNs reside in bright elliptical galaxies, “strongly suggests a link between radio loudness and black hole mass” and further proposed that this can explain the increase in the fraction of radio-loud quasars with luminosity, from less than 10% at $M_p > -24$ to $\sim$50% at $M_p = -28$ seen in some surveys (Hooper et al. 1996; Goldschmidt et al. 1999). This rise is consistent with the $M_{\text{BH}}$-relationship since a magnitude of $M_p = -28$ corresponds to $L_{\text{bol}}(4400 \AA) \sim 5 \times 10^{46}$ ergs s$^{-1}$, or $L_{\text{bol}} \sim 5 \times 10^{37}$ ergs 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 $\zeta > 4$ radio-loud quasars to be constant up to $M_p = -28$. Thus, the validity of the $M_{\text{BH}}$-relationship at high redshifts remains an open question.

The $M_{\text{BH}}$-relationship may help explain the low fraction of radio-loud AGNs at $M_p > -24$ in some quasar surveys (e.g., Hooper et al. 1996). Radio-loud AGNs 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 because of color or morphology criteria. Radio-squet AGNs 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 $M_{\text{BH}}$-relationship maintained? The relation between bulge luminosity and $L_p$ presented by Nelson & Whittle (1996) suggests (through the $M_{\text{BH}}$ vs. $M_{\text{bulge}}$ relation) that the $M_{\text{BH}}$-relationship holds down to the Seyfert luminosity level. Further down, at the level of very weakly active galaxies, little data is currently available. Ho (1999b) provides a rough spectral energy distribution for seven very weak AGNs ($L_{\text{bol}} \sim 10^{41}$ to $10^{42}$ ergs s$^{-1}$) with measured

![Diagram of an $M_{\text{BH}}$, $L/L_{\text{Edd}}$, $\theta$ unification scheme.](image-url)
$M_{\text{BH}}$. The standard $R$-parameter may not be a useful indicator of the relative jet power in these AGNs since the optical emission carries a very small fraction of $L_{\text{bol}}$. I therefore use $L_{\text{R}}/L_{\text{bol}}$ instead of $R$ for the relative jet power, where $L_{\text{R}}$ is obtained from single-dish broad-beam (rather than VLBI) radio fluxes to roughly match the spatial scales measured for the PG quasars. The two AGNs in the sample of Ho with $M_{\text{BH}} = 4 \times 10^6 M_\odot$ have $\langle \log (L_{\text{R}}/L_{\text{bol}}) \rangle = -4.1$, while the other five AGNs with $M_{\text{BH}} \geq 5 \times 10^6 M_\odot$ have $\langle \log (L_{\text{R}}/L_{\text{bol}}) \rangle = -2.2$. 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 & Rodríguez 1998; $\log (L_{\text{R}}/L_{\text{bol}}) \sim -7$].

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 AGNs. It is important to study this relationship in a similarly complete, well-defined, and deep sample of radio-selected AGNs, such as the FIRST Bright Quasar Survey sample (although this sample includes relatively few “proper” radio-quiet AGNs). Optical spectroscopy of a relatively large and heterogeneous sample of radio-selected quasars is presented by Brotherton (1996). The lack of accurate spectrophotometry, nonuniform 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 $M_{\text{BH}} \geq 10^7 M_\odot$, and about two-thirds 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 AGNs 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 AGNs in the $M_{\text{BH}}$, $L/L_{\text{Edd}}$, $\theta$ cube. All radio-loud AGNs are located on the high-$M_{\text{BH}}$ side, and all AGNs 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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