THE RADIO QUIESCENCE OF ACTIVE GALAXIES WITH HIGH ACCRETION RATES

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ABSTRACT

We present 6 cm Very Large Array observations of the Greene & Ho sample of 19 low-mass active galaxies with high accretion rates. This is one of the only studies of a uniform sample of narrow-line Seyfert 1 (NLS1) galaxies with such high sensitivity and resolution. Although we detect only one source, the entire sample is very radio quiet down to strong limits. GH 10 was found to have a radio power of $8.5 \times 10^{21}$ W Hz$^{-1}$ and a ratio $R = f_{6\text{ cm}}/f_{44\text{ GHz}}$ of 2.8. The 3$\sigma$ upper limits for the remaining nondetections correspond to radio powers from $3 \times 10^{20}$ to $8 \times 10^{21}$ W Hz$^{-1}$ and $0.47 < R < 9.9$. Stacking all nondetections yields an even stronger upper limit of $R \leq 0.27$. An assessment of existing observations in the literature confirms our finding that NLS1s are consistently radio-quiet, with a radio-loud fraction of 0%–6%, which is significantly lower than the 10%–20% observed in the general quasar population. By analogy with stellar mass black holes, we argue that AGNs undergo a state transition at $L_{\text{bol}}/L_{\text{Edd}} \approx 0.01$. Below this value a radiatively inefficient accretion flow effectively drives an outflow, which disappears when the flow turns into an optically thick, geometrically thin disk, or a radiation pressure–dominated slim disk at still higher $L_{\text{bol}}/L_{\text{Edd}}$.

Subject headings: galaxies: active — galaxies: jets — galaxies: nuclei — galaxies: Seyfert — galaxies: structure — radio continuum: galaxies

1. INTRODUCTION

Very little is known about the mass function of nuclear black holes (BHs) with mass below $10^6 M_\odot$. Until recently there were only two secure candidates of intermediate-mass BHs in galactic nuclei: NGC 4395 (Filippenko & Ho 2003) and POX 52 (Barth et al. 2004). The tight correlation between host bulge velocity dispersion and BH mass (the $M_{\text{BH}}$–$\sigma$ relation: Gebhardt et al. 2000; Ferrarese & Merritt 2000) suggests that BHs play an essential role in the evolution of galaxies, and yet we know next to nothing empirical about the starting conditions, or seeds, of supermassive BHs. An understanding of the low-mass end of the BH mass function may provide one of the few observational constraints on seed BHs, at least prior to the Laser Interferometer Space Antenna (LISA; Hughes 2002). Furthermore, it remains unclear whether small galaxies, without classical bulges, may host central BHs and whether they obey the same $M_{\text{BH}}$–$\sigma$ relation. For these reasons, Greene & Ho (2004) performed a systematic search for such a population of intermediate-mass BHs. They used the First Data Release of the Sloan Digital Sky Survey (SDSS; York et al. 2000; Abazajian et al. 2003) to select a sample of broad-line active galactic nuclei (AGNs) with virial mass estimates of $M_{\text{BH}} < 10^6 M_\odot$. This sample of 19 galaxies represents the only uniformly selected sample of intermediate-mass BHs in active galaxies. Remarkably, these objects appear to obey the same $M_{\text{BH}}$–$\sigma_*$ relation as that established for high-mass systems (Barth et al. 2005), suggesting that a single physical mechanism operates over nearly 5 orders of magnitude to maintain the observed relation.

This sample provides the opportunity to examine the broad spectral energy distributions (SEDs) of BHs in a new mass regime. As discussed by Greene & Ho (2004), the Eddington ratios $[L_{\text{bol}}/L_{\text{Edd}}, \text{ where } L_{\text{Edd}} \equiv 1.26 \times 10^{38} (M_{\text{BH}}/M_\odot) \text{ ergs s}^{-1}]$ of the sample are all close to unity. To begin to characterize the SEDs of this unique sample, we obtained high-resolution 6 cm continuum observations using the Very Large Array (VLA). Our sample probes a poorly explored region of parameter space, in terms of BH mass and Eddington ratio, and so may provide new insights into the physical drivers of radio properties in AGNs. Throughout this paper we assume the following cosmological parameters to calculate distances: $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_L = 0.75$ (Spergel et al. 2003).

2. OBSERVATIONS AND DATA ANALYSIS

All observations were taken over 22.5 hr on 2004 October 9, when the VLA was in A configuration (Thompson et al. 1980). During the observations only two antennas were excluded from the array, and the weather conditions were good. We observed at 4.860 GHz (6 cm, C band) with a bandwidth of 50 MHz for each of two intermediate frequencies separated by 50 MHz. Integration times ranged from 10 minutes to 2 hr, depending on the $[\text{O III}]$ $\lambda 5007$ line luminosity of the sources given in Greene & Ho

1 Virial masses are calculated from the relation between AGN luminosity and broad-line region radius calibrated with reverberation-mapped AGNs (Kaspi et al. 2000) and a measurement of velocity dispersion in the broad-line gas from the FWHM of the broad H$\alpha$ emission line (see, e.g., Greene & Ho 2005). If $v_{\text{FWHM}}$ is the broad-line gas velocity dispersion, and $L_{5100}$ is the AGN luminosity measured at 5100 Å, the luminosity-radius relation from Kaspi et al. (2000) yields $M_{\text{BH}} = 4.82 \times 10^9 (L_{5100}/10^{44} \text{ ergs s}^{-1})^{0.7} (v_{\text{FWHM}}/1000 \text{ km s}^{-1})^6 M_\odot$.

2 The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
FIG. 1.—Trend of increasing radio power with increasing [O \text{ iii}] λ5007 luminosity. Upper limits from this paper are shown as triangles, while the GH 10 detection is shown as a cross. For clarity, our data are plotted alone in the inset. The solid line represents the fit from Ho & Peng (2001) to radio-quiet Seyfert galaxies and PG quasars: \( P_{\text{16m}} = (0.46 \pm 0.15) L_{\text{[O \text{ iii}]}}, + (2.68 \pm 6.21). \) The Ho & Peng sample is overplotted with filled (radio-loud sources) and open (radio-quiet sources) symbols. PG quasars are shown as squares, and Seyferts are shown as circles. NGC 4395 (adjusted to a distance of 4.2 Mpc; Thim et al. 2004) is highlighted as a dotted circle. See text for details.

TABLE 1

| Name  | \( D_L \) | \( t \) | \( \sigma \) | \( \sigma_t \) | \( f_{\lambda_{\text{400}}} \) | \( R \) | \( P_{\text{6cm}} \) | \( L_{\text{[O \text{ iii}]}}, \) |
|-------|----------|-------|------|-------|--------|------|---------|---------|
| GH 01 | 344      | 27    | 0.035 | 0.051 | 0.11   | <0.94 | <21.17  | 40.71   |
| GH 02 | 127      | 9     | 0.060 | 0.084 | 0.052  | <3.5  | <20.54  | 40.00   |
| GH 03 | 465      | 94    | 0.282 | 0.050 | 0.042  | <2.0  | <21.33  | 40.70   |
| GH 04 | 189      | 9     | 0.062 | 0.086 | 0.22   | <0.86 | <20.90  | 40.91   |
| GH 05 | 332      | 42    | 0.029 | 0.034 | 0.13   | <0.68 | <21.07  | 40.44   |
| GH 06 | 455      | 111   | 0.021 | 0.029 | 0.053  | <1.2  | <21.20  | 40.41   |
| GH 07 | 428      | 36    | 0.029 | 0.033 | 0.056  | <1.5  | <21.33  | 41.00   |
| GH 08 | 364      | 46    | 0.030 | 0.043 | 0.19   | <0.47 | <21.15  | 40.58   |
| GH 09 | 945      | 92    | 0.025 | 0.039 | 0.014  | <5.2  | <21.90  | 42.05   |
| GH 10 | 363      | 10    | 0.061 | 0.088 | 0.19   | <2.8  | <21.93  | 41.53   |
| GH 11 | 366      | 11    | 0.060 | 0.083 | 0.16   | <1.1  | <21.46  | 41.26   |
| GH 12 | 486      | 47    | 0.027 | 0.037 | 0.075  | <1.1  | <21.36  | 41.12   |
| GH 13 | 589      | 115   | 0.019 | 0.022 | 0.067  | <0.85 | <21.38  | 40.72   |
| GH 14 | 122      | 10    | 0.055 | 0.059 | 0.056  | <2.9  | <20.46  | 39.98   |
| GH 15 | 594      | 117   | 0.019 | 0.029 | 0.029  | <2.0  | <21.39  | 40.55   |
| GH 16 | 367      | 29    | 0.036 | 0.047 | 0.041  | <2.6  | <21.08  | 40.46   |
| GH 17 | 453      | 47    | 0.026 | 0.032 | 0.063  | <1.3  | <21.29  | 40.98   |
| GH 18 | 885      | 112   | 0.019 | 0.025 | 0.019  | <3.1  | <21.73  | 40.67   |
| GH 19 | 154      | 10    | 0.055 | 0.073 | 0.017  | <9.9  | <20.67  | 40.86   |

Notes.—Col. (1): Identification number from Greene & Ho (2004). Col. (2): Luminosity distance (Mpc) calculated from the SDSS redshifts and assuming \( H_0 = 100 h = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27, \) and \( \Omega_{\Lambda} = 0.75. \) (Spengler et al. 2003). Col. (3): Integration time (minutes). Col. (4): The rms (mJy beam\(^{-1}\)) of natural-weighted images, in all cases consistent with theoretical noise limits. Col. (5): The rms (mJy beam\(^{-1}\)) in natural-weighted and tapered images, constructed with a Gaussian taper with 30% intensity at 200 k\( \lambda. \) Col. (6): Flux density (mJy) at 4400 \( \lambda, \) as derived from power-law fits to the SDSS spectra; see text for details. Col. (7): Shows \( R = (3/2)f_{\lambda_{\text{400}}}, \) Col. (8): Radio power (W Hz\(^{-1}\)) at 6 cm; all but GH 10 are 3 \( \sigma \) upper limits. Col. (9): The [O \text{ iii}] luminosity (ergs s\(^{-1}\)) from Greene & Ho (2004).
of more extended emission, we also constructed images with a Gaussian tapering function that fell to 30% power at 200 kλ, which resulted in a typical synthesized beam of ~1". We note that our minimum spacing is ~11 kλ, corresponding to a maximum angular scale of ≤10".

3. RESULTS

Only one object in this study, GH 10, was detected. For the remaining undetected targets, we computed 3 σ upper limits on their 6 cm radio powers, which range from 3 × 10²⁰ to 8 × 10²¹ W Hz⁻¹ and are shown as a function of L₁₆₄ in Figure 1 (triangles). The solid line is the L₁₆₄-P₁₆₄ from Ho & Peng (2001) that we used to calculate observing times for our sample. Clearly, our measurements do not follow this relation (note that the majority of the upper limits lie below the line, since our integration times were designed to achieve 5 σ detections; exceptions are objects that required more than 2 hr of integration time). In order to illustrate the probable cause of the discrepancy, we include in Figure 1 the data from Ho & Peng (2001) used to derive our adopted L₁₆₄-P₁₆₄ relation. Three samples were included, to span the maximum range in optical nuclear luminosity (−8 mag ≤ MB ≤ −28 mag). The highest luminosity sources are the 87 Palomar-Green (PG) quasars with z < 0.5 (Schmidt & Green 1983), while low-luminosity Seyfert galaxies are drawn from the Palomar spectroscopic survey of nearby galaxies (Ho et al. 1995, 1997), supplemented at intermediate luminosity by the sample of Seyferts selected from the CfA redshift survey (Huchra & Burg 1992). The radio observations for the CfA Seyferts are presented in Kukula et al. (1995); those for the Palomar Seyferts are from Ho & Ulvestad (2001) and Ulvestad & Ho (2001a), and the PG quasars were observed by Kellermann et al. (1989). As shown in Figure 1, our upper limits are lower than the typical PG quasars, whose radio powers range from 7 × 10²⁵ to 3 × 10²⁷ W Hz⁻¹. (For reference, the 3.6 cm radio power of the quasars in the Large Bright Quasar Survey [LBQS] ranges from 10²³ to 10²⁸ W Hz⁻¹; Visnovsky et al. 1992.) They are more consistent with the distribution of radio powers of the Seyfert nuclei (~10¹⁸–10²⁵ W Hz⁻¹). Radio powers alone, however, are somewhat misleading, since BHs of different mass have different (limiting) Eddington luminosities. Complementary information is provided by the ratio R ≡ f₁₆₄/f₄₄₀₀ Å, where “radio-loud” objects are conventionally defined as those with R ≥ 10 (Kellermann et al. 1989). Radio-loud and radio-quiet objects are represented as filled and open symbols in Figure 1, respectively. Among quasars, the radio-loud fraction is ~20% for the PG sample and ~10% for the LBQS sample. In contrast, ~60% of the Ho & Peng (2001) Seyfert sample is radio-loud, once the nuclear emission is properly isolated.

Now we investigate possible reasons why the Ho & Peng (2001) L₁₆₄-P₁₆₄ relation might overpredict the radio power of our sources. The relation was fitted to the radio-quiet points only, and since our entire sample is radio-quiet (GH 10 has R = 2.8, while the mean R for the rest is <2.3), the discrepancy cannot be explained by our choice of the optical-radio relation. However, very few of the radio-quiet objects from Ho & Peng (2001) have [O iii] luminosities less than 10⁴⁰ erg s⁻¹, while the majority of our objects do. Either there is a break in the L₁₆₄-P₁₆₄ relation at low L₁₆₄, or the true slope of the L₁₆₄-P₁₆₄ relation is steeper than that found by Ho & Peng, due to their limited dynamic range. Actual detections of a sample such as that presented here are required to distinguish between these two possibilities.

3.1. GH 10

GH 10 is the only object in the sample detected by the Faint Images of the Radio Sky at Twenty cm survey (FIRST; Becker et al. 1995) and is the only object detected here. Because of the relatively large beam (~5") of FIRST and the low radio power of GH 10 (2.0 × 10²² W Hz⁻¹), Greene & Ho (2004) argue that the 20 cm emission from GH 10 may originate from the host galaxy rather than from the AGN. Given the much superior angular resolution of our current image (Δθ = 0.57° × 0.42°), most of the radio emission probably originates from the AGN itself (see Fig. 2). Using the task JMFIT within AIPS, we find that the image is marginally resolved, with a deconvolved size of 0.3 × 0.2 (530 pc × 350 pc), a position angle of 9°, and a total flux density of 0.7 ± 0.1 mJy. Since the source is slightly resolved, there is most likely some host galaxy contribution, and so the peak flux density may give a better measure of the unresolved AGN emission. The peak flux density of 0.54 ± 0.05 mJy corresponds to a radio power of 8.5 × 10²¹ W Hz⁻¹. Using the 4400 Å flux density from Table 1, we find an R value of 2.8 for this source. Since the source was also detected with FIRST, we can estimate a crude spectral index α, where f₁₆₄ ∝ ν⁻α. This calculation is problematic because the observations were nonsimultaneous and made with very different resolutions. In order to minimize the uncertainties resulting from differing resolutions, we use the FIRST peak flux density, 1.2 mJy beam⁻¹, to find α = 0.62. We emphasize that this is a very uncertain value. Unless otherwise stated, we omit GH 10 from the following discussion.

3.2. Upper Limits

Given that all but one of the objects in our sample were non-detections, we have devoted some care to deriving the most stringent possible upper limits on the radio emission from these sources. We derive rms values from our final images within a box enclosing the inner quarter of the image, and our nominal upper limits are simply 3 times this measured rms. At worst, the instrumental and atmospheric phase for each antenna on a given calibrator vary by no more than ~20" over a 5 minute period. There are no substantial phase changes even between calibrators in very different regions of the sky; over the course of 18 hr of our 24 hr observation, the phase calibration remained stable within 10" for each antenna. This implies a coherence loss of less...
than 1% for our target objects, independent of the angular separation between calibrator and target, leading to the conclusion that our cited upper limits are accurate and quite robust.

While we were unable to detect any of our objects individually, we can construct a single, deep image by co-adding all the observations. This approach has been applied successfully with nondetections in FIRST of the SDSS (Glikman et al. 2004) and 2dF QSO Redshift Survey (2QZ; Wals et al. 2005) AGNs. Stacking is performed in the image plane. Since the FIRST observations have uniform sensitivity, they can be summed directly. In our case, because exposure times varied between observations, we give additional weight to those with the highest sensitivity. We compute a weighted-average image using the task COMB within AIPS, where the weights are simply $1/rms^2$ and the images are aligned to their central pixel. We expect all the sources to lie within the central 0′, since our positions depend on SDSS astrometry, which has an accuracy of $\leq0.1"$ (Stoughton et al. 2002), and the astrometric accuracy of the VLA phase calibrators is also $\leq0.1"$ (VLA calibrator manual; Wilkinson et al. 1998). The individual maps used in the stacking analysis were thus constructed with 0′1 pixels. The effective rms of our stacked image is 0.0069 mJy beam$^{-1}$, which is approximately one-third of our best rms for a single exposure. This is roughly as expected, since we have increased the on-source exposure time from a maximum of 2–16 hr. We take our upper limit as 3 $\times$ rms and an average $f_{4400\lambda} = 0.077$ mJy (from the values published in Greene & Ho 2004; see our Table 1) to find an effective limit on the $R$ parameter of 0.27. We are therefore able to place a far more stringent upper limit for the sample ensemble than for any individual source.

For completeness, we also derived upper limits on extended emission from the host galaxies themselves, using lower resolution, tapered images with a synthesized beam $\Delta\theta = 1"$. Our upper limits correspond to an average 6 cm radio power of $\sim1.8 \times 10^{21}$ W Hz$^{-1}$, which is roughly similar to the 1.4 GHz power of normal (inactive) $L^*$ galaxies (Condon 1992). Given that the galaxies in this sample are relatively faint, $\sim1$ mag fainter than $L^*$ (Greene & Ho 2004), this is not a very strong limit, but it does indicate that the hosts are not experiencing any vigorous starburst activity. Assuming a radio spectral index of $\alpha = 0.7$, the inferred average 20 cm radio power of $4.2 \times 10^{21}$ W Hz$^{-1}$ translates into an approximate star formation rate of $\sim2.5 M_\odot$ yr$^{-1}$ (Yun et al. 2001).

### 3.3. Comparison with Narrow-Line Seyfert 1 Galaxies

A natural comparison may be drawn between our sample and NGC 4395, the prototypical AGN with an intermediate-mass BH. NGC 4395 has been imaged in the radio with the VLA (Moran et al. 1999; Ho & Ulvestad 2001) and the Very Long Baseline Array (VLBA; Wrobel et al. 2001). At an assumed distance of 4.2 Mpc (Thim et al. 2004), the VLA observations of Ho & Ulvestad (2001) give a 6 cm power of $1.7 \times 10^{21}$ W Hz$^{-1}$, a 20 cm power of $3.5 \times 10^{21}$ W Hz$^{-1}$, and a spectral index of $\alpha = 0.6$. The 20 cm VLBA image has a diameter of less than 11 mas and a total power of $1.1 \times 10^{21}$ W Hz$^{-1}$, implying that some of the flux has been resolved by the VLBA. Deeper VLBA imaging of NGC 4395 is underway to search for a potential jet component (J. Wrobel, J. S. Ulvestad, & L. C. Ho 2006, in preparation). Using the $f_{4400\lambda}$ measurement from Filippenko & Ho (2003), we find that NGC 4395 has $R \approx 2.0$.

More generally, the objects presented here technically belong to the subclass of AGNs known as narrow-line Seyfert 1 galaxies (NLS1s; Osterbrock & Pogge 1985). Formally, these are broad-line AGNs with $\text{FWHM} \leq 2000$ km s$^{-1}$ for the H$\beta$ line. They also tend to have low $[\text{O} \text{III}] / \text{H}\beta$ ratios, high Fe $\text{II} / \text{H}\beta$ ratios, and prominent soft X-ray excesses (e.g., Boller et al. 1996; but see Williams et al. 2004). This set of properties suggests that NLS1s are low-mass BHs radiating near their Eddington limits (Pounds et al. 1995). All of our objects (as does NGC 4395) qualify as NLS1s based on the $\text{H}\beta$ line width criterion, although their Fe $\text{II}$ and $[\text{O} \text{III}]$ strengths cover a wider range than typical NLS1s (Greene & Ho 2004), and therefore comparisons with NLS1 properties are natural.

Anecdotally, NLS1s are thought to be radio-quiet as a class, although few statistical samples have been considered in the literature. Ulvestad et al. (1995) assembled new and published radio data for a total of 15 NLS1s, of which nine were detections. We have gathered optical continuum luminosities for 11 of the Ulvestad et al. objects (excluding Mrk 291, Mrk 957, IRAS 1509–211, and 1747.3+6836), using $\text{H}\beta$ flux and equivalent-width measurements from Osterbrock & Pogge (1985) when available, or else manually estimating the continuum fluxes from spectra published in Véron-Cetty et al. 2001). Mrk 783, with $R = 400$, is the only radio-loud object in the sample. As pointed out by Ulvestad et al., their sample of NLS1s is by no means complete, making this statistic difficult to interpret.

A number of other studies have used large radio surveys to estimate the radio-loud fraction among NLS1s. Zhou & Wang (2002) collected SEDs from the literature for a sample of 205 NLS1s in the Véron-Cetty & Véron (2001) catalog. They defined a subsample of 182 sources that fall within the footprint of the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). Of these, 63 are detected and 11 (6%) qualify as radio-loud ($R > 10$), although none are “very” radio loud ($R > 300$). Zhou et al. (2003) discuss the radio properties of a sample of 175 NLS1s from the SDSS Early Data Release (Stoughton et al. 2002). It is unclear exactly what the selection criteria were for this sample, but ~6% are detected by FIRST, and two (1%) of those can be deemed radio-loud. Finally, Stepanian et al. (2003) presented SEDs from the literature for the NLS1s in the Second Byurakan Survey (Markarian et al. 1983), selected to have $\text{FWMH}_{\text{H}\beta} < 2000$ km s$^{-1}$ and $[\text{O} \text{III}] / \text{H}\beta < 3$. Ten of their 26 objects have radio detections, and all are radio-quiet. In all the above cases, the fraction of radio-loud NLS1s seems to be low (0%–6%) in comparison to the parent samples of normal, luminous broad-line AGNs (10%–20%). Unfortunately, our ability to interpret the nondetections is hampered by the use of relatively shallow surveys at low resolution (e.g., NVSS or FIRST). Nondetections may be radio-loud or radio-quiet, while detections may contain significant contamination from the host galaxy. For instance, a typical NLS1 at $z = 0.1$ with $M_{\text{BH}} = 10^6 M_\odot$ and $L_{\text{bol}} / L_{\text{edd}} = 1$ will not be detected by FIRST below a limiting $R$ of 17 [assuming a 1 mJy detection limit and a flat ($\alpha = 0$) radio spectrum]. Moreover, the definition of NLS1s varies from study to study, with unknown consequences for the underlying properties of each group.

A possibly more pertinent comparison with our sample comes from the PG survey, since it has available sensitive, high-resolution radio observations (Kellermann et al. 1989) and homogeneous optical spectrophotometric data (Neugebauer et al. 1987). Among the $87 z < 0.5$ sources, 18 meet the $\text{H}\beta$ line width criterion of NLS1s (Boroson & Green 1992). Their 6 cm radio powers range from $1.7 \times 10^{21}$ to $2.5 \times 10^{24}$ W Hz$^{-1}$, and they are predominantly radio-quiet (94%), with only a single radio-loud object (PG 1211+143). The radio-quiet objects have $R$ from 0.2 to 2.5 and a mean of 0.54. Interestingly, the stacked upper limit of our sample is lower than the mean $R$ for the PG NLS1s.

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3 See http://www.vla.nrao.edu/astro.
While the evidence summarized above suggests that NLS1s, as a class, are exceptionally radio-quiet, it is worth noting that a few bona fide radio-loud NLS1s have been identified in the literature (Siebert et al. 1999; Oshlack et al. 2001; Zhou et al. 2003, 2005; see also Maccarone et al. 2005). As discussed by Zhou et al. (2003, 2005), this is not entirely unexpected, since NLS1s are unlikely to be a homogeneous class. To the extent that the broad-line region, or at least the portion emitting Hβ, may have a disk-like geometry, it seems unavoidable that some NLS1s must be sources with intrinsically large velocity dispersions viewed preferentially face-on as opposed to having low $M_{BH}$ (see also Bian & Zhao 2004). Perhaps more baffling is why such a small fraction of NLS1s are radio-loud, as compared to the general quasar population.

4. PHYSICAL INTERPRETATION

This is the first high-resolution radio study of a uniformly selected sample of AGNs with low mass and high Eddington ratio. As a class, these objects are radio-quiet down to very strong limits. Our observations thus provide new support for a model in which radio loudness is anticorrelated with $L_{bol}/L_{Edd}$, as proposed, for example, by Ho (2002).

AGNs at the lowest $L_{bol}/L_{Edd}$ are observed to be generically radio-loud (Ho 1999, 2002, 2006). At low $L_{bol}/L_{Edd}$ the conventional optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973) is replaced by a radiatively inefficient accretion flow (RIAF: Quataert 2001; Narayan 2006 and references therein). The RIAF itself efficiently produces radio emission while simultaneously lacking the optical-ultraviolet thermal emission from the standard accretion disk, which acts to boost $R$ (Rees et al. 1982; Quataert et al. 1999; Ho et al. 2000; Ho 2002). At the same time, it has been shown in many cases that an RIAF alone cannot account for all of the observed radio emission, suggesting that an additional radio-emitting component, most likely associated with a jet, is required (Yi & Boughn 1999; Ulvestad & Ho 2001b; Yuan et al. 2002; Anderson et al. 2004; Falcke et al. 2004). On the opposite extreme, NLS1s, probably high-$L_{bol}/L_{Edd}$ systems as discussed above, are systematically radio-quiet (although radio-loud quasars are exceptions; see below). Broad absorption line (BAL) quasars are also predominantly radio-quiet (Stocke et al. 1992; cf. Becker et al. 2000), and at least a subset of them (the low-ionization subclass) are thought to be radiating at high $L_{bol}/L_{Edd}$ (Meier 1996; Boroson 2002). Principal component analysis of AGNs has identified radio quietness as a property that is statistically linked with strong Fe II emission and weak [O III] lines, a family of properties, common to NLS1s and BAL quasars, that is thought to correspond to high-$L_{bol}/L_{Edd}$ systems (Boroson & Green 1992; Marziani et al. 2001, 2003; Boroson 2002).

The trend of decreasing $R$ with increasing $L_{bol}/L_{Edd}$ is shown graphically in Figure 3 (cf. Fig. 5b in Ho 2002), using a representative sample of AGNs with radio and optical luminosities and BH mass estimates. To extend the dynamic range in the plot, we have augmented the sample from this study with (1) the $z < 0.5$ PG quasars from Boroson & Green (1992) for which we can estimate virial BH masses and (2) a sample of low-luminosity nuclei with BH masses derived from direct dynamical modeling (Ho 2002). Following standard practice, we infer the bolometric luminosity directly from the optical continuum luminosity by assuming a fixed bolometric correction (see, e.g., the discussion in Greene & Ho 2004). In low-luminosity sources lacking reliable measurements of the optical AGN continuum, Ho (2002) makes use of an additional empirical correlation between Hβ and continuum luminosity (Ho & Peng 2001). Our upper limits on $R$, and in particular the stronger limit derived from our stacking analysis (large crossed box in Fig. 3), are consistent with the observed trend, given the $L_{bol}/L_{Edd}$ distribution of the sample. To properly sample the low-mass regime, we should include objects at low $L_{bol}/L_{Edd}$ as well. While these sources are intrinsically faint even when radiating at their Eddington luminosities, and thus difficult to find, one example is known. NGC 4395, with $M_{BH} \approx 10^4 - 10^5 M_\odot$, is believed to have a $L_{bol}/L_{Edd} \approx 0.01$ (Filippenko & Ho 2003). It has $R \approx 2.0$, which is significantly higher than our stacked upper limit ($R = 0.27$), and consistent with the trend delineated in Figure 3. Thus, the inverse correlation between radio loudness and accretion rate ($L_{bol}/L_{Edd}$) previously reported for supermassive BHs ($10^6$ to a few times $10^9 M_\odot$) appears to continue to hold in the mass regime $10^4 - 10^6 M_\odot$.

To aid us in the physical interpretation of these results, we turn to X-ray binaries (XRBs) that host BHs with $M_{BH} \approx 10 M_\odot$. Because the lower BH masses result in faster dynamical timescales, it is possible to observe a single XRB in different accretion modes and link them directly with changes in spectral properties. XRBs are in fact found to occupy certain characteristic X-ray spectral states (see McClintock & Remillard [2006] for a review) corresponding to different accretion regimes. Typically, at low X-ray luminosity, during which the accretion flow is thought to transform into a quasi-spherical RIAF radiating at $L_{bol}/L_{Edd} \approx 0.01$ (Esin et al. 1997), the spectrum is nonthermal and hard (the "low/hard" state). This state is usually accompanied by persistent, flat-spectrum radio emission, correlated with the X-ray emission.

![Figure 3: Trend of decreasing $R$ with increasing $L_{bol}/L_{Edd}$. The upper limits from this study are shown as triangles, GH 10 is shown with a cross, and our stacked upper limit is plotted as the boxed cross. NGC 4395 is highlighted with a dotted circle. For comparison, we include the 87 PG quasars with $z < 0.5$, using radio continuum data from Kellermann et al. (1989) and optical continuum data from Neugebauer et al. (1987). We obtained BH masses with the method of Kaspi et al. (2000) using FWHM of $P_{bol}$ from Boroson & Green (1992), and we estimated $L_{bol}$ following Ho (2002). PG objects with FWHM of $< 2000$ km s$^{-1}$ (NLS1s) are boxed; they have a mean $R = 0.54$. The data for the low-$L_{bol}/L_{Edd}$ objects come from Ho (2002), as does the overplotted best-fit line. Inset: Our current sample shown on an expanded scale for clarity. Top histogram: The solid histogram plots the distribution of $L_{bol}/L_{Edd}$ for all the objects shown for comparison; the dash-dotted histogram highlights the 19 objects from this study. Right histogram: Same format as above, but for the distribution of $R$. Note that all but one of the objects in the solid histogram are upper limits. Upper limits in $R$ for the PG objects are shown with a hatched histogram.](image-url)
and likely including a jet component (e.g., Dhawan et al. 2000; Stirling et al. 2001; Corbel et al. 2003; Fender & Belloni 2004). At higher X-ray luminosities ($0.01 \leq L_{\text{bol}}/L_{\text{Edd}} \leq 0.3$), a conventional, optically thick, geometrically thin disk (Shakura & Sunyaev 1973) produces a spectrum dominated by thermal, soft X-ray emission (the “high/soft” state), during which the radio emission is quenched (Tananbaum et al. 1972; Fender et al. 1999, 2004; Gallo et al. 2003; Tigea et al. 2004). Finally, for systems with the highest luminosities ($L_{\text{bol}}/L_{\text{Edd}} \geq 0.3$), in which the accretion flow might take the form of a radiation pressure-dominated slim disk (Abramowicz et al. 1988), the X-ray spectrum can be dominated by a very steep power-law component (the “very high” or “SPL” state). The very high state itself is radio-quiet, but transitions from the very high to the high state may be accompanied by optically thin ejection events in the radio (e.g., Corbel et al. 2001; Hannikainen et al. 2001; Fender et al. 2004).

Since jet physics is basically scale-free (Heinz & Sunyaev 2003), a number of authors have drawn a direct analogy between the spectral states of XRBs and AGNs (e.g., Meier 2001; Maccarone et al. 2003; Merloni et al. 2003; Falcke et al. 2004; Jester 2005). The most thorough comparison has been made for low-luminosity AGNs, whose characteristic radio loudness, hard X-ray spectra, and radiative inefficiency bear close resemblance to the properties of XRBs in their low/hard state (Ho 2006). The RIAF at low accretion rates may be particularly conducive to jet production because its vertical thickness supports a strong poloidal magnetic field (Meier 2001), in addition to providing a population of weakly bound or unbound particles that are unstable toward outflow (Blandford & Begelman 1999).

Extending the comparison to the high and very high states, however, presents a greater challenge. This is in part due to the somewhat nebulous luminosity criterion various authors use to differentiate the high state from the very high state, and to the fact that the current estimates of bolometric luminosities and BH masses in AGNs are still rather uncertain. NLS1s, with their characteristically soft X-ray spectra, are often thought to be the direct analog of XRBs in the high state (Pounds et al. 1995). On the other hand, many NLS1s (e.g., Collin & Kawaguchi 2004), although certainly not all (e.g., NGC 4395), evidently have Eddington ratios—when taken at face value—that exceed 0.3, the formal upper limit for the stability of a Shakura & Sunyaev (1973) disk. If we take this theoretically motivated criterion as a definition for the very high state, then most well-studied NLS1s, including the sample of Greene & Ho (2004) highlighted here, would technically qualify as being in the very high state, rather than in the high state. Regardless of which choice one adopts for NLS1s, our study emphasizes a distinctive feature of NLS1s as a class: they appear to be abnormally radio-quiet. If the currently estimated bolometric luminosities and BH masses are robust, the implication is that jet production in AGNs is suppressed when their Eddington ratios approach or exceed 1. This empirical result for NLS1s is consistent with the tendency for radio emission to be quenched in XRBs in their high and very high states. The quenching of radio emission in the high state may be related to the weakness of the poloidal component of the magnetic field, central to driving a jet, in a geometrically thin disk (Livio et al. 1999; Meier 2001). As mentioned above, XRBs undergoing very high state transitions often exhibit rapid radio flares, perhaps generated from the relativistic ejection of the corona as the optically thick accretion disk moves inward (Fender et al. 2004). Since the general quasar population is thought to radiate at high $L_{\text{bol}}/L_{\text{Edd}}$, it has been suggested that the radio-loud quasar population consists of objects that have recently undergone a state transition involving a relativistic ejection event (Marscher et al. 2002; Gallo et al. 2003; Jester 2005). In that case, it is puzzling that NLS1s have such a low fraction (0%–6%) of radio-loud objects as compared to quasars (10%–20%). BAL quasars are similar in this respect (e.g., Stocke et al. 1992). Apparently at the highest accretion rates, even relativistic ejection events are uncommon. This result warrants further theoretical exploration.

5. SUMMARY

We present a high-resolution study of radio emission from a well-defined sample of low-mass active galaxies radiating at a high fraction of their Eddington luminosity ($L_{\text{bol}}/L_{\text{Edd}}$). Only a single object (GH 10) in our sample of 19 is detected, with a radio power of $8.5 \times 10^{21} \, \text{W Hz}^{-1}$, while we place 3 $\sigma$ upper limits of $3 \times 10^{20}$ to $8 \times 10^{21} \, \text{W Hz}^{-1}$ for the nondetections. All the objects have very low ratios of radio to optical flux ($R$). GH 10 has $R = 2.8$, and a stacked image of the remaining observations provides an upper limit of $R \leq 0.27$. While this study represents one of the few deep, high-resolution radio surveys of a uniform sample of narrow-line Seyfert 1 galaxies (NLS1s), a review of the literature reveals that NLS1s are generically radio-quiet. In contrast, low-$L_{\text{bol}}/L_{\text{Edd}}$ sources are ubiquitously radio-loud. Therefore, our observations provide renewed support for an inverse relation between $L_{\text{bol}}/L_{\text{Edd}}$ and radio loudness. Further support for this picture is provided by black holes in X-ray binaries (XRBs), whose radio emission is quenched when they radiate at high ($\geq 0.01$) fractions of their Eddington luminosity. This same analogy has been used to suggest that radio-loud quasars may be undergoing a relativistic ejection event similar to those observed when XRBs transition from the very high state. In that case, it is quite intriguing that objects at the highest accretion rates, namely NLS1s and BAL quasars, have abnormally low radio-loud fractions, a finding for which we currently have no clear explanation.

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