X-RAY PROPERTIES OF INTERMEDIATE-MASS BLACK HOLES IN ACTIVE GALAXIES

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ABSTRACT

We present a pilot study of the X-ray properties of intermediate-mass (∼10^5 − 10^6 M⊙) black holes in active galaxies using the Chandra X-ray telescope. Eight of the 10 active galaxies are detected with a significance of at least 3σ, with X-ray luminosities in the range L_{0.5-2keV} ≈ 10^{41} − 10^{43} ergs s^{-1}. The optical-to-X-ray flux ratios are consistent with expectations, given the known correlations between α_{ox} and ultraviolet luminosity, while a couple of objects appear to be anomalously X-ray weak. The range of 0.5–2 keV photon indices we measure, 1 < Γ_{ph} < 2.7, is entirely consistent with values found in samples of more luminous sources with more massive black holes. Black hole mass evidently is not a primary driver of soft X-ray spectral index. On the other hand, we do find evidence for a correlation between X-ray power-law slope and both X-ray luminosity and Eddington ratio, which may suggest that X-ray emission mechanisms weaken at high Eddington ratio. Such a weakening may explain the anomalous X-ray weakness of one of our most optically luminous objects.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

Astrophysical black holes (BHs) are typically found in two mass ranges: stellar-mass BHs have masses ∼ 10 M⊙, and are the remnants of massive star death, while supermassive BHs have masses in the range ∼ 10^6 − 10^9 M⊙, and are a ubiquitous component of galaxy bulges. There is thus ∼ 5 orders of magnitude in BH mass that remains unexplored; BHs in this mass range have been dubbed “intermediate-mass” BHs, and their existence remains the subject of debate. In particular, there are anomalously luminous (“ultraluminous”; L_X ≥ 10^{39} ergs s^{-1}) off-nuclear extragalactic X-ray sources that may be BHs with masses of 100−1000 M⊙ (see, e.g., van der Marel 2004 for a review). We have a complementary program to find intermediate-mass BHs with masses of 10^4−10^5 M⊙ in active galactic nuclei (AGNs).

These objects are of interest not only because they begin to fill the mass gap between supermassive and stellar-mass BHs, but also as potential analogues of the primordial seeds of supermassive BHs. Furthermore, the mergers of BHs with masses ∼ 10^5 M⊙ are expected to provide a strong signal for the Laser Interferometric Space Antenna (e.g., Hughes 2002). The tight correlations between supermassive BH mass (M_{BH}) and both the luminosity (Kormendy & Richstone 1995) and stellar velocity dispersion (the M_{BH}−σ relation; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Barth et al. 2005; Greene & Ho 2006) of spheroids suggest that BHs play an important role in the evolution of bulges. On the other hand, very little is known about the prevalence of nuclear BHs in late-type, bulgeless galaxies. Unfortunately, intermediate-mass BHs are difficult to find, because we are currently unable to resolve the gravitational sphere of influence of α ∼ 10^5 M⊙ BHs outside the Local Group, and thus we cannot detect them directly through resolved kinematics. We are forced to rely on indirect evidence of the presence of a BH from radiative signatures. Two prototypical low-mass AGNs are known, in the late-type spiral NGC 4395 (Filippenko & Ho 2003) and in the dwarf elliptical galaxy POX 52 (Barth et al. 2004). Greene & Ho (2004) systematically defined a sample of similar objects using the First Data Release of the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2003). Their sample of 19 galaxies forms the parent sample for the present paper, and throughout we will refer to the sample using the identification numbers from Greene & Ho (2004).

The Greene & Ho objects represent a very homogeneously selected sample of BHs with low masses, and thus presents an ideal sample to investigate how the broad-band spectral properties of AGNs depend on BH mass. The spectral properties of intermediate-mass BHs are important not only for the insight they may provide into accretion processes, but also to place observational constraints on the radiative properties of “mini-quasars” that may have contributed significantly to the reionization of the Universe (e.g. Madau et al. 2004). We are thus in the process of measuring the multiwavelength properties of the sample. Using the Very Large Array, we found that the objects are very faint in the radio (Greene et al. 2006). Here we present the results of a pilot study to constrain the X-ray properties of the sample.

Throughout we assume the following cosmological parameters to calculate distances: H_0 = 100 h km s^{-1} Mpc^{-1}, Ω_m = 0.27, and Ω_Λ = 0.75 (Spergel et al. 2003).

2. OBSERVATIONS AND DATA ANALYSIS

We observed 10 of the nearest intermediate-mass BHs from the sample of Greene & Ho (2004; see Table 1) with the Advanced CCD Imaging Spectrometer (ACIS) onboard Chandra (Weisskopf et al. 1996). The 5 ks observations were obtained during the Guest Observer Cycle 6, between December 2004 and February 2006. Images were obtained at the aim point of the S3 CCD in faint mode. In order to mitigate the effects of pile-up, we read out only 1/8 of the chip to yield a minimum read-out time of 0.4 s. The effective exposure times ranged from 5.01 to 5.67 ks.

All analysis was performed using the standard Level 2 event...
file processed by the Chandra X-ray Center, which has cosmic ray rejection and good time interval filtering included. We use wavdetect within CIAO (Chandra Interactive Analysis of Observations) to extract positions for each source, in order to verify that they are indeed the program objects. Of the 10 objects observed, eight are detected with a significance of $3 \sigma$ or greater (Table 1), where $\sigma$ is measured from the background within the extraction aperture. For the detected objects the SDSS and Chandra positions agree within 0′′1 for all but GH10 and GH11, which agree within 0′′1′′ (these are the faintest detections). The on-axis point-spread function of Chandra contains 95% of the encircled energy within 1′′. We therefore extract counts from a 2′′ radius around each source, in the soft (0.5-2 keV; C0) and hard (2-8 keV; C1) bands, while background rates are calculated using annuli of inner radius 7′′ and outer radius 15′′. The task dmextract within CIAO is used to extract the background-corrected count rates. The background rates within this aperture are truly negligible, consisting of fewer than 1 count in each energy range over the total integration time. We verify that there is no extended emission by repeating the extraction for 1′′ and 3′′ extraction radii, and in all cases the extractions are consistent with 95% of the energy falling within the 1′′ radius. In GH02 we see marginal evidence for extended emission; there is a 10% increase in flux between the 1′′ and 2′′ extractions, but the result is only marginally significant.

### 2.1. Hardness Ratios

Only five objects are bright enough (>200 cts) to perform proper spectral fitting. The “hardness ratio” $H \equiv (C_{1}-C_{0})/(C_{1}+C_{0})$ (Table 1) provides a crude estimate of the spectral shapes of all the detected targets. However, we would like to derive a photon index over 0.5-2 keV ($\Gamma_{x}; N(E) \propto E^{-\Gamma_{x}}$) for each target in a uniform manner. We therefore follow Gallagher et al. (2005) and use the observed hardness ratios combined with the instrumental response to infer $\Gamma_{HR}$ for each source. The instrumental response is expressed in two matrices, the auxiliary response file (ARF) and the redistribution matrix file (RMF), which we compute for each observation using the task psextract in CIAO. The ARF describes the energy-dependent modifications to an input spectrum due to the effective area and quantum efficiency of the telescope, while the RMF modifies the input energy spectrum into the observed distribution of pulse heights, due to the finite energy resolution of the detectors. We use the spectral-fitting package XSPEC (Arnaud 1996) to generate artificial spectra with known spectral slopes and Galactic absorption (Table 1) over a range of soft photon indices 1 < $\Gamma_{x}$ < 4. We then “observe” the artificial spectra using the ARF and RMF calculated for each observation, and measure a hardness ratio for each input slope. With this mapping between observed hardness ratio and underlying slope, we infer $\Gamma_{HR}$ from hardness ratios, as shown in Table 1. Below we verify that $\Gamma_{HR}$ is consistent with more detailed spectral analysis for the brightest objects (see Table 2), which gives us some confidence that our approach is valid. In the interest of uniformity, however, when we compare distributions of $\Gamma_{x}$, we will use only the values derived in this fashion. We also derive the fluxes shown in Table 1 using the measured count rates and assuming $\Gamma_{HR}$.
FIG. 1.— Extracted spectra of GH01, GH02, GH04, GH08, and GH14 from 0.3 to 4 keV, grouped to ensure a minimum of 20 counts in each energy bin. Each spectrum is fit with an absorbed power-law, where the absorption is fixed to the Galactic value (see Table 1). The best fits correspond to photon indices of $\Gamma_s = 2.5 \pm 0.1, 2.4 \pm 0.3, 2.3 \pm 0.1, 2.7 \pm 0.2,$ and $2.2 \pm 0.2,$ respectively. The bottom panel in each plot shows the residuals normalized by sigma ($\chi$).

FIG. 2.— (a) Spectral fit to GH04 using a single absorbed power-law, restricted to energies 1.5–4 keV. Extraction and binning as in Fig. 1, with absorption fixed to the Galactic value. The best-fit photon index is $\Gamma_s = 1.9 \pm 0.5$; however, there is clearly an excess at low energies. (b) Same as in (a), but with the power-law component fixed to a photon index of $\Gamma_s = 1.9$ and an additional blackbody component (in the rest frame of the AGN) included. A blackbody component with a best-fit temperature of $kT = 0.15 \pm 0.24$ keV accounts for 40% of the flux at 0.6 keV.
Five (GH01, GH02, GH04, GH08, and GH14) of the 10 observed targets had a sufficient total number of counts to enable a reliable spectral fit. First, the observations were binned to contain no fewer than 20 counts per bin, such that the \( \chi^2 \) statistic is valid. Quoted errors are for 90% confidence in a single parameter. The spectra were then extracted using the aperture (2\('' \)) defined for the aperture photometry. Since the background within this aperture is negligible, no background subtraction is done. We limit our attention to the 0.3–5 keV range to avoid detector-related uncertainties at the lowest energies and because there is virtually no signal above 5 keV.

We fit the spectra within XSPEC. All of the spectra are well fit by a simple absorbed power-law model, with the absorption fixed to the Galactic value (Dickey & Lockman 1990). We show these fits in Figure 1 and Table 2. This very simple model results in reasonable values of \( \chi^2 \) in all cases, which suggests that we cannot justify additional components. Note also that we find good agreement between \( \Gamma_{HR} \) and \( \Gamma_{S} \) in all cases. The fits with only Galactic absorption are reasonable, but for completeness we have also performed fits with the absorption allowed to vary. In all cases, the derived values of \( \Gamma_{S} \) and \( N_H \) agree within the uncertainties, while the goodness-of-fit is not significantly improved. We therefore find no compelling evidence for intrinsic neutral absorption. Since the effective area of the S3 chip peaks between 1 and 2 keV, with such short exposures we cannot constrain well the hard (\( \geq 2 \) keV) continuum shapes. If the spectra are actually composed of multiple components, such as a thermal excess at soft energies and a power-law at higher energies, we have neither the required spectral coverage nor the needed depth to adequately model these components.

However, significant soft excesses are a distinct possibility; the soft component can dominate the spectrum up to energies as high as 1 keV (Brandt et al. 1997; Leighly 1999b). For this reason, we investigate whether we can place any constraints on the presence of a soft excess. It is common to model the soft excess as a blackbody component (e.g., Leighly 1999b), and so we attempt to fit each spectrum with a single blackbody component to investigate whether our spectra are dominated by a soft excess component. In all cases, the blackbody provides a poor fit to the data, with significant excesses at both low and high energies, and with unnaturally high energies of \( kT = 0.26 \) keV, significantly higher than the typical temperatures of \( kT = 0.15 \) keV seen in the soft X-ray excess of both narrow-line Seyfert 1 (NLS1) galaxies (Leighly 1999b) and Palomar-Green (PG; Schmidt & Green 1983) quasars (Gierlotki & Done 2004). Unfortunately, we do not have sufficient counts to warrant a multi-component fit for objects other than GH01 and GH04. For these objects, we adopt a two-step procedure. We first fit the power-law component using only data \( \geq 1.5 \) keV, using the extraction regions and binning as above, and fixing the absorption to the Galactic value. We then remodel the entire spectrum with the derived power-law and an additional blackbody component at the redshift of the AGN. In the case of GH01, the putative extra blackbody component would account for only 10% of the flux at 0.6 keV. The situation is different for GH04. In this case, the best-fit spectral index is marginally flatter, with \( \Gamma_{S} = 1.9 \pm 0.5 \). As is apparent from Figure 2a, when the model is extrapolated to lower energies there is a significant excess above the simple power law. We then model the full spectrum (0.3–5 keV) with the power law fixed and an additional blackbody component added in the rest-frame of the AGN. The combined fit (Fig. 2b) is quite reasonable, although it is statistically indistinguishable from the single power-law fit. The blackbody component has a temperature of \( kT = 0.15 \pm 0.24 \) keV and accounts for \( \sim 40\% \) of the flux at 0.6 keV. Apparently the data are completely consistent with a soft excess in GH04. Because of the decreased sensitivity of \( Chandra \) above 2 keV, however, we cannot place strong constraints on the spectral shape at higher energies, and thus can only roughly decompose the hard and soft shapes.

3. RESULTS

3.1. Comparison with Narrow-line Seyfert 1 galaxies

The Greene & Ho (2004) sample occupies a unique regime in terms of BH mass and Eddington ratio, and thus the distribution of X-ray properties should provide interesting new constraints on physical models of X-ray emission in AGNs. The sample properties are, however, well-bracketed at low mass by the prototypical intermediate-mass BHs NGC 4395 and POX 52, and at high masses by the subclass of AGNs known as NLS1 galaxies. NLS1 galaxies were originally identified on the basis of unusually narrow, but still kinematically distinctly narrow permitted lines—specifically FWHM(H\beta) \( < 2000 \) km s\(^{-1}\). By this definition, the Greene & Ho sample, NGC 4395 and POX 52, all qualify as NLS1s. In general, however, NLS1s are also characterized by high Fe II/H\beta and low [O III]/H\beta ratios\(^1\) in their optical spectra (Osterbrock & Pogge 1985). They have since been found to have very uniform X-ray properties, including a soft X-ray excess (e.g., Boller et al. 1996), steep X-ray spectra (e.g., Leighly 1999b; Grupe et al. 2004), and extreme variability in the X-rays (e.g, Leighly 1999a). Currently the best explanation for NLS1 properties is that they contain low-mass BHs\(^2\) radiating at a high fraction of their Eddington rates (e.g., Pounds et al. 1995). In this picture, the broad lines are rather narrow due to the low BH mass (and thus small virial velocities in the broad-line region). The characteristic strong Fe II and weak [O III] emission are thought to be generic spectral characteristics of AGNs in a high accretion state (Boroson & Green 1992; Boroson 2002). NLS1s are also characteristically radio-quiet, much like Galactic stellar-mass BHs in a high accretion state (Greene et al. 2006; McClintock & Remillard 2006). The Greene & Ho objects are technically NLS1s, based on the linewidth criterion, and they are selected to have low masses. They also appear to be radiating close to their Eddington luminosities, and they are uniformly radio-quiet (Greene & Ho 2004; Greene et al. 2006). However, in terms of optical properties, the Fe II and [O III] strengths of the Greene & Ho sample span a larger range than typical NLS1s (Greene & Ho 2004). We are now able to compare the X-ray properties, particularly the spectral shapes and broader spectral energy distributions, of this sample with NLS1s in general.

Prototypical NLS1 samples are characterized by an extreme soft X-ray excess (e.g., Boller et al. 1996), which can dominate the spectrum below \( \leq 1 \) keV (e.g., Brandt et al. 1997; Leighly 1999b). While GH04 may have a weak soft excess, we do not

\(^1\)Here H\beta refers to the flux of the narrow component of the line.

\(^2\)Collin et al. (2006) revisit the possibility that some NLS1s are most consistent with having larger BH masses and a high inclination and suggest that the Williams et al. sample is dominated by such objects. While we cannot rule out this possibility, the observation that the Greene & Ho sample obeys the low-mass extrapolation of the \( M_{\text{BH}} - \sigma_* \) relation (Barth et al. 2005; Greene & Ho 2006) suggests that our objects are truly low-mass BHs, as does the finding that the host galaxies themselves are low-luminosity, late-type systems (Greene & Ho 2004, based on SDSS images; J. E. Greene, A. J. Barth, & L. C. Ho, in preparation, based on \textit{Hubble Space Telescope} images).
find compelling evidence for a strong soft excess in our sample. Only two objects (GH07 and GH08) have notably steep soft spectral slopes compared to $\Gamma_s \approx 2.5$ typical of AGNs (Yuan et al. 1998). This finding is in keeping with the results of Williams et al. (2004) that optically selected NLS1s need not have steep soft X-ray photon indices. With a FWHM$_{1.5}\beta$ of 1500 km s$^{-1}$ (Filippenko & Ho 2003) and a soft X-ray slope of $\Gamma_s \approx 0.9$ (Lira et al. 1999; Moran et al. 1999), NGC 4395 perhaps provides the most dramatic example that low BH mass (or small FWHM$_{1.5}\beta$) does not guarantee a steep soft slope. However, the flat slope of NGC 4395 may be misleading, since it probably results partly from the presence of a warm absorber (e.g., Crenshaw et al. 2004). While the hard spectral slope of NGC 4395 is also quite flat ($0.6 < \Gamma_b < 1.7$), it is also observed to vary considerably, possibly due to variations in the intrinsic absorption (Iwasawa et al. 2000; Shu et al. 2003; Moran et al. 2005). In contrast, we do not see evidence for significant absorption in our spectra (at least from neutral material).

Many NLS1 spectra are also found to have complicated features around 1 keV (e.g., Brandt et al. 1994; Leighly et al. 1997; Fiore et al. 1998; Turner et al. 1998; Nicastro et al. 1999). These features have been explained in the literature as either absorption edges from highly ionized oxygen, with blueshifts of $0.2c \pm 0.6c$ (Leighly et al. 1997), or resonant absorption lines (e.g., predominantly Fe L; Nicastro et al. 1999). More recently, Crummy et al. (2005, 2006) find that the 1 keV feature results naturally in relativistically blurred photoionized emission from the accretion disk (e.g., Ross & Fabian 2005). If the first explanation is correct, then these systems are able to drive highly ionized outflows. We do not have the energy resolution nor the sensitivity to detect such features with high confidence, but we note that all of our spectra show interesting anomalies at $\sim 0.8 - 1$ keV. We may be seeing the O VII absorption edge at 0.74 keV, or we may be seeing a dip at $\sim 1$ keV, as seen by the authors above. We note, too, that Williams et al. (2004) see a similar feature in their brightest object, SDSS J1449+0022.

A final important characteristic of NLS1s in the X-rays is their impressively rapid temporal variability (Boller et al. 1996). The variability amplitude appears to be correlated with soft excess (Leighly 1999a, 1999b). NGC 4395 is extremely variable; it was seen to increase by a factor of 10 in $< 2000$ s. Unfortunately, we cannot constrain the variability properties of our sample from such short observations. However, we can look for long-term variability by comparing our fluxes with those seen by the ROSAT All-sky Survey (RASS). GH07, GH08, and GH14 were all detected by the RASS, and are consistent with only small-amplitude ($< 50\%$) variability over a $\sim 10$ yr timescale. In contrast, GH01 is $\sim 5$ times brighter than in the RASS observation. Also, GH04 was undetected by the RASS but very clearly detected by Chandra, which is consistent with a factor of $\sim 2$ variability. Interestingly GH04 is our best candidate for significant optical variability as well (T. Morton et al., in preparation).

3.2. Broad-band Spectral Properties

We turn briefly now to the broader spectral energy distributions of this sample. As noted above, the Greene & Ho sample is extremely radio-quiet, which is very similar to NLS1s in general (Greene et al. 2006). We now examine the ratio of X-ray to optical flux for this subsample, using $\alpha_{ox}$, the slope of a hypothetical power law extending from 2500 Å to 2 keV (e.g., Tananbaum et al. 1979). We adopt the definition of Strateva et al. (2005): $\alpha_{ox} \equiv -0.3838 \log (f_{2500}/f_{2\text{keV}})$. The flux density at 2500 Å, $f_{2500}$, is calculated using the 5100 Å continuum flux densities and optical power-law continuum slope measurements from Greene & Ho (2005), in which the total continuum of each source was modeled as a combination of host galaxy emission, AGN power-law continuum, and Fe II pseudocontinuum. There is a well-known correlation between $\alpha_{ox}$ and continuum luminosity, typically measured at 2500 Å (e.g., Avni & Tananbaum 1982; see Bechtold et al. 2003). We have plotted $\alpha_{ox}$ against $L_{2500}$ in Figure 3, with the derived relation of Strateva et al. (2005). GH14 and GH19 have particularly strong galaxy continua and so their continuum slopes and luminosities are not well constrained. We also include the Williams et al. (2004) sample of NLS1s with relatively weak X-ray luminosities and the subset of PG quasars that qualify as NLS1s according to the FWHM$_{1.5}\beta$ criterion, with FWHM$_{1.5}\beta$ taken from Boroson & Green (1992). Our sample as a whole agrees reasonably well with a low-luminosity extrapolation of the Strateva et al. relation; based on the median luminosity log $L_{2500} = 27.7$, the relation predicts $\alpha_{ox}$ of $-1.1 \pm 0.5$, which is consistent with the observed value for the majority of the objects. However, there are two possible outliers, GH05 and GH11. (Recall that we are plotting the $3\sigma$ upper limit for GH05). GH05 has optical properties very similar to NLS1s in general, particularly a large Fe II/H/β and small [O III]/H/β ratio. These are properties typically associated with high Eddington ratios (e.g., Boroson 2002). On the other hand, GH11 has no apparent Fe II lines, and it has a high [O III]/H/β ratio.

4. PHYSICAL INSIGHTS

The primary goal of this study is to investigate the dependence of X-ray properties on BH mass, since this AGN sample was uniformly selected to have the lowest BH masses known. In particular, we can investigate the degree to which characteristic NLS1 properties are driven by the BH mass. Boller et
al. (1996) found that FWHM$_{H\alpha}$ is correlated with the soft X-ray slope and suggested that low BH mass may be a necessary condition for steep soft photon indices (see also Puchnarewicz et al. 1992; Laor et al. 1994; Wang et al. 1996). Porquet et al. (2004) make a similar claim based on XMM-Newton observations of PG quasars. However, our sample covers a range of 600 ≤ FWHM$_{H\alpha}$ ≤ 1800 km s$^{-1}$ (10$^5$ ≤ M$_{BH}$/M$_{\odot}$ < 10$^6$) and 1 ≤ Γ$_s$ ≤ 3. We (and Williams et al. 2004) thus fill the regions avoided by the Boller et al. sample. Our mean Γ$_{BH}$ = 2.1 ± 0.5 (note that this mean neglects the non-detections) is, if anything, flatter than Γ$_s$ = 2.56 ± 0.44 measured in PG quasars from 0.3–2 keV with XMM-Newton by Porquet et al. (2004) or Γ$_s$ = 2.58 ± 0.05 measured for general ROSAT samples (Yuan et al. 1998). We illustrate this in Figure 4a, where we plot Γ$_s$ against M$_{BH}$ for our sample, and the samples of Williams et al. and, in order to increase the dynamic range in BH mass and luminosity, the radio-quiet$^3$ sample of PG quasars with XMM-Newton observations presented by Porquet et al. (2004). The masses for the Williams et al. sample were derived using the virial slope versus luminosity correlations. Given that M$_{BH}$ does not appear to be the main driver of soft X-ray photon index, we seek correlation with other parameters. In particular, we consider both the soft (0.5–2 keV) X-ray luminosity, L$_{0.5-2\text{keV}}$, and the Eddington ratio, L$_{bol}$/L$_{Edd}$ (Figs. 4b,c). The X-ray luminosities are derived from Chandra observations for our sample and that of Williams et al., while they are measured from 0.3 to 2 keV with XMM-Newton for the Porquet et al. sample, and converted to a common bandpass of 0.5–2 keV using the spectral slopes derived by Porquet et al. The Eddington ratios are derived using L$_{5100}$ and assuming L$_{bol}$ = 9L$_{5100}$ (e.g., Kaspi et al. 2000). We have used the optical luminosities here to avoid a potentially spurious correlation between Γ$_s$ and L$_X$ which may arise because we are more sensitive to soft sources with Chandra. From this (incomplete and heterogeneous) sample, we find the strongest correlation between α$_{ox}$ and X-ray luminosity (τ = 0.46, P$_{null}$ = 6 × 10$^{-6}$), subject to the caveat mentioned above, while the correlation with Eddington ratio is also significant (τ = 0.30, P$_{null}$ = 0.003).

We are by no means the first to claim a correlation between X-ray spectral slope and X-ray luminosity. It has been found that Γ$_s$ correlates with soft X-ray luminosity in NLS1s (Forster & Halpern 1996; Williams et al. 2004), and more general AGN populations (Lu & Yu 1999), while Γ$_{h}$ (the photon index from 2–10 keV) has been found to correlate with hard X-ray luminosity as well (Dai et al. 2004; Gierliński & Done 2004; Porquet et al. 2004; Wang et al. 2004). Interestingly, individual objects have been observed to obey a similar correlation as they vary (e.g., Chiang et al. 2000; Petrucci et al. 2000; Vaughan & Edelson 2001). Furthermore, strong correlations between Γ$_s$ and Fe II strength (or the Fe II/H$\beta$ ratio) have long been known (e.g., Wilkes et al. 1987; Shastri et al. 1993; Laor et al. 1994; Wang et al. 1996; but see also Boroson 1989), which may support a trend between Eddington ratio and Γ$_s$, since Fe II strength correlates with Eddington ratio (e.g., Boroson 2002). However, we are still wary that the presence or absence of X-ray slope versus luminosity correlations may depend on the particular sample chosen, since many people have not found this trend (Leighly 1999b for NLS1s; George et al. 2000; Reeves & Turner 2000). Clearly, a well-defined sample covering a com-

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$^3$Radio-loudness is defined as f$_{6cm}$/f$_{4500}$ > 10.
plete range in BH mass and luminosity using a single instrument is needed to address this question definitively. For the time being, we consider the above trend suggestive.

Various groups have proposed explanations for the trend between hard X-ray luminosity and hard photon index. Dai et al. (2004) hypothesize that their sample occupies a narrow range in Eddington ratio, with a wide range in BH mass. They invoke the disk-corona model of Haardt & Maraschi (1993), in which cool disk photons provide the seeds for Compton cooling of the hard X-ray emitting corona, as well as thermally reprocessing and reflecting some fraction of the hard X-ray emission. Haardt et al. (1997) show that within this model if the optical depth of the corona is dominated by electron-positron pairs, then there will be a correlation between 2–10 keV spectral shape and luminosity. On the other hand, Wang et al. (2004) find that the fraction of bolometric luminosity emitted in the hard X-ray band decreases with increasing bolometric luminosity. In this case, the soft X-ray emitting region weakens at high Eddington ratio. They propose that the coupling between the disk and the corona depends on magnetic turbulence, which may depend on the Eddington ratio, depending on the form of the magnetic stress tensor. Generalizing these models to the soft photon index is made complicated by the fact that the origin of the soft X-ray excess is unknown.

Pounds et al. (1995) proposed that low-mass BHs at high Eddington ratios would have a soft thermal disk component observable in the ROSAT band. However, we have seen that BH mass does not drive $\Gamma_s$, and furthermore, Gierliński & Done (2004) argue that the soft X-ray excess is too hot by $0.1 \text{ keV}$ and (particularly) too constant in temperature ($\sim 0.15 \text{ keV}$; see also Laor et al. 1994; Leighly 1999b) to arise from the accretion disk. They propose that relativistically blurred absorption from a wind causes an apparent excess at soft energies. In this context, it is possible that a higher luminosity (and thus more vigorous wind; e.g., Proga et al. 2000) may lead to a steeper apparent slope. On the other hand, Crummy et al. (2006) model the soft excess using the ionized-reflection models of Ross & Fabian (2005). In this case, the soft X-ray emission arises from photoionization of a highly ionized, relativistically rotating inner accretion disk. In this model, the apparent soft spectral slope does steepen for steeper input hard X-ray slopes.

In light of the finding of Wang et al. (2004) that the corona weakens at high Eddington ratio, one would expect $\alpha_{\text{ox}}$ to steepen with increasing ultraviolet (UV) luminosity, particularly for a relatively narrow range in $M_{\text{BH}}$. However, we would then expect our low-mass, low-luminosity, and high-$L_{\text{bol}}/L_{\text{Edd}}$ sample to deviate significantly from the relation derived for more massive BHs, which is not the case (Fig. 3). In fact, we do not see a significant correlation between Eddington ratio and $\alpha_{\text{ox}}$ in our sample; it spans more than an order of magnitude in $L_{\text{bol}}/L_{\text{Edd}}$ and yet is nearly constant in $\alpha_{\text{ox}}$. Rather, our observations support a scenario in which the bolometric importance of the X-ray-emitting region is determined by the strength of the UV continuum. Disk-corona models (e.g., Haardt & Maraschi 1993), in which the soft disk photons cool the corona and the corona heats the disk photons, naturally explain such a relationship. Nevertheless, $\alpha_{\text{ox}}$ must vary with $L_{\text{bol}}/L_{\text{Edd}}$ as well. At very low accretion rates, there is believed (and observed) to be a transition from an optically thick, geometrically thin disk (Shakura & Sunyaev 1973) to a radiatively inefficient, optically thin and geometrically thick flow (e.g., Ho 1999, 2005; Quataert 2001; Narayan 2005 and references therein). If there is no optically thick accretion disk at all, and thus no peak in the thermal disk emission in the far-UV, then $\alpha_{\text{ox}}$ should flatten considerably (L. C. Ho, in preparation). NGC 4395, for instance, has both a very low Eddington ratio ($\sim 0.04$; Moran et al. 1999) and an abnormally flat spectral slope (see Figure 3).

There is also some evidence that $\Gamma_s$ may steepen considerably at very high Eddington ratios. Specifically, there is a subset of NLS1s that appear to be intrinsically X-ray-weak (Leighly 2001; Leighly et al. 2001; Williams et al. 2004). While X-ray absorption can also cause anomalously steep $\alpha_{\text{ox}}$ values (e.g., Brandt et al. 2000; Gallagher et al. 2002), there is no evidence for neutral absorption in the X-ray spectra (or the UV spectra in the case of the Leighty objects). Extreme variability may explain the X-ray weakness in some of these objects, but it cannot reasonably account for all of them. Leighly et al. (2001) speculate that the X-ray weakness reflects a truly weak corona, either because the accretion disk extends so close to the BH that there is physically no space for a corona, or, like in the Wang et al. (2004) picture, because the disk-corona energy transport mechanism is quenched at high luminosity. We note, as an aside, that low-ionization broad absorption-line quasars, which are believed to be in a high accretion state (e.g., Meier 1996; Boroson 2002), are also proving particularly difficult to detect in the X-rays (e.g., Green et al. 2001; Gallagher et al. 2006). While these objects may simply be Compton-thick, it is also possible that they are intrinsically X-ray-weak. In our own sample, GH11 has a flat $\Gamma_{\text{HR}}$, and is quite consistent with absorption driving the low X-ray flux. On the other hand, it would be very useful to obtain deeper X-ray observations of GH05 in order to determine whether it is intrinsically X-ray-weak or heavily absorbed. The interpretation that X-ray weakness is related to high Eddington ratio is quite speculative, but could provide a powerful diagnostic to isolate objects in a specific accretion regime.

5. SUMMARY

We present a pilot study of the X-ray properties of intermediate-mass BHs in active galaxies. We have detected eight out of the 10 objects surveyed with 5 ks Chandra observations. From an analysis of their hardness ratios, we find that the objects have a range in $0.5–2 \text{ keV}$ photon index of $1 < \Gamma_s < 3$ [$N(E) \propto E^{-\Gamma}$], in keeping with general AGN samples previously studied. In the five objects for which there are sufficient counts to extract spectra, there is no evidence for neutral absorption, although we do see evidence for spectral complexity at energies $\leq 1 \text{ keV}$, which may indicate ionized absorption. The X-ray-to-optical flux ratios for the majority of the sample obey the same correlation with optical/UV luminosity seen in the literature, but there are two X-ray-weak sources. Given the apparent correlation between Eddington ratio and spectral slope, we speculate that X-ray weakness in at least one of these sources may be related to a high Eddington ratio. We find that the soft X-ray slope correlates strongly with soft X-ray luminosity, but not with BH mass.

This study demonstrates the feasibility of detecting $\sim 10^5–10^6 M_\odot$ BHs with relatively short Chandra observations. With them, we have begun to probe the accretion properties of AGNs in an unexplored mass regime. It is our goal to build broad spectral energy distributions for the entire sample, in order to properly measure their bolometric luminosities. We will then be in a good position to search for mass-dependent spectral properties, as well as calibrate various common average bolometric corrections (such as [O III] luminosity) for objects in this mass regime. Finally, while we are unable to address the variability properties
of the sample with short observations, there are strong indications that the X-ray variability amplitude (e.g., O’Neill et al. 2005) and detailed power spectrum (McHardy et al. 2005) can serve as indicators of the BH mass. Extended X-ray observations of this sample would provide a powerful new test of these important BH mass measurement techniques.

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