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

JENNY E. GREENE
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

AND

LIUIS C. HO
Observatories of the Carnegie Institution of Washington, Pasadena, CA

Received 2006 April 6; accepted 2006 September 11

ABSTRACT

We present a pilot study of the X-ray properties of intermediate-mass ($\sim 10^5$–$10^6$ $M_\odot$) 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 3 $\sigma$, with X-ray luminosities in the range $L_{0.5-2\text{ keV}} \approx 10^{41}$–$10^{43}$ erg s$^{-1}$. The optical to X-ray flux ratios are consistent with expectations, given the known correlations between $\sigma_{\text{sys}}$ and ultraviolet luminosity, while a couple of objects appear to be anomalously X-ray weak. The range of 0.5 to 2 keV photon indices we measure, $1 < \Gamma_x < 2.7$, is entirely consistent with values found in samples of more luminous sources with more massive black holes. Black hole mass is evidently not a primary driver of soft X-ray spectral index. On the other hand, we do find evidence for a correlation between the 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 ratios. 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 $\sim 10^2$–$10^3$ $M_\odot$, and are the remnants of massive star death, while supermassive BHs have masses in the range $10^6$–$10^9$ $M_\odot$, and are a ubiquitous component of galaxy bulges. There are thus $\sim$5 orders of magnitude in BH mass that remain 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”; $L_X \geq 10^{39}$ erg s$^{-1}$) off-nuclear extragalactic X-ray sources that may be BHs with masses of $100$–$1000$ $M_\odot$ (see, e.g., van der Marel 2004 for a review). We have a complementary program to find intermediate-mass BHs with masses of $10^4$–$10^6$ $M_\odot$ 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 analogs of the primordial seeds of supermassive BHs. Furthermore, the mergers of BHs with masses $\sim 10^5$ $M_\odot$ are expected to provide a strong signal for the Laser Interferometric Space Antenna (e.g., Hughes 2002). The tight correlations between supermassive BH mass ($M_{\text{BH}}$) and both the luminosity (Kormendy & Richstone 1995) and stellar velocity dispersion (the $M_{\text{BH}}$–$\sigma$ 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 a $\sim 10^5$ $M_\odot$ BH 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 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 broadband 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 “miniquasars” 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: $H_0 = 100\ h = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.75$ (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) on board Chandra (Weisskopf et al. 1996). The 5 ks observations were obtained during Guest Observer Cycle 6, between 2004 December and 2006 February. 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
| ID    | $D_L$ | $N_H$   | $C_i$     | $C_h$     | $H$   | $\Gamma_{HR}$ | log $f_{05}$ | log $f_{2-8}$ | log $L_{0.5-2}$ | log $L_h$ | log $L_x$ | $\beta$ | $\alpha_{OX}$ |
|-------|-------|---------|-----------|----------|-------|---------------|--------------|--------------|-----------------|-----------|-----------|--------|-----------|
| GH01  | 343   | 20.59   | 0.183 ± 0.007 | 0.0258 ± 0.003 | 2.5 ± 0.1 | -12.10 ± 0.01 | -12.35 ± 0.02 | 43.05 ± 0.05 | 42.81 ± 0.05 | 42.83 | 0.6       | -1.0   |
| GH02  | 127   | 20.60   | 0.0437 ± 0.003 | 0.0104 ± 0.002 | 2.2 ± 0.2 | -12.75 ± 0.02 | -12.82 ± 0.04 | 41.54 ± 0.05 | 41.47 ± 0.05 | 41.79 | 0.5       | -1.2   |
| GH04  | 189   | 20.61   | 0.176 ± 0.006 | 0.0415 ± 0.003 | 2.2 ± 0.1 | -12.14 ± 0.06 | -12.22 ± 0.07 | 42.49 ± 0.06 | 42.42 ± 0.06 | 42.74 | 1.0       | -1.2   |
| GH05  | 331   | 20.35   | <0.00111   | < 0.0001   | ...   | ...           | <-14.97      | <-14.37      | <40.15          | <40.75 | 42.74     | 0.5    | <-1.7     |
| GH07  | 427   | 20.59   | 0.0245 ± 0.003 | 0.00362 ± 0.001 | 2.5 ± 0.1 | -12.89 ± 0.22 | -13.13 ± 0.16 | 42.45 ± 0.22 | 42.21 ± 0.22 | 42.52 | 0.3       | -1.1   |
| GH08  | 364   | 20.37   | 0.0811 ± 0.004 | 0.00942 ± 0.002 | 2.7 ± 0.2 | -12.44 ± 0.09 | -12.79 ± 0.08 | 42.76 ± 0.09 | 42.41 ± 0.09 | 42.89 | 0.4       | -1.2   |
| GH10  | 363   | 20.27   | 0.00727 ± 0.001 | 0.00747 ± 0.001 | 1.0 ± 0.1 | -13.53 ± 0.12 | -12.92 ± 0.09 | 41.66 ± 0.12 | 42.28 ± 0.15 | 43.10 | 0.8       | -1.5   |
| GH11  | 365   | 20.24   | 0.00317 ± 0.001 | 0.00145 ± 0.001 | 1.7 ± 0.1 | -14.04 ± 0.82 | -13.81 ± 0.83 | 41.17 ± 0.82 | 41.40 ± 0.82 | 43.16 | 1.4       | -1.8   |
| GH14  | 121   | 20.40   | 0.0568 ± 0.004 | 0.0114 ± 0.002 | 2.3 ± 0.1 | -12.58 ± 0.11 | -12.69 ± 0.18 | 41.67 ± 0.11 | 41.55 ± 0.11 | 41.46 | -0.4      | -1.0   |
| GH19  | 154   | 20.58   | <0.00117   | <0.00113   | ...   | ...           | <-14.94      | <-14.35      | <39.52          | <40.10 | 40.90     | -1.8   | <-1.2     |

Notes.—Col. (1): Identification number from Greene & Ho (2004). Col. (2): Luminosity distance (Mpc) calculated from the SDSS redshifts. Col. (3): Galactic column density $N_H$ (cm$^{-2}$), calculated followingDickey & Lockman (1990). Col. (4): 0.5-2 keV count rate (counts s$^{-1}$). Col. (5): 2-8 keV count rate (counts s$^{-1}$). Col. (6): Hardness ratio, $(C_h - C_i)/(C_h + C_i)$. Col. (7): Photon index $[\Gamma; N(E) \propto E^{-\gamma}]$, derived from the hardness ratios (see text). Col. (8): Flux in the 0.5–2 keV band (ergs s$^{-1}$ cm$^{-2}$). Col. (9): Flux in the 2–10 keV band (ergs s$^{-1}$ cm$^{-2}$). Col. (10): 0.5–2 keV luminosity (ergs s$^{-1}$). Col. (11): 2–8 keV luminosity (ergs s$^{-1}$). Col. (12): Luminosity at 2500 Å as inferred from $L_{5100}$ using $\beta$ (Greene & Ho 2005; ergs s$^{-1}$). Col. (13): Optical continuum slope; $f_i \propto \lambda^{-\beta}$. Col. (14): $\alpha_{OX} \equiv -0.3838(f_{2500} / f_{2-8})$. 
wave\texttt{detect} within CIAO (\textit{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 \textit{Chandra} positions agree within $0.1^\prime\prime$ for all but GH10 and GH11, which agree within $1^\prime\prime$ (these are the faintest detections). The on-axis point-spread function of \textit{Chandra} contains $95\%$ of the encircled energy within $1^\prime\prime$. We therefore extract counts from a $2^\prime\prime$ radius around each source, in the soft ($0.5$–$2$ keV; $C_s$) and hard ($2$–$8$ keV; $C_h$) bands, while background rates are calculated using annuli of inner radius $7^\prime\prime$ and outer radius $15^\prime\prime$. The task \texttt{ds9extract} 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 $1^\prime\prime$ and $3^\prime\prime$ extraction radii, and in all cases the extractions are consistent with $95\%$ of the energy falling within the $1^\prime\prime$ radius. In GH02 we see slight evidence for extended emission; there is a $10\%$ increase in flux between the $1^\prime\prime$ and $2^\prime\prime$ extractions, but the result is only marginally significant.

### 2.1. Hardness Ratios

Only five objects are bright enough ($\geq200$ counts) to perform proper spectral fitting. The “hardness ratio” $[H \equiv (C_h - C_s)/(C_h + C_s)]$ (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 ($\Gamma_s$; $N(E) \propto E^{-\Gamma_s}$) 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 $\Gamma_{\text{IR}}$ 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 \texttt{ds9extract} 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 $1 < \Gamma_s < 4$. 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 $\Gamma_{\text{IR}}$ from hardness ratios, as shown in Table 1. Below we verify that $\Gamma_{\text{IR}}$ 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 $\Gamma_s$, 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 $\Gamma_{\text{IR}}$.

### 2.2. Spectral Fitting

Five (GH01, GH02, GH04, GH08, and GH14) of the 10 observed targets had a sufficient total number of counts to enable a reliable power-law fit. In preparation for fitting, the observations were binned to contain no fewer than 20 counts per bin, such that the $\chi^2$ statistic is valid. The spectra were then extracted using the aperture ($2^\prime\prime$) defined for the aperture photometry, and 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. Quoted errors are for $90\%$ confidence in a single parameter. 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 $\Gamma_{\text{IR}}$ 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 the hard ($\geq2$ keV) continuum shapes well. 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 unusually high energies of $kT \approx 0.26$ keV, significantly higher than the typical temperatures of $kT \approx 0.15$ 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 (Gierlinski & Done 2004). Unfortunately, we do not have sufficient counts to warrant a multicomponent fit for objects other than GH01 and GH04. In these two cases, we adopt a two-step procedure. We first fit the power-law component using only data $\geq1.5$ 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

| ID         | $\Gamma_s$ | Norm. | $\chi^2$/dof |
|------------|------------|-------|--------------|
| GH01       | 2.50 ± 0.10| 3.7   | 21.06        |
| GH02       | 2.36 ± 0.29| 0.9   | 4.51         |
| GH04       | 2.33 ± 0.12| 3.6   | 13.01        |
| GH08       | 2.66 ± 0.18| 1.5   | 4.74         |
| GH14       | 2.22 ± 0.24| 1.3   | 1.06         |

Notes.—Col. (1): Identification number from Greene & Ho (2004). Col. (2): Power-law index ($N(E) \propto E^{-\Gamma_s}$). Col. (3): Normalization ($10^{37}$ photons s$^{-1}$ keV$^{-1}$). Col. (4): $\chi^2$. Col. (5): Degrees of freedom.
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 $\sim40\%$ of the flux at 0.6 keV. Apparently the data are completely consistent with a soft excess in GH04. 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 ratios, 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 broad permitted lines, specifically FWHMH _n_ <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_/Hβ and low [O III]/Hβ ratios 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 1999a, 1999b; Grupe et al. 2004), and extreme variability in the X-rays (e.g., Leithy 1999a). Currently the best explanation for NLS1 properties is that they contain low-mass BHs 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 line-width 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 1 keV (e.g., Brandt et al. 1997; Leithy 1999a). While GH04 may have a weak soft excess, we do not 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 Γ_s ~ 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 FWHMH _Hβ_ of 1500 km s⁻¹ (Filippenko & Ho 2003) and a soft X-ray slope of Γ_s ~ 0.9 (Lira et al. 1999; Moran et al. 1999), NGC 4395 perhaps provides the most dramatic example that low BH mass (or small FWHMH _Hβ_) 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 even the hard spectral slope of NGC 4395 is quite flat (0.6 < Γ_h < 1.7), it is also observed to vary considerably, possibly due to variations in the intrinsic absorption (Iwasawa et al. 2000; Shih 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; Leithy 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 0.2–0.6c (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 features result naturally in a 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 ~0.8–1 keV. We may be seeing the O _VI_ absorption edge at 0.74 keV, or we may be seeing a dip at ~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, for instance, 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 Röntgensatellit (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 ~10 yr timescale. In contrast, GH01 is ~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 ~2 variability. Interestingly GH04 is our best candidate for significant optical variability as well (T. Morton et al., in preparation).

3.2. Broadband 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 optical to X-ray flux for this subsample, using α_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): α_ox ≡ −0.3838 log (f_2500 Å/f_2 keV). The flux density at 2500 Å, f_2500 Å, 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 α_ox and continuum luminosity, typically measured at 2500 Å (e.g., Avni & Tananbaum 1982; but see Bechtold et al. 2003). We have plotted α_ox against monochromatic UV luminosity, L_2500 Å, 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

---

1 Here Hβ 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 BH–σ 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 Hubble Space Telescope images).
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$_{H_\beta}$ criterion, with FWHM$_{H_\beta}$ taken from Boroson & Green (1992) and $\alpha_{ox}$ from Brandt et al. (2000). 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 $L_{2500} \lambda = 27.7$, the relation predicts $\alpha_{ox}$ of $\sim -1.1 \pm 0.5$, 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$\beta$ and small [O III]/H$\beta$ 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$\beta$ 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$_{H_\beta}$ 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_\beta} < 1800$ km s$^{-1}$ ($10^5 < M_{BH}/M_\odot < 10^6$) and $1 < \Gamma_s < 3$. We (and Williams et al. 2004) thus fill the region avoided by the Boller et al. sample. Our mean $\Gamma_{IR} = 2.1 \pm 0.5$ (note that this mean neglects the nondetections) is, if anything, flatter than $\Gamma_s = 2.56 \pm 0.44$ measured in PG quasars from 0.3 to 2 keV with XMM-Newton by Porquet et al. (2004) or $\Gamma_s = 2.58 \pm 0.05$ measured for general ROSAT samples (Yuan et al. 1998). We illustrate this in Figure 4a, where we plot $\Gamma_s$ 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 scaling relations of Kaspi et al. (2000), while the BH masses for the Porquet et al. sample come from Ho (2002), using the same scaling relation. The masses in our sample are derived using a similar scaling relationship based on the FWHM$_{H_\beta}$ luminosity and linewidth (Greene & Ho 2005), as presented in Greene & Ho (2006). Finally, we also include NGC 4395, using the $\Gamma_s$ measured with ROSAT by Moran et al. (1999) and the reverberation-mapped mass from Peterson et al. (2005), as adapted by Greene & Ho (2006). Clearly, low BH mass is not a sufficient condition for

\[ \Gamma_s = 3 \frac{f_{0.5} / L_{2500} \lambda}{f_{2500} \lambda} > 10. \]
steep soft X-ray slopes. The nonparametric Kendall’s $\tau = 0.18$ with a probability $P_{\text{null}} = 0.08$ of no correlation. However, we note that while we have populated the region of low BH mass (or narrow H/β) and shallow Γx, there is still an unpopulated region of high BH mass (or broad H/β) and steep soft Γx, as originally noted by Boller et al. This may indicate that mass still plays a secondary role in determining the spectral shape. On the other hand, it may indicate a selection effect, in that high-accretion rate, high-mass BHs are scarce in the local universe, while at higher redshift the relevant energy range is no longer available.

Given that $M_{\text{BH}}$ does not appear to be the main driver of soft X-ray photon index, we seek a correlation with other parameters. In particular, we consider both the soft (0.5–2 keV) X-ray luminosity, $L_{\text{soft}}$, and the Eddington ratio, $L_{\text{bol}}/L_{\text{Edd}}$ (Figs. 4a and 4c). 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 to 2 keV using the spectral slopes derived by Porquet et al. The Eddington ratios are derived using $\dot{L}_{2k}\AA$ and assuming $L_{\text{bol}} = 9.7 \times 10^{46} \dot{L}_{2k}\AA$ (e.g., Kaspi et al. 2000). We have used the optical luminosities here to avoid a potentially spurious correlation between Γx 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 $\alpha_{\text{ox}}$ and X-ray luminosity ($\tau = 0.46$, $P_{\text{null}} = 6 \times 10^{-5}$), subject to the caveat mentioned above, while the correlation with Eddington ratio is also significant ($\tau = 0.30$, $P_{\text{null}} = 0.003$).

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 Γx correlates with soft X-ray luminosity in NLS1s (Forster & Halpern 1996; Williams et al. 2004), and more general AGN populations (Lu & Yu 1999), while Γx (the photon index from 2 to 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 Γx and Fe ii strength (or the Fe ii/H/β 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 the Eddington ratio and Γx, since Fe ii strength correlates with Eddington ratios (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 complete 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.

There are various 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 the 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. Within this model, Haardt et al. (1997) show that 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 $L_{\text{bol}}/L_{\text{Edd}}$, and thus conclude that the hard X-ray emitting region weakens at high Eddington ratio. They propose that the coupling between the disk and the corona is due to magnetic turbulence, which depends on the Eddington ratio, for some forms 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 Γx, and furthermore, Gierliński & Done (2004) argue that the soft X-ray excess is too hot by ~0.1 keV and (particularly) too constant in temperature (~0.15 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 ratios, one would expect $\alpha_{\text{ox}}$ to steepen with increasing ultraviolet (UV) luminosity, given 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 the 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 (~0.04; Moran et al. 1999) and an abnormally flat spectral slope (see Fig. 3).

There is also some evidence that Γx 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; Gallo 2006). 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 Leighly 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.

\footnote{See http://www.pha.jhu.edu/groups/astro/workshop2001.}
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 $f_{\text{1keV}}$, 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 ratios 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 to 2 keV photon index of $1 < \Gamma < 3$ [$N(E) \propto E^{-\Gamma}$], 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 $\leq 1$ 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 ratios 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 to better understand the connection between BH mass and 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.

We are grateful for helpful assistance on observing the Chandra X-ray Center and on data analysis from J. D. Gelfand, R. C. Hickox, S. Bogdanov, and E. M. Kellogg. We thank I. V. Strateva for useful discussions. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center. L. C. H. acknowledges support by the Carnegie Institution of Washington and by NASA grant SAO 0670600.
