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X-RAY SPECTROSCOPIC EVIDENCE FOR INTERMEDIATE-MASS BLACK HOLES: COOL ACCRETION DISKS IN TWO ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

We have analyzed an *XMM-Newton* observation of the nearby spiral galaxy NGC 1313, which contains two "ultraluminous" X-ray (ULX) sources. We measure isotropic luminosities of $L_X = 2.0 \times 10^{40}$ ergs s^{-1} and $L_X = 6.6 \times 10^{39}$ ergs s^{-1} for NGC 1313 X-1 and X-2 (0.2–10.0 keV, assuming a distance of 3.7 Mpc). The spectra *statistically require* soft and hard spectral components to describe the continuum emission; some prior studies of ULX sources have claimed cool soft components with lower statistics. The improvement over several single-component models exceeds the 8 σ level of confidence for X-1; the improvement for X-2 is significant at the 3 σ level. The soft components in these ULX spectra are well fitted by multicolor disk blackbody models with color temperatures of $kT \simeq 150$ eV. This temperature differs markedly from those commonly measured in the spectra of stellar mass (10 $M_\odot$) black holes in their brightest states ($kT \simeq 1$ keV). It is expected that the temperature of an accretion disk orbiting a black hole should decrease with increasing black hole mass. If the soft components we measure are due to emission from the inner region of an accretion disk, and disks extend close to the innermost stable circular orbit at the accretion rates being probed, the low color temperatures may be interpreted as spectroscopic evidence of black holes with intermediate masses: $M_{\rm BH} \simeq 10^3\ M_\odot$. Simple Eddington scaling arguments suggest a minimum mass of $M_{\rm BH} \sim 10^2\ M_\odot$. NGC 1313 X-1 and X-2 are found in optical nebulae, which may indicate that anisotropic emission geometries are unlikely to account for the fluxes observed.

Subject headings: black hole physics — X-rays: stars

1. INTRODUCTION

Ultraluminous X-ray (ULX) sources may be defined as pointlike off-nuclear X-ray sources in normal galaxies for which measured luminosities exceed the isotropic Eddington limit for a stellar mass (less than approximately 10 $M_\odot$) black hole. The existence of such sources was first revealed with *Einstein* (Fabbiano 1989). Variability has been observed in many ULX sources on timescales of months and years (in rare cases, on shorter timescales), which suggests that they are accreting objects.

Although intermediate-mass black holes (IMBHs; 10^2–$10^5\ M_\odot$) provide an attractive explanation for the nature of ULX sources, strong evidence for this interpretation has been lacking—especially from X-ray spectroscopic studies. Anisotropic emission from stellar mass black holes may be able to account for the flux observed in some ULX sources (King et al. 2001). Single-component fits with the multicolor disk blackbody (MCD) model (Mitsuda et al. 1984) have measured color temperatures above those commonly reported in stellar mass black holes ($kT = 1$–2 keV; see, e.g., Sobczak et al. 2000; Makishima et al. 2000); as inner disk temperatures should fall with increasing black hole mass, these findings again point toward stellar mass black holes or Kerr black holes.

NGC 1313 is a nearby spiral galaxy ($d = 3.7$ Mpc; Tully 1988). Two ULX sources—NGC 1313 X-1 and X-2—are associated with this galaxy and are approximately 1 and 8 kpc from the photometric center of the galaxy, respectively (Colbert et al. 1995). Variability was observed in *ROSAT*/HRI observations of these sources (Colbert & Ptak 2002). Colbert & Mushotzky (1999) claim evidence for a cool ($kT = 120$ eV) disk in fits to an *ASCA* spectrum of NGC 1313 X-1 with a model consisting of MCD and power-law components; however, the spectrum is fitted acceptably by a simple power law ($\Gamma = 1.74$, χ^2/degrees of freedom [dof] = 244/259). Similarly, a cool disk may be implied in joint fits to *BeppoSAX*/MECS and *ROSAT* Position Sensitive Proportional Counter spectra of M81 X-9 (La Parola et al. 2001) but not in fits to MECS and LECS spectra (both aboard *BeppoSAX*).

We have analyzed the archival *XMM-Newton* spectra of NGC 1313 X-1 and X-2. Separate soft and hard components are statistically required to describe the spectra. We measure low temperatures ($kT \simeq 150$ eV) for the soft components. We interpret the soft component as arising from the inner region of an accretion disk and explore the implications of cool accretion disks for the mass of black holes, if such objects power X-1 and X-2.

2. DATA REDUCTION AND ANALYSIS

NGC 1313 was observed by *XMM-Newton* on 2000 October 17 starting at 03:59:23 (UT). We used only the European Photon Imaging Camera (EPIC) data for this analysis. The EPIC cameras were operated in "PrimeFullWindow" mode with the "medium" optical blocking filter. The *XMM-Newton* reduction and analysis suite SAS version 5.3.3 was used to filter the standard pipeline event lists, to detect sources within the field and to make spectra and responses. The pipeline processing and our own both failed to produce an event list for the pn camera. We therefore restricted our analysis to the MOS-1 and MOS-2 cameras. Application of the standard time filtering resulted in a net exposure of 29.3 ks.

The source locations were determined by running the SAS tool EDETECT_CHAIN. With this tool, we find NGC 1313 X-1 at $3^{\rm h}18^{\rm m}19\overset{\rm s}{.}99$, $-66°29'10\overset{''}{.}97$ and NGC 1313 X-2 at $3^{\rm h}18^{\rm m}22\overset{\rm s}{.}34$, $-66°36'03\overset{''}{.}68$ (J2000.0). The tool returns an error

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of 0″.2 for these positions; an uncertainty of 4″ may be more appropriate (e.g., Foschini et al. 2002). Source counts were extracted in a circle within 24″ of the detected source position. Background counts were extracted in an annulus between 24″ and 30″. To create spectra, we then applied the selection criteria described in the MPE "cookbook." These selections are as follows: we set "FLAG = 0" to reject events from bad pixels and events too close to the CCD chip edges, event patterns 0–12 were allowed, and the MOS spectral channels were grouped by a factor of 15. Response files were made using the SAS tools RMFGEN and ARFGEN. Spectral files were grouped to require at least 20 counts bin^{-1} before fitting to ensure the validity of χ^2 statistics.

Model spectra were fitted to the data using XSPEC version 11.2 (Arnaud 1996). The MOS-1 and MOS-2 spectra were fitted jointly with an overall normalizing constant. The constant indicates that the overall flux normalizations of these cameras differ by less than 5%. Models were fitted to the spectra in the 0.2–10.0 keV band. Systematic errors were not added to the spectra. Errors quoted in this work are at the 90% confidence level. Using the SAS tool EPATPLOT, we found photon pileup to be negligible in our source spectra; this was confirmed with the HEASARC tool PIMMS using the parameters reported by Colbert & Mushotzky (1999) for X-1 and X-2.

3. RESULTS

Light curves of the source event lists do not show strong variability on the timescale of this observation. We therefore proceeded to make fits to the time-averaged spectra. The results of joint fits to the MOS-1 and MOS-2 spectra in the 0.2–10.0 keV band are listed in Table 1.

We began by fitting single-component models commonly applied to ULX sources, modified by photoelectric absorption (via the PHABS model within XSPEC). For both X-1 and X-2, MCD, thermal Bremsstrahlung, and Raymond-Smith plasma models all fail to yield acceptable fits. Simple power-law models provide improved but statistically unacceptable fits. Broken power-law models with breaks in the 0.2–10.0 keV range also yield improved but statistically unacceptable fits.

An observation of NGC 1313 with *Chandra* finds that the diffuse emission in our *XMM-Newton* extraction region is not well described with any thermal model; the best model is a $\Gamma = 1.7$ power law with an unabsorbed flux of $F_{0.3-7.0} = 5.9 \times 10^{-14}$ ergs s^{-1} (A. Kong 2002, private communication). This signals that the soft components may indeed arise in accretion disks, and we explored fits with a model consisting of MCD and power-law components and the CompTT model. The MCD model describes a standard Shakura-Sunyaev (1973) accretion disk as a series of blackbody annuli. The latter model describes Compton upscattering in a corona of optical depth τ with electron temperature $kT_{\rm corona}$ from a Wien distribution of soft seed photons (Titarchuk 1994); we used the version of the model that assumes a disk geometry for the seed photons. The coronal temperature could not be constrained, and we therefore fixed $kT_{\rm corona} = 50$ keV, which is a moderate value. X-2 is fitted acceptably by both of these models; the MCD plus power-law model is a significantly better fit to the spectrum of NGC X-1. The inability of single-component models to describe the spectra of X-1 is demonstrated in Figure 1; MCD plus power-law fits to X-1 and X-2 are shown in Figures 2 and 3. The *F*-test indicates that the improved fits given by the MCD plus power-law model are significant over single-component models at more than the 8 σ level of confidence for X-1 and at the 3 σ level of confidence for X-2. With the MCD plus power-law model, we measure isotropic luminosities of $L_{\rm X\text{-}1} = 2.0^{+1.6}_{-0.3} \times 10^{40}$ ergs s^{-1} and $L_{\rm X\text{-}2} = 6.6^{+1.8}_{-2.0} \times 10^{39}$ ergs s^{-1} (0.2–10.0 keV, assuming $d = 3.7$ Mpc). If ULX sources are like Galactic black holes and active galactic nuclei, a corona may be the source of hard X-rays. Extrapolating to the 0.05–100.0 keV band, we find that isotropic luminosities increase by approximately 50%.

TABLE 1

Spectral Fit Parameters

Parameter	NGC 1313 X-1	NGC 1313 X-2
Power-Law Model		
$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	$2.0^{+0.2}_{-0.1}$	$2.7^{+0.3}_{0.2}$
Γ	1.90 ± 0.05	2.4 ± 0.1
Normalization ($\times 10^{-4}$)	$6.3^{+0.3}_{-0.4}$	$3.9^{+0.4}_{-0.3}$
χ^2/dof	497.7/384	177.7/167
MCD Model		
$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	$0.41^{+0.09}_{-0.08}$	$0.6^{+0.2}_{-0.1}$
kT (keV)	1.41 ± 0.06	$0.91^{+0.06}_{0.05}$
Normalization ($\times 10^{-2}$)	$3.0^{+0.5}_{-0.4}$	$6.4^{+1.8}_{-1.4}$
χ^2/dof	809.5/384	265.5/167
Bremsstrahlung Model		
$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	1.27 ± 0.09	1.5 ± 0.02
kT (keV)	$5.9^{+0.6}_{-0.5}$	2.6 ± 0.3
Normalization ($\times 10^{-4}$)	6.4 ± 0.2	3.7 ± 0.3
χ^2/dof	573.3/384	205.6/167
Raymond-Smith Model		
$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	1.16 ± 0.08	1.0 ± 0.1
kT (keV)	5.4 ± 0.3	$3.7^{+0.3}_{-0.2}$
Normalization ($\times 10^{-3}$)	1.58 ± 0.05	0.68 ± 0.03
χ^2/dof	749.8/384	252.2/167
CompTT Model		
$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	$1.1^{+0.3}_{-0.2}$	$1.7^{+0.7}_{-0.9}$
$kT_{\rm seed}$ (keV)	0.18 ± 0.01	$0.15^{+0.05}_{-0.04}$
$kT_{\rm corona}$ (keV)	50[a]	50[a]
τ	$0.80^{+0.07}_{-0.08}$	$0.37^{+0.07}_{-0.06}$
Normalization ($\times 10^{-5}$)	$2.8^{+0.4}_{-0.3}$	1.7 ± 0.4
χ^2/dof	431.8/383	164.2/166
MCD+Power-Law Model		
$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	$4.4^{+1.2}_{-0.6}$	3^{+3}_{-1}
kT (keV)	$0.15^{+0.02}_{-0.04}$	$0.16^{+0.16}_{-0.04}$
Normalization	1000^{+2100}_{-200}	180^{+80}_{-60}
Γ	$1.82^{+0.06}_{-0.09}$	$2.3^{+0.2}_{-0.1}$
Normalization ($\times 10^{-4}$)	$6.1^{+0.6}_{-0.9}$	$3.6^{+1.0}_{-0.8}$
χ^2/dof	385.8/382	167.1/165
F ($\times 10^{-12}$ ergs cm^{-2} s^{-1})[b]	12^{+10}_{-2}	$4.0^{1.1}_{-1.2}$
$F_{\rm power\ law}/F_{\rm total}$	0.33	0.63
$L_{0.2-10}$ ($\times 10^{40}$ ergs s^{-1})[c]	$2.0^{+1.6}_{-0.3}$	$0.66^{+0.18}_{-0.20}$
$L_{0.05-100}$ ($\times 10^{40}$ ergs s^{-1})[c]	$3.3^{+4.8}_{-0.3}$	$1.0^{+0.6}_{-0.1}$

Note.—Results of fitting simple models to the EPIC MOS spectra of NGC 1313 X-1 and NGC 1313 X-2. The XSPEC model PHABS was used to measure the equivalent neutral hydrogen column density along the line of sight.

[a] The temperature of the upscattering corona was not constrained by fits with the XSPEC model CompTT and was therefore fixed at a reasonable value.

[b] The absorption-corrected or "unabsorbed" flux.

[c] The luminosity in the 0.2–10.0 or 0.05–100.0 keV range, assuming a distance of 3.7 Mpc.

We note that some H II regions within NGC 1313 may have low metallicity (50–75% relative to solar abundances; Zaritsky, Kennicutt, & Huchra 1994). The metallicity assumed for absorbing material can impact low-energy spectral measurements. For X-1, our best-fit cool disk plus power-law model represents an improvement at the 5 σ level of confidence relative to simple single-component fits with the abundances of O and Fe fixed at

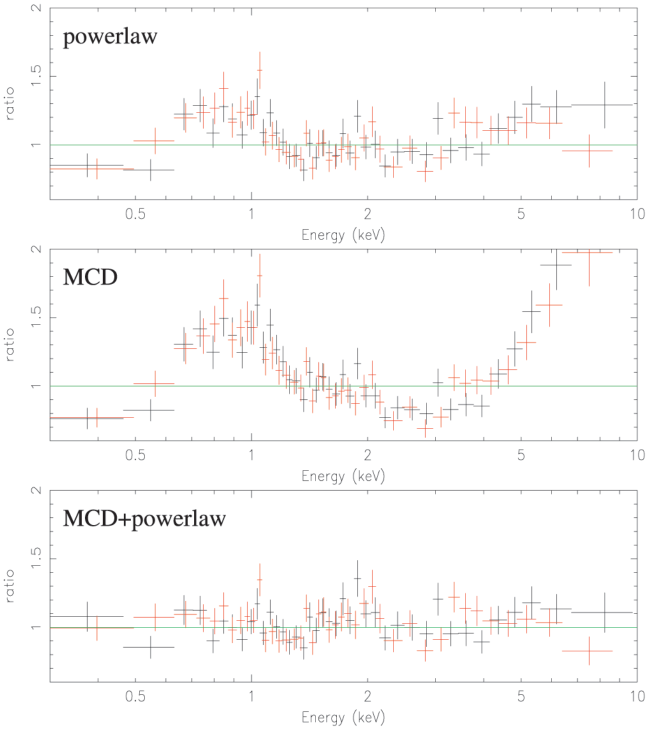

FIG. 1.—Data/model ratios from fits to the MOS-1 (*black*) and MOS-2 (*red*) spectra of NGC 1313 X-1 with standard ULX models (the spectra are rebinned for visual clarity). The ratios correspond to fits with a simple power law, the MCD model, and a model with both components (see Table 1).

0.25 times solar in the absorption model. With such an absorption model, single-component fits to the spectra of X-2 are acceptable. The low-abundance absorption model is likely inappropriate, however; fits with this model underestimate the depth of the O edge in the X-1 spectra. The Galactic column density along the line of sight to NGC 1313 is 4.0×10^{20} cm^{-2}; our significantly higher measurements may indicate significant neutral absorption within NGC 1313 or intrinsic to the sources (see Table 1).

The most remarkable result of our analysis is that both models require cool accretion disks ($kT \simeq 150$ eV). These temperatures differ from those derived from the spectra of stellar mass black holes in bright states; in such spectra, $kT \simeq 1$ keV is typical (e.g., Sobczak et al. 2000) but temperatures can reach nearly 2 keV in extreme cases. These temperatures also differ considerably from those measured with single-component fits with the MCD model to the spectra of some ULX sources, which approach $kT \simeq 2$ keV (e.g., Makishima et al. 2000).

The MCD model is based on the following relationship: $T \propto M^{-1/4}$. This can be used for scaling by writing $M_{\rm ULX}/M_{10\,M_\odot} \propto (kT_{10\,M_\odot}/kT_{\rm ULX})^4$. If we assume that $kT = 1$ keV is a typical inner disk color temperature for 10 $M_\odot$ black holes for values of $L_{\rm X}/L_{\rm Edd}$ similar to those being observed in ULX sources, the best-fit MCD color temperatures measured for X-1 and X-2 then imply black hole primaries with masses near $M_{\rm BH} \sim 2 \times 10^4\ M_\odot$. If we assume $kT = 0.5$ keV may be more appropriate for 10 $M_\odot$ black holes at high accretion rates, this scaling still suggests masses of $M_{\rm BH} \sim 1.2 \times 10^3\ M_\odot$ for X-1 and X-2.

Shimura & Takahara (1995) derived a hardening factor correction to account for the effects of opacity on the measured disk temperature and inner radius. This correction is very simple: $kT_{\rm corr} = f^{-1}kT_{\rm obs}$, and $R_{\rm in,\,corr} = \eta f^2 R_{\rm obs}$ (where $f = 1.7$ is the hardening factor and $\eta = 0.63$ is valid for $i < 70°$ and accounts for the difference between the innermost radius and the radius of peak temperature; see Sobczak et al. 2000 and Makishima et al. 2000). Merloni, Fabian, & Ross (2000) have found that hardening corrections may not be constant against changes in the physical parameters of the disk.

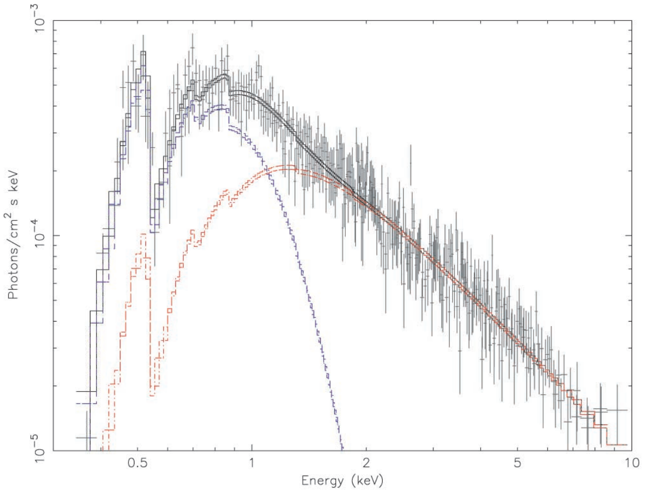

FIG. 2.—Unfolded MOS-1 and MOS-2 spectra of NGC 1313 X-1. The total spectrum, cool ($kT \simeq 150$ eV) disk component, and power-law components are shown in black, blue, and red, respectively.

The normalization of the MCD model allows for more direct estimates of the black hole masses if we assume that $R_{\rm in} = R_{\rm ISCO} = 8.85\ {\rm km}(M_{\rm BH}/M_\odot)$ (where $R_{\rm ISCO}$ is the radius of the innermost stable circular orbit), appropriate for Schwarzschild holes. Simply, $M_{\rm BH} = \eta f^2 (K/\cos i)^{1/2}(d/10\ {\rm kpc})(8.85\ {\rm km})^{-1}$, where K is the model normalization and i is the inclination of the system. Using the 90% confidence lower limit MCD normalizations (see Table 1), we find lower limit masses of $M_{\rm X\text{-}1} \gtrsim 2200\ M_\odot$ and $M_{\rm X\text{-}2} \gtrsim 830\ M_\odot$ (assuming $i = 0$ and $d = 3.7$ Mpc; note that higher values of i and d would *increase* the minimum mass estimates, as would significant black hole spin).

Defining $L_{\rm Edd} = 1.3(M_{\rm BH}/M_\odot) \times 10^{38}$ ergs s^{-1} (Frank, King,

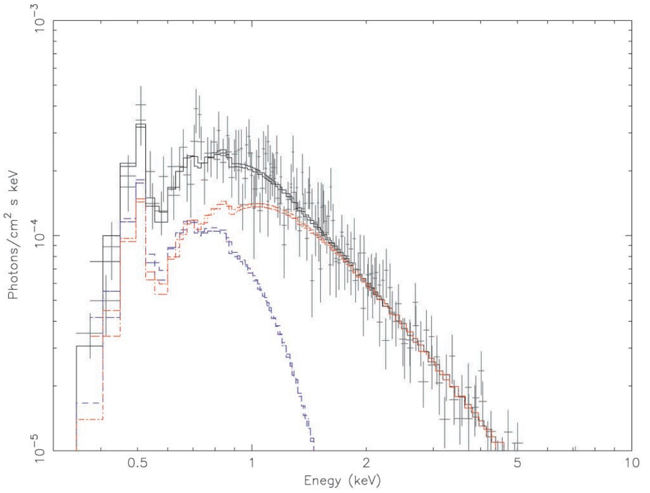

FIG. 3.—Unfolded MOS-1 and MOS-2 spectra of NGC 1313 X-2. The total spectrum, cool ($kT \simeq 160$ eV) disk component, and power-law components are shown in black, blue, and red, respectively.

& Raine 2002) and taking L_X in the 0.05–100.0 keV range as a better approximation to a bolometric luminosity, we find lower limit isotropic luminosity masses of $M_{X\text{-}1} \gtrsim 230\ M_\odot$ and $M_{X\text{-}2} \gtrsim 70\ M_\odot$. These mass estimates are roughly an order of magnitude below those obtained by scaling from the MCD fit parameters; it is possible that X-1 and X-2 are observed at $0.1L_{\rm Edd}$, similar to many Galactic black holes. We caution that the mass limits are only as good as the MCD model and our best-fit continuum models.

4. DISCUSSION

We have analyzed the EPIC MOS-1 and MOS-2 spectra of the ULX sources NGC 1313 X-1 and X-2. The spectra statistically require soft and hard components to describe the continuum emission. When the soft components in X-1 and X-2 are fitted with models for accretion disks, low disk temperatures are obtained ($kT \simeq 150$ eV). Scaling these temperatures and the normalization of the MCD model suggests that X-1 and X-2 harbor black holes with $M_{\rm BH} \simeq 10^3\ M_\odot$, or higher. Isotropic Eddington luminosity scaling suggests that X-1 and X-2 may harbor black holes with masses on the order of $M_{\rm BH} \simeq 10^2\ M_\odot$. It is possible that we have observed X-1 and X-2 at $L_X \simeq 0.1L_{\rm Edd}$; however, it is not clear which scaling method is superior.

Colbert et al. (1995) estimate the radio power at the position of X-1 to be 10^{19} W Hz^{-1} at 1.4 GHz, implying an isotropic radio luminosity of 10^{35} ergs s^{-1}. The radio to X-ray luminosity ratio is then approximately 5×10^{-6}; this makes it unlikely that relativistic beaming can account for the flux of X-1, because beaming tends to produce flat νF_ν spectra (Fossati et al. 1998). Pakull & Mirioni (2003) have found that X-1 lies in the center of a diffuse Hα nebula with a radius of approximately 240 pc and a high [O I] λ6300/Hα ratio implying X-ray photoionization. An optical survey of massive young star clusters in nearby galaxies by Larsen (1999) reveals no cluster candidates within approximately 380 pc of our position for X-1. Similarly, Pakull & Mirioni (2003) find that X-2 lies at the center of an Hα nebula with strong [Si II] and [O I] lines, implying that X-2 is acting on the local interstellar medium. Larsen (1999) reports no clusters within a few kiloparsecs of X-2. These findings suggest that X-1 and X-2 may emit nearly isotropically and illuminate their local nebulae. It is unlikely, then, that models based on anisotropic emission from stellar mass black holes (e.g., King et al. 2001) can explain the observed fluxes.

IMBHs may be the endpoints of very massive low-metallicity stars (Heger et al. 2002) or perhaps Population III stars from the era of galaxy formation (Madau & Rees 2001). Miller & Hamilton (2002) have suggested that IMBHs may grow in globular clusters. Ebisuzaki et al. (2001) have proposed that IMBHs may form in young compact star clusters. If the disk temperature and normalization scalings are correct, our estimates for the masses of X-1 and X-2 are inconsistent with black holes in X-1 and X-2 being the endpoints of low-metallicity or Population III stars; X-1 and X-2 may be the result of growth by mergers.

Although a power law produced a statistically acceptable fit to the *ASCA* spectrum of X-1 ($\chi^2/{\rm dof} = 244/259$), the values we have measured with the MCD plus power-law model are broadly consistent with those reported by Colbert & Mushotzky (1999) using the same model. We measure a lower disk temperature and harder power-law index in X-2. Makishima et al. (2000) fitted two *ASCA* spectra of NGC 1313 X-2 separated by 2 yr with the MCD model and found $kT = 1.47$ keV and $kT = 1.07$ keV. Our fits to the *XMM-Newton* spectra of X-2 with only an MCD component are not acceptable, but we measure $kT = 0.91$ keV—consistent with the latter *ASCA* result.

Results from a *Chandra* observation of NGC 5408 X-1 may also reveal a cool disk in a two-component spectrum (Kaaret et al. 2003). We speculate that future observations of ULX sources may also reveal cool accretion disks in some cases. Future theoretical studies of anisotropic accretion flows at high accretion rates may be able to explain such results in terms of stellar mass black holes.

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