XMM-NEWTON SPECTRA OF INTERMEDIATE-MASS BLACK HOLE CANDIDATES: APPLICATION OF A MONTE CARLO SIMULATED MODEL
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ABSTRACT

We present a systematic spectral analysis of six ultraluminous X-ray sources (NGC 1313 X-1 and X-2, IC 342 X-1, Ho IX X-1, NGC 5408 X-1, and NGC 3628 X-1) observed with the XMM-Newton observatory. These extranuclear X-ray sources in nearby late-type galaxies have been considered as intermediate-mass black hole candidates. We have performed Monte Carlo simulations of Comptonized multicolor blackbody accretion disks. This unified and self-consistent spectral model assumes a spherically symmetric, thermal corona around each disk and accounts for the radiation transfer in the Comptonization. We find that the model provides satisfactory fits to the XMM-Newton spectra of the sources. The characteristic temperatures of the accretion disks ($T_{\text{in}}$), for example, are in the range of $0.05$–$0.3$ keV, consistent with the intermediate-mass black hole interpretation. We find that the black hole mass is typically about a few times $10^3 M_\odot$, and has an accretion rate of $\sim 10^{-6}$ to $10^{-5} M_\odot$ yr$^{-1}$. For the spectra considered here, we find that the commonly used multicolor blackbody accretion disk model with an additive power-law component, although not physical, provides a good mathematical approximation to the Monte Carlo simulated model. However, the latter model provides additional constraints on the properties of the accretion systems, such as the disk inclination angles and corona optical depths.

Subject headings: galaxies: general — galaxies: individual (NGC 1313, IC 342, Holmberg IX, NGC 5408, NGC 628) — X-rays: galaxies — X-rays: general

1. INTRODUCTION

Probably the most exciting recent development in the field of black hole (BH) study is the discovery of numerous candidates for intermediate-mass BHs (IMBHs) with masses in the range of $10^3$–$10^5 M_\odot$ (see Miller & Colbert 2004 for a recent review). The presence of such BHs was first proposed to explain extranuclear X-ray sources (ULXs), defined as having inferred isotropic X-ray luminosities in excess of $10^{39}$ ergs s$^{-1}$, about an order of magnitude greater than the Eddington limit of a solar mass object (e.g., Fabian 1989; Colbert & Mushotzky 1999; Miller et al. 2003, 2004; Strohmayer & Mushotzky 2003). While unambiguous detections of individual IMBHs currently do not exist, there are observational hints from studies of microlensing events, globular clusters, and centers of nearby galaxies (van der Marel 2004 and references therein). Although ULXs actually represent a heterogeneous population, a majority of them are likely to be accreting BHs. The controversy is centered on the X-ray emission mechanisms and on the masses of the BHs (e.g., Makishima et al. 2000; King et al. 2001; Begelman 2002).

The IMBH interpretation, although probably the most straightforward and exciting, has serious difficulties (e.g., King et al. 2001; Kubota et al. 2002). In addition to their high X-ray luminosities, many ULXs show convex-shaped spectra, especially in the energy band $\lesssim$ a few keV. Such spectra are characteristic of the “soft state” of accreting BH binaries and are often approximated by blackbody-like models, such as the multicolor disk model (MCD) [e.g., Makishima et al. 1986; diskbb in the XSPEC spectral analysis software package (Arnaud 1996)]. In the MCD model, each annulus of the axisymmetric optically thick accretion is assumed to radiate as a blackbody with a radius-dependent temperature. The characteristic temperature $T_{\text{in}}$ of the innermost portion of the disk is $\propto (M/M_\odot)^{1/4}$, where $M$ and $M_\odot$ are the BH mass and the accretion mass rate, respectively. However, the $T_{\text{in}}$ inferred from the model fit is almost always too high for the required high mass, assuming the Eddington limit on $M$. Equivalently, the inner-disk radius $R_{\text{in}}$ is much smaller than the last stable orbit for a nonspin BH. Even more disturbing is the inferred value of $R_{\text{in}}$ is sometimes found to be time-variable, in contrast to the soft state of confirmed BH X-ray binaries, for which $R_{\text{in}}$ is approximately constant for each source.

Furthermore, it has been shown recently that many X-ray spectra of ULXs cannot be satisfactorily described by a single MCD model, especially in observations with good counting statistics and with a broad energy coverage (e.g., Miller et al. 2003, 2004). The usual practice is then to fit such a spectrum with an additive combination of an MCD and a power law (PL; e.g., Miller et al. 2003, 2004; Cropper et al. 2004). The requirement of this latter component, which often becomes important at energies $\gtrsim$ a few keV and may extend up to 200 keV, as indicated by stellar-mass BH systems, suggests that a high-temperature electron cloud (corona) exists around an accretion disk, producing inverse-Compton scattering of the disk photons (e.g., Kubota et al. 2002; Page et al. 2003). A spectral fit with this additive, phenomenological model combination typically leads to an acceptable fit and a much lower (and apparently more reasonable) disk temperature. Nevertheless, the model is oversimplified in the following two aspects:

First, the straight extension of the power-law component to the low-energy limit of the spectrum is nonphysical. Because the power-law component is assumed to mimic the effect of the inverse-Compton scattering, a low-energy cutoff, as in the MCD component, must be present in the Comptonized component (see also Page et al. 2003). Neglecting this low-energy
cutoff could mischaracterize the spectral shape of the MCD component and could lead to an artificially high absorption in spectral fitting.

Second, the additive combination of the MCD and the PL components does not account for the radiative-transfer process or the removal of photons from the MCD component to the Comptonized component. Furthermore, this process depends on both disk-photon and corona-electron energies. Therefore, one may not, in general, directly take the MCD normalization derived from the spectral model fitting to infer the inner-disk radius or the BH mass, as realized by some authors (e.g., Kubota et al. 2001). Otherwise, the inferred (but probably nonphysical) inner-disk radius, for example, may appear to vary significantly when an accretion system changes from its hard state to its soft state or vice versa, as in XTE J2012+381 (Campana et al. 2002).

These oversimplifications in the MCD+PL model certainly obscure the physical dependence of the Comptonization on the corona and disk properties, and could also seriously affect the inference of accretion disk parameters. Yao et al. (2003; hereafter Paper I) have recently developed a Comptonized multicolor disk (CMCD) model. They use Monte Carlo simulations to directly generate the Comptonized X-ray spectra, removing the abovementioned oversimplifications and avoiding the complications of using the two (unrelated)-component model and then trying to correct for various radiative transfer effects. While the MCD model is still used to describe the accretion-disk emission, the Comptonized radiation is no longer an independent component. This self-consistent treatment thus provides a new tool to constrain the physical properties of the corona and to study its relationship to the accretion disk. But most importantly, the model enables us to recover the same original disk flux in a spectral fit, which is essential to a reliable mass estimate of the putative BH.

In the present work, we apply the CMCD model to the analysis of XMM-Newton spectra of six ULXs that have been suggested as IMBH candidates. Our main objectives are to check whether or not the CMCD model provides an adequate spectral description of these sources and to see what potential new insights we may gain from such an application. The sources and data are described in § 2, whereas the implementation of the model for this application is discussed in § 3, which also includes a summary of various corrections required to infer BH masses from the present model fits. We also test the PL, MCD, and MCD+PL models and compare them with the CMCD model. We present the results of our spectral fits in § 4 and discuss the implications and conclusions in § 5.

2. SELECTED ULXs AND XMM-NEWTON DATA

For our initial application of the CMCD model to the IMBH candidates, we concentrate on XMM-Newton X-ray observations of six previous known ULXs in nearby galaxies (D ≤ 10 Mpc; Table 1). The moderate spatial resolution of XMM-Newton observations (e.g., FWHM ~ 6″ at 1 keV) is sufficient to isolate the emission from these individual ULXs in the galaxies. Compared to similar Chandra observations, XMM-Newton observations typically had substantially higher sensitivities and covered a broader energy range (0.2–15 keV), particularly important for constraining the Comptonization-related parameters. If these ULXs are indeed accreting IMBHs, they should then have lower $T_{\text{in}}$ values than those of stellar-mass BH systems (if the effect of BH spins is not important). The corresponding spectral shift of the disk emission to lower energies increases the importance of the Comptonized component in the XMM-Newton energy range. Therefore, XMM-Newton data alone may allow us to constrain simultaneously both the disk emission and the effect of the Comptonization.

Table 1 lists our selected sources, along with salient parameters of the host galaxies and the corresponding XMM-Newton observations. These six sources are located in five galaxies, each with exposures longer than 10 ks, for good counting statistics. The source positions and their offsets from galactic nuclei are listed in Table 2. All these ULXs are “persistent” sources and have been studied previously based on the data from ASCA, Chandra, and/or XMM-Newton.

We obtained the X-ray data from the XMM-Newton Science Archive and used the Science Analysis System (SAS ver. 5.4.1, 2003) for data reduction, following the procedure described in the ABC Guide for XMM-Newton Data Analysis (ver. 1.3, 2002). We checked light curves of individual observations and filtered out time intervals with significant contamination from soft background flares. The final effective live time for each data set is included in Table 1. We utilized imaging data from all three X-ray detectors: the EPIC detectors MOS1, MOS2, and pn. The XMM-Newton observations of the four sources, NGC 1313 X-1 and X-2, IC 342 X-1, and Ho IX (Holmberg IX) X-1 (sometimes referred to as M81 X-9) have been reported previously, although not all of the data were used in individual studies. Observations for both NGC 5408 X-1 and NGC 3628 X-1 are presented here for the first time. The following is a brief summary of key results from existing work:

NGC 1313 X-1 and X-2.—These two ULXs have been studied by Miller et al. (2003, 2004), based on the XMM-Newton MOS and pn observations, respectively. From various acceptable additive two-component models, chiefly MCD+PL, they infer $T_{\text{in}} \sim 0.15$ keV for X-1 and 0.16 keV for X-2. These inferred low disk temperatures have been used as the key evidence for consistency with the IMBH scenario. Several ROSAT HRI observations of these two sources show variability on the order of a factor ~2 (Colbert & Ptak 2002). X-1 has a radio counterpart with a luminosity of $\sim 10^{35}$ ergs s$^{-1}$ (Colbert et al. 1995). An optical counterpart to X-2 with an R magnitude of 21.6 has been reported by Zampieri et al. (2003). Both sources are associated with H$\alpha$ nebulae (Pakull & Mirioni 2003).

IC 342 X-1.—This is one of the most intensively studied ULXs and has shown strong variability over the years. For example, its luminosity in the 0.5–10 keV band was 1.3 $\times 10^{35}$ ergs s$^{-1}$ in 1993 September (Okada et al. 1998) and decreased to $4.1 \times 10^{34}$ ergs s$^{-1}$ in 2000 February (Kubota et al. 2002). The XMM-Newton observation, as used in the present work, displays a further decrease in the source’s luminosity to $5.0 \times 10^{34}$ ergs s$^{-1}$. Furthermore, the source is probably associated with a supernova remnant (Roberts et al. 2003).

Ho IX X-1.—This source has been observed extensively by Einstein, ROSAT, BeppoSAX, and ASCA over 20 yr. These observations show a strong time variability of the source (La Parola et al. 2001), including apparent spectral state changes. Its highest luminosity reached $\sim 1 \times 10^{35}$ ergs s$^{-1}$ (Wang 2002) during an ASCA observation in 1999 April. The source is also associated with a giant shelllike H$\alpha$-emitting nebula (Wang 2002). Miller et al. (2004) have presented an analysis of the XMM-Newton pn data. The $T_{\text{in}}$ value inferred from an MCD+PL model fit is 0.21–0.26 keV, again supporting the IMBH interpretation.

NGC 5408 X-1.—Kaaret et al. (2003) have reported a Chandra observation taken in 2002 May that indicates a


| Galaxy                        | Hubble Type | $D^a$ (Mpc) | $N_{HI}^b$ ($10^{21}$cm$^{-2}$) | Observation ID | Observation Date | MOS1  | MOS2  | pn   | Filter |
|-------------------------------|-------------|-------------|---------------------------------|----------------|------------------|-------|-------|------|--------|
| NGC 1313 X-1 and X-2......... | SB(s)d      | 3.7         | 0.40                            | 010680101      | 2000 Oct 17     | 28.9  | 28.9  | 28.4 | (29.3) | medium |
| IC 342 X-1........................ | Scd         | 3.3         | 3.03                            | 0093640901     | 2001 Feb 11     | 9.5   | 9.5   | 5.0  | (9.8)  | medium |
| Ho IX X-1 (M81 X-9)........... | Im          | 3.6         | 0.40                            | 0112521001     | 2002 Apr 10     | 10.0  | 10.0  | 6.8  | (10.1) | thin1  |
|                               |             |             |                                 | 0112521101     | 2002 Apr 16     | 7.9   | 7.9   | 7.4  | (10.8) | thin1  |
| NGC 5408 X-1 ................... | IB(s)m      | 4.8         | 0.57                            | 0112290601     | 2001 Aug 8      | 5.9   | 5.9   | 4.2  | (5.7)  | thin1  |
| NGC 3628 X-1 ................... | Sbc         | 10.0        | 0.22                            | 0110980101     | 2000 Nov 27     | 42.2  | 42.3  | 32.2 | (54.5) | thin1  |

$^a$ The $D$ (galaxy distance) values are from Tully 1988 (NGC 1313), Saha et al. 2002 (IC 342), Freedman et al. 1994 (Ho IX), Karachentsev et al. 2002 (NGC 5408), and Soifer et al. 1987 (NGC 3628).

$^b$ The $N_{HI}$ values are from the Galactic H I survey by Dickey & Lockman (1990).

$^c$ Exposure times given for MOS1, MOS2, and pn are the cleaned time intervals used for our analysis, with the original exposure times in parentheses.
luminosity of $1.1 \times 10^{40}$ ergs s$^{-1}$ in the 0.3–8 keV band. They have also proposed radio and optical counterparts for the source. NGC 3628 X-1.—A strong time variability has been observed from this source. Its 0.1–2 keV flux was drastically reduced by a factor of $\gtrsim 27$ between 1991 December and 1994 May (Dahlem et al. 1995). A 52 ks Chandra observation in 2000 December showed a luminosity of $1.1 \times 10^{40}$ ergs s$^{-1}$ in the 0.3–8.0 keV band (Strickland et al. 2001). No counterpart in other wavelengths has been reported for the source.

We extracted the XMM-Newton spectral data from a circular region with a radius in the range of 20″–30″ around each source, depending on the source position. For each source, the MOS1 and MOS2 data were combined. Each spectrum was grouped to contain a minimum 25 counts per bin. The corresponding background spectrum was taken from a concentric annulus, removing any apparent sources enclosed. A response matrix file and auxiliary response file were produced using the SAS tasks rmfgen and arfgen. The MOS and pn spectra are jointly fitted to tighten the constraints on spectral parameters.

3. DESCRIPTION OF THE CMCD MODEL

The construction of the CMCD model has been detailed in Paper I, including a discussion of various assumptions, comparisons with previous works, and an application to the broadband BeppoSAX spectra of the stellar mass BH candidate XTE J2012+381 in our Galaxy. This application successfully removes the need for the varying inner-disk radius and makes the specific predictions of both the size of the corona and the inclination angle of the accretion disk as well as a more reliable estimate of both $T_{\text{in}}$ and $R_{\text{in}}$ (Paper I).

We have also applied the model to the spectral analysis of the two persistent X-ray binaries, LMC X-1 and LMC X-3, which contain BH candidates (Y. Yao et al. 2004, in preparation; hereafter Paper II). Our derived foreground absorption column density ($N_{\text{H}}$) values, BH masses, and system inclinations are all consistent with those from the independent measurements based on optical and X-ray grating spectral data. These tests demonstrate the applicability and predictive capability of the CMCD model in the study of accreting BH systems.

Here we briefly describe the implementation of the CMCD model for the study of ULXs. For simplicity, we assume that the corona around the disk is spherical and that the electron energy distribution in the corona takes a thermal form, as in some previous works (e.g., Titarchuk 1994; Hua & Titarchuk 1995; Poutanen & Svensson 1996). In Paper I, we also used the “slab” geometry, which may be considered to be the opposite extreme of the spherical corona shape. However, we note that these two different geometries do not make significant differences in the fitted values of our most interesting parameters ($T_{\text{in}}$ and the model normalization). The thermal assumption is another approximation. As discussed by Coppi (1999), a more realistic electron energy distribution might be a hybrid between a thermal plasma and a nonthermal high-energy tail. The thermal part would dominate the radiative transfer process in the low-energy band, whereas the nonthermal part would be important at high energies (beyond a few tens of keV). Because the XMM-Newton energy band used here only extends up to $\sim$10 keV, our results are insensitive to the deviation from the assumed thermal form.

The parameters of the CMCD model are the electron temperature ($T_e$), optical depth ($\tau$), and radius of the corona ($R_c$), as well as the inner-disk temperature ($T_{\text{in}}$) and the disk inclination angle ($\theta$). Figure 1 illustrates the parameter dependency of the inclination angle-averaged spectra. The spectral dependency on the inclination angle is rather simple: whereas the direct soft disk emission is proportional to $\cos \theta$, the Comptonized component is not affected.

Our implementation of the CMCD model is in a standard XSPEC table format. This direct implementation avoids the unnecessary complications and approximations in constructing an analytic expression (if possible) and is convenient for any adjustments and changes to the model. The table contains a grid of spectra: $T_{\text{in}}$ and $\theta$ values are spaced by steps of 0.1 keV and $10^7$ linearly in the ranges 0.05–2 keV and 22°–79°, respectively, whereas $T_e$, $\tau$, and $R_c$ have 4, 7, and 4 steps evenly spaced logarithmically between 10 and 100 keV, 0 and 5, and 10$R_g$ and 1000$R_g$ (where $R_g = GM/c^2$), respectively.

In a spectral fit, XSPEC automatically interpolates between the spectra in the table and employs a $\chi^2$-minimization algorithm. The normalization obtained from such a fit is similar to that of the MCD model, except without the cosine factor, since the disk projection effect has been taken into account in our simulation, i.e.,

\[ K = \left( \frac{R_{\text{in}}}{D/10 \text{ kpc}} \right)^2, \]

where $D$ is the distance to the source and $R_{\text{in}}$ is the apparent radius with a peak disk temperature.

We estimate the mass of each putative BH as $M = c^2 R_{\text{in}}^3 / G \alpha$, where the inner-disk radius, $R_{\text{in}} = fR_{\text{in}}$, is assumed to be the same as the last stable circular orbit radius around the BH, $\alpha R_g$ ($\alpha = 6$ or 1 for a nonspin or extreme-spin BH, respectively). The factor $f = \eta f_{\text{opt}} f_{\text{GR}}^{1/2} (\cos \theta / g_{\text{GR}})$ includes various corrections that have been dealt with in previous works (Fig. 2):

1. The terms $f_{\text{GR}}$ and $g_{\text{GR}}$ relate the apparent and intrinsic radii of the peak disk temperature (Zhang et al. 1997); $f_{\text{GR}}$ is due to the color temperature change caused by the gravitational red shift and Doppler shift, whereas $g_{\text{GR}}$ is due to the integrated flux change caused by the gravitational focusing, time dilation, and Doppler boosting. Both factors depend on the BH spin and $\theta$ and account for general relativity effects. We estimate the factors from the quadratic interpolation of the tabulated values obtained by Zhang et al. (1997). Values for $g_{\text{GR}}$ and $f_{\text{GR}}$ are

See ftp://legacy.gsfc.nasa.gov/caldb/docs/memos/ogip_92_009/ogip_92_009.ps.
in the ranges of 0.036–0.797 and 0.355–1.657, respectively, compared to \( g_{GR} = \cos(\theta) \) and \( f_{GR} = 1 \) in the Newtonian case.

2. The terms \( f_{\text{col}} \) is the spectral-hardening correction factor (Ebisuzaki et al. 1984). Because of the high temperature at the inner-disk region, which is responsible for the bulk of the emission, the inverse-Compton scattering at the surface of the disk becomes important (Ross et al. 1992). The hardening of the spectrum effectively results in an underestimate of the inferred radius from the spectral fitting. This spectral-hardening correction factor (\( f_{\text{col}} = 1.7 \)) has been calculated by Shimura & Takahara (1995) by solving the disk structure and radiative transfer self-consistently. The above corrections give the intrinsic radius for peak disk temperature.

3. The terms \( \eta \) is the ratio between the \( R_{in} \) and the intrinsic radius for peak disk temperature. We use \( \eta = 0.7 \) (nonspin) and 0.77 (extreme spin), derived by Zhang et al. (1997) based on a fully relativistic calculation. In the Newtonian case, \( \eta = 1 \).

4. RESULTS

We summarize the results from our spectral fitting with the commonly-used MCD, PL, and MCD+PL models (Table 3), as well as the CMC model (Table 4). The XMM-Newton spectra of these sources are of the highest quality available for ULXs, which allows us to test whether or not they can be characterized by these models. Table 3 shows that either PL or MCD alone can be rejected at a confidence greater than 4 \( \sigma \) for four out of the six sources. IC 342 X-1 can be fitted reasonably well with either MCD or PL, although the latter is significantly better. The MCD model alone gives an acceptable fit to NGC 3628 X-1, but the inferred \( T_{in} \) value (~1.9 keV) is much too high to be consistent with the IMBH interpretation. The additive MCD+PL combination is acceptable for all the sources, but it also changes the same spectral parameters drastically. For example, \( T_{in} \) for IC 342 X-1 is reduced by a factor of ~4, compared to the MCD fit. Let us now compare the results in Table 3 with those from the previous studies of the individual sources:

NGC 1313 X-1 and X-2.—Our results on these sources are fully consistent with those from Miller et al. (2003, 2004). Their results are based on the same XMM-Newton observations but with MOS and pn data analyzed independently, whereas ours are obtained from joint fits of the data.
IC 342 X-1.—Kong (2003) and Bauer et al. (2003) have shown that both PL and MCD models give satisfactory fits to the same XMM-Newton spectrum of this source. Our results are generally consistent with theirs. Our $N_H$ value is slightly smaller than that obtained by Kong (2003; $5.14 \times 10^{21}$ versus $6.0 \times 10^{21}$ cm$^{-2}$) but is consistent with that from Bauer et al. (2003) within the quoted statistical errors. Such a small, although statistically significant difference may perhaps be due to various possible subtle differences in the data reduction and analysis (e.g., spectral extraction radius and binning).

Ho IX X-1.—Whereas individual spectra of this source from previous X-ray observations can be modeled satisfactorily with either PL or MCD (La Parola et al. 2001; Wang 2002), these previous X-ray observations can be modeled satisfactorily with a combination of PL and MCD (La Parola et al. 2001; Wang 2002), and the variability of the source. However, the higher $N_H$ value from the present work (the correction software was only corrected in the work) could be due to the low-energy sensitivity degradation of the ACIS-S with time, which was apparently not corrected in the work (the correction software was only available recently).

Table 4 shows that the CMCD model fits are satisfactory (or cannot be rejected at $\sim 2 \sigma$ confidence) for all the sources.
Both \( N_H \) and \( T_{\text{in}} \) are well constrained. In particular, the \( T_{\text{in}} \) values are within a range of \( \sim 0.1 \)–\( 0.3 \) keV, although the upper limit for IC 342 X-1 can reach \( \sim 1.3 \) keV. For both \( N_H \) and \( T_{\text{in}} \) values, the CMCD and MCD+PL models are consistent with each other within the statistical uncertainties.

5. DISCUSSION

The satisfactory fits of the CMCD model to the XMM-Newton spectra of our selected ULXs suggest that they are consistent with the IMBH interpretation. In particular, the model does not have the high \( T_{\text{in}} \) problem that is faced by the MCD model. The problem is apparently caused by the neglect of Comptonization in the model. Although this neglect is statistically allowed when both the counting statistics and the energy-band coverage of an observed spectrum are poor, the fitted spectral parameters are far from being physical. We conclude that the MCD model alone should not be used in the interpretation of ULXs as IMBHs.

We confirm that both \( T_{\text{in}} \) and \( N_H \) inferred from the MCD+PL model are reasonably accurate for the sources considered here. This apparent agreement between the CMCD and MCD+PL models suggests that the latter model as a whole is mathematically a good representation of the former model, at least for the IMBH candidates considered here. This is rather surprising when one considers the oversimplifications in the MCD+PL model, as discussed in § 1. It appears that the nonphysical extrapolation of the PL to low energy nearly compensates for the failure to include the radiation-transfer loss of soft disk photons. However, this does not mean that the MCD+PL model could be used to describe the Comptonized disk emission in general. The various nonphysical effects can cause problems for other sources, especially those with higher \( T_{\text{in}} \) values (\( \sim 1 \) keV; e.g., LMC X-1 and LMC X-3; see the discussion in § 3 and Paper II).

In comparison, the CMCD model provides more reliable measurements of the disk parameters as well as unique constraints on the physical properties of the coronae. In the following, we briefly discuss both the function of these new parameters and the physical reason for their different degrees of constraints:

1. The opacity \( \tau \) is relatively well constrained, which is the key parameter that determines the total number of Comptonized photons (e.g., Fig. 4). For example, IC 342 X-1 with the largest best-fit \( \tau \) value appears to have the disk emission nearly completely Comptonized, which explains why the spectrum of the source can be characterized by a PL alone. Because the
saturated Comptonization dominates over the thermal emission, the constraints on $T_{\infty}$, $R_{\infty}$, and eventually, on BH mass are very weak for this source.

2. The corona electron temperature $T_{e}$ is chiefly responsible for the overall energy extent of the Comptonized spectral component. Because $T_{e}$ is $\gtrsim 30$ keV for all the sources, the high-energy turning-off of the component is well beyond the XMM-Newton band limit. Therefore, the data do not constrain the upper limit of $T_{e}$. The lower limit is determined, because a minimum electron energy is needed to up-scatter soft disk photons to the high energies covered by the spectra.

3. Whereas the nearly isotropic Comptonized flux is barely affected by the disk inclination angle $\theta$, the observed strength of the soft disk component is proportional to $\cos(\theta)$. In a spectral fit, however, this difference in the disk-inclination dependence may be partially compensated for by a change in the $\tau$ value. But if $\theta$ is large (for a nearly edge-on disk), its geometric effect cannot be canceled by adjusting other parameters, which would also effectively alter the spectral shapes of both the disk and Comptonized components in a spectral fit (e.g., Fig. 4). Consequently, we may constrain the upper limit to $\theta$. This constraint, although not very tight, is important for the estimation of the BH masses ($\S$ 3).

4. The parameter $R_{\infty}$ determines the effective corona radius, within which the disk emission is most affected by the Comptonization. Photons from larger radii have relatively little chance to be scattered and may contribute to the un-Comptonized disk component, even if $\tau$ is large ($\geq 1$). However, the amount of soft X-ray radiation from the disk also decreases with the increasing radius. The combination of these two effects may thus place a constraint on $R_{\infty}$.

Apparently, these parameters are correlated in a spectral fit. This, together with the limited counting statistics and bandwidth of the data, explains why the parameters are not tightly constrained. Nevertheless, the results presented above demonstrate the potential of the CMCD model to shed new insights into the physical properties of the accretion-disk coronae, in addition to a more reliable mass estimate of the putative BHs.

Table 5 includes our estimated BH masses, assuming no spin and the best-fit $\theta$ values. The typical BH mass is in the range of $10^{6} - 10^{8} M_{\odot}$, although the upper limit for IC 342 X-1 is slightly higher. If a BH spins rapidly, the inferred BH mass could be several times higher than the value quoted in the table (depending on $\theta$; Fig. 2).

Assuming that the bolometric luminosity (estimated in the 0.05–100 keV range) $L_{\text{bol}} = 0.1 M_{\odot} c^{2}$, we further estimate the accretion rate $\dot{M}$ for each source (Table 5), which is in the range of $(1 - 10) \times 10^{-6} M_{\odot}$ yr$^{-1}$.

The present work represents, at most, an incremental step in developing a fully self-consistent model for accreting BH systems. The CMCD model used here deals only with the Comptonization by static disk coronae. To study the dynamics, one needs to understand the formation and evolution of the coronae as well as the physics of the accretion disks. We also have not considered other proposed scenarios that may explain some of the ULXs; e.g., the anisotropic emission of the radiation (King et al. 2001), the relativistic motion of the X-ray–emitting plasmas (Fabrika & Mescheryakov 2001), and the possible super-Eddington emission (Begelman 2002).

Spectral models, yet to be developed for such scenarios, need to account for the apparent presence of the soft thermal component in addition to the power law for these sources, except in the case of IC 342 X-1. The bottom line here is that the XMM-Newton spectra are consistent with the IMBH interpretation of the sources.

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### TABLE 5

| Source         | $f_{L_{\text{2-10}}} / f_{L_{\text{0.2-10}}}$ | $L_{\text{2-10}} / L_{\text{0.2-10}}$ | log($R_{\infty}$ km$^{-1}$) | log($M_{\text{BH}} / M_{\odot}$) | $M / M_{\odot}$ |
|----------------|--------------------------------------------|--------------------------------------|-----------------------------|----------------------------------|-----------------|
| NGC 1313 X-1   | 1.9/9.1                                    | 3.1/14.8                             | 4.04 (4.02, 4.20)           | 3.09 (3.08, 3.25)                | 4.9             |
| NGC 3115 X-2   | 0.6/2.8                                    | 1.0/4.6                              | 3.83 (3.76, 4.06)           | 2.88 (2.81, 3.11)                | 1.2             |
| IC 342 X-1     | 2.4/4.1                                    | 3.1/5.4                              | 3.77 (3.48, 5.41)           | 2.82 (2.53, 4.46)                | 3.1             |
| Ho IX X-1 (obs. 1) | 5.7/19.5                                 | 8.8/30.3                             | 4.23 (4.14, 4.63)           | 3.29 (3.20, 3.68)                | 11.3            |
| Ho IX X-1 (obs. 2) | 6.3/20.8                                 | 9.8/32.2                             | 4.33 (4.22, 4.76)           | 3.38 (3.28, 3.81)                | 10.2            |
| NGC 5408 X-1   | 0.6/7.1                                    | 1.6/19.6                             | 4.38 (4.16, 4.66)           | 3.43 (3.21, 3.71)                | 5.0             |
| NGC 3628 X-1   | 0.6/2.1                                    | 7.3/25.3                             | 4.05 (3.83, 4.78)           | 3.10 (2.88, 3.83)                | 9.7             |

**Notes:** The fluxes $f_{L_{\text{2-10}}}$ and $f_{L_{\text{0.2-10}}}$ have been corrected for the absorption and are in units of $10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ and in the energy ranges 2–10 and 0.2–10 keV, respectively. The luminosities $L_{\text{2-10}}$ and $L_{\text{0.2-10}}$ are in units of $10^{38}$ ergs s$^{-1}$ and are calculated from the fluxes and the distances in Table 1. The parameter $M_{\odot}$ is $10^{-6} M_{\odot}$ yr$^{-1}$. Values given assume no spin and $L_{\text{bol}} = 0.1 M_{\odot} c^{2}$. See text for details.
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