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

J. M. Miller1,4, G. Fabbiano1, M. C. Miller2, A. C. Fabian3

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ABSTRACT

We have analyzed an XMM-Newton observation of the nearby spiral galaxy NGC 1313, which contains two “ultra-luminous” X-ray (ULX) sources. We measure isotropic luminosities of \( L_X = 2.0 \times 10^{40} \text{ erg s}^{-1} \) and \( L_X = 6.6 \times 10^{39} \text{ erg s}^{-1} \) 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 ULXs have claimed cool soft components with lower statistics. The improvement over several single-component models exceeds the 8\( \sigma \) level of confidence for X-1; the improvement for X-2 is significant at the 3\( \sigma \) level. The soft components in these ULX spectra are well-fit by multi-color disk blackbody models with color temperatures of \( kT \simeq 150 \text{ eV} \). This temperature differs markedly from those commonly measured in the spectra of stellar-mass (\( 10 M_\odot \)) black holes in their brightest states (\( kT \simeq 1 \text{ keV} \)). 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 (\( M_{BH} \simeq 10^2 M_\odot \)). This range agrees with simple isotropic Eddington limit scaling arguments and the disk blackbody normalization. We note that NGC 1313 X-1 and X-2 are found in optical nebulae (Pakull & Mirioni 2002); this may indicate that anisotropic emission geometries are unlikely to account for the fluxes observed.

1. INTRODUCTION

ULX sources may be defined as point-like 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). Although a fraction of these sources may be young supernova remnants, variability has been observed in many ULX sources on the timescales of months and years (in rare cases, on shorter timescales), which suggests that they are accreting objects.

Although black holes with intermediate mass (\( 10^2-10^3 M_\odot \)) 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 multi-color disk blackbody model (MCD; Mitsuda et al. 1984) have measured color temperatures above those commonly reported in stellar-mass black holes (\( kT \approx 1-2 \text{ keV} \); 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 towards stellar-mass black holes or Kerr black holes.

NGC 1313 is a nearby spiral galaxy (\( d = 3.7 \text{ Mpc}, \text{Tully} \ 1988 \) noted for containing supernova SN 1978K. Two ULX sources — NGC 1313 X-1 and NGC 1313 X-2 — are associated with this galaxy. X-1 was found to be approximately 1 kpc from the photometric center of the galaxy, and X-2 is approximately 8 kpc from the center (Colbert et al. 1995). These sources have been studied extensively in X-rays in the past. Variability was observed in ROSAT/HRI observations of these sources (Colbert & Ptak 2002). Colbert and Mushotzky (1999) claim evidence for a cool (\( kT \approx 120 \text{ eV} \)) 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 fit acceptably by a simple power-law (\( \Gamma = 1.74, \chi^2/\text{d.o.f.} = 244/259 \)). Similarly, a cool disk may be implied in joint fits to BeppoSAX/MECS and ROSAT/PSPC 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 an XMM-Newton observation of NGC 1313, available in the public archive. The spectra of NGC 1313 X-1 and NGC X-2 cannot be fit acceptably by the single-component models commonly applied to ULX sources. Separate soft and hard components are statistically required to describe ULX spectra. We measure low temperatures (\( kT \simeq 150 \text{ eV} \)) 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 17 October 2000 starting at 03:59:23 (UT). We used only the EPIC data for...
this analysis. The EPIC cameras were operated in “PrimeFull-
Window” 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 ksec.

The source locations were determined by running the SAS
tool “edetect_chain”. With this tool, we find NGC 1313 X-
1 at 3h18m19.99s, −66°29′10.97″, and NGC 1313 X-2 at
3h18m22.34s, −66°36′03.68″ (J2000). The tool returns an
error of 0.2″ for these positions; an uncertainty of 4″ may be
more appropriate (e.g., Froschini et al. 2002). Source counts
were extracted in a circle within 24″ of the detected source posi-
tion. Background counts were extracted in an annulus between
24″–30″. To create spectra, we then applied the selection crite-
ria described in the MPE “cookbook.” These selections are as
follows: the pulse-height-invariant (PI) channel range was re-
stricted to 200–15000; 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 us-
ing the SAS tools “rmfgen” and “arfgen.” Spectral files were
were grouped to require at least 20 counts per bin before fitting to
ensure the validity of χ² statistics.

Model spectra were fit to the data using XSPEC version 11.2
(Arnaud 1996). The MOS-1 and MOS-2 spectra were fit jointly
with an overall normalizing constant. The constant indicates
that the overall flux normalizations of these cameras differ by
less than 5%. Models were fit 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 pile-up to be negligible
in our source spectra; this was confirmed with the HEASARC
tool “PIMMS” using the parameters reported by Colbert &

3. RESULTS

Lightcurves of the source event lists do not show significant
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 ap-
plied 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. A simple power-law
model provides a improved fit to spectra of both sources, espe-
cially X-2. However it is clear that the spectrum is not accept-
ably modeled in either case. Broken power-law models with
breaks in the 0.2–10.0 keV range yield improved but statisti-
cally unacceptable fits.

We therefore 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) ac-
cretion disk as a series of blackbody annuli. The latter model
describes Compton-upsescattering in a corona of optical depth τ
with electron temperature $kT_{\text{corona}}$ from a Wien distribution
of soft seed photons (Titarchuk 1994); we used the version of the
model which assumes a disk geometry for the seed pho-
tons. The coronal temperature could not be constrained and we
therefore fixed $kT_{\text{corona}} = 50$ keV, which is a moderate value.
X-2 is fit 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 and is demonstrated in Figure 1;
MCD plus power-law fits to X-1 and X-2 are shown in Fig-
ures 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 8σ level of confidence for
X-1, and at the 3σ level of confidence for X-2. With the MCD
plus power-law model, we measure isotropic luminosities of
$L_{X-1} = 2.0^{+3.0}_{-1.5} \times 10^{39}$ erg/s and $L_{X-2} = 6.6^{+1.3}_{-0.5} \times 10^{38}$ erg/s (0.2–
10.0 keV, assuming $d = 3.7$ Mpc). If ULX sources are like
Galactic black holes and AGN, 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%.

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

The MCD model is based on a specific radius–temperature
relationship: $T(R) \propto R^{-3.4}$. This can be used for scaling by
writing $(R_{\text{ISCO}}(ULX)/R_{\text{ISCO}}(10M_\odot)) \propto (kT_{10M_\odot}/kT_{ULX})^{4/3},$
where $R_{SCD}$ is the innermost stable circular orbit around the black hole. If we assume that $kT = 1$ keV is a typical inner disk color temperature for $10 M_\odot$ black holes for values of $L_X / L_{Edd}$, 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 $M_{BH} \sim 10 M_\odot$. This scaling depends on the disk temperature assumed for 10 $M_\odot$ holes, and is less robust than the following attempts at scaling.

Several authors have discussed corrections to the MCD model. Shimura & Takahara (1995) derived a hardening factor correction to account for the effects of opacity on the measured disk temperature and inner radius (see also Merloni, Fabian, & Ross 2000). The correction is very simple: $kT_{corr} = f^{-1} kT_{obs}$, and $R_{in,corr} = \eta^2 R_{obs}$ (where $f = 1.7$ is the hardening factor, and $\eta = 0.63$ is valid for $i < 70^\circ$ 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).

The normalization of the MCD model allows for more direct estimates of the black hole masses if we assume that $R_{in} = R_{SCD} = 8.85$ km ($M_{BH} / M_\odot$), appropriate for Schwarzschild holes. Simply, $M_{BH} = (K / \cos i)^{1/2} \times (d / 10$ kpc) $\times (8.85$ 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) and noting the above corrections, we find lower-limit masses of $M_{X-1} \gtrsim 600 M_\odot$ and $M_{X-2} \gtrsim 200 M_\odot$ (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). These estimates are broadly consistent with those from isotropic Eddington limit scaling. Defining $L_{Edd} = 1.3 (M_{BH} / M_\odot) \times 10^{38}$ erg/s (Frank, King, & 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 $M_{X-1} \gtrsim 230 M_\odot$ and $M_{X-2} \gtrsim 70 M_\odot$. 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 sensitivity of these cameras, the high effective area of XMM-Newton, and the duration of the observation have permitted sensitive measurements of the source spectra. These clearly statistically require soft and hard components to describe the continuum emission. When the soft components in X-1 and X-2 are fit with models for accretion disks, low disk temperatures are obtained ($kT \sim 150$ eV). Scaling these temperatures, the normalization of the MCD model, and isotropic Eddington luminosity scaling suggest that X-1 and X-2 may harbor black holes with masses of on the order of $10^2 M_\odot$. The more reliable mass estimates from isotropic Eddington limit scaling and MCD normalizations suggest black hole masses closer to the top of this range.

Colbert et al. (1995) estimate the radio power at the position of X-1 to be $10^{19}$ W/Hz at 1.4 GHz, implying an isotropic radio luminosity of $10^{35}$ erg/s. The radio to X-ray luminosity ratio is then approximately $5 \times 10^{-6}$, this makes it unlikely that relativistic beaming can account for the flux of X-1, because beaming tends to produce flat $\nu F_\nu$ spectra. Pakull and Mirioni (2002) have found that X-1 lies in the center of a diffuse H$_\alpha$ nebula with a radius of approximately 240 pc, and a high [O I] $\lambda$6300/H$_\alpha$ 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 (2002) find that X-2 lies at the center of an H$_\alpha$ 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 kpc 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.

Several mechanisms have been proposed for the formation of such black holes. Intermediate mass black holes 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). We note that NGC 1313...
has a low metallicity (Zaritsky, Kennicutt, & Huchra 1994). Miller and Hamilton (2002) have suggested that intermediate mass black holes may grow in globular clusters. Ebisuzaki et al. (2001) have proposed that intermediate mass black holes may form in young compact star clusters. 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 single Population I or II stars with standard metallicity, which are known to be unstable to strong mass loss above 100 $M_\odot$. The limits for X-1 and X-2 are consistent with the sources being the endpoints of low-metallicity or Population III stars, or the result of growth by mergers.

Though a power-law produced a statistically acceptable fit to the ASCA spectrum of X-1 ($\chi^2$/d.o.f. = 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 than these authors. Makishima et al. (2000) fit two ASCA spectra of NGC 1313 X-2 separated by two years 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. It is likely that the high effective area of XMM-Newton at low energies has allowed us to detect and require very different disk components. Contemporaneous results from an Chandra observation of NGC 5408 X-1 may also reveal a cool disk in a two-component spectrum (Kaaret et al. 2002). We speculate that future observations of ULX sources may also reveal cool accretion disks in some cases.

5. ACKNOWLEDGEMENTS

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REFERENCES

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Table 1
Spectral Fit Parameters

<table>
<thead>
<tr>
<th>Model/Parameter</th>
<th>NGC 1313 X-1</th>
<th>NGC 1313 X-2</th>
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<td>power-law</td>
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<td>$N_H$ ($10^{21}$ cm$^{-2}$)</td>
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<td>2.7$^{+0.3}_{-0.2}$</td>
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<td>$\Gamma$</td>
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<td>Norm. ($10^{-4}$)</td>
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<tr>
<td>$\chi^2$/dof</td>
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<td>$\chi^2$/dof</td>
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<td>$kT_{med}$ (keV)</td>
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<td>50$^{+1}_{-1}$</td>
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<td>$\chi^2$/dof</td>
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<td>$L_{0.05-100}$ (10$^{40}$ erg s$^{-1}$)$^b$</td>
<td>3.3$^{+0.8}_{-0.8}$</td>
<td>1.0$^{+0.05}_{-0.04}$</td>
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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.

† The temperature of the up-scattering corona was not constrained by fits with the XSPEC model “CompTT” and was therefore fixed at a reasonable value.

$^a$ The absorption-corrected or “unabsorbed” flux.

$^b$ The luminosity in the 0.2–10.0 keV or 0.05–100.0 keV range, assuming a distance of 3.7 Mpc.