

A COMPARISON OF INTERMEDIATE-MASS BLACK HOLE CANDIDATE ULTRALUMINOUS X-RAY SOURCES AND STELLAR-MASS BLACK HOLES

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ABSTRACT

Cool thermal emission components have recently been revealed in the X-ray spectra of a small number of ultraluminous X-ray sources (ULXs) with $L_x \geq 10^{40}$ ergs s^{-1} in nearby galaxies. These components can be well fitted with accretion disk models, with temperatures approximately 5–10 times lower than disk temperatures measured in stellar-mass Galactic black holes when observed in their brightest states. Because disk temperature is expected to fall with increasing black hole mass, and because the X-ray luminosity of these sources exceeds the Eddington limit for $10 M_\odot$ black holes ($L_{\text{Edd}} \approx 1.3 \times 10^{39}$ ergs s^{-1}), these sources are extremely promising intermediate-mass black hole candidates. In this Letter, we directly compare the inferred disk temperatures and luminosities of these ULXs, with the disk temperatures and luminosities of a number of Galactic black holes. The sample of stellar-mass black holes was selected to include different orbital periods, companion types, inclinations, and column densities. These ULXs and stellar-mass black holes occupy distinct regions of a L_x - kT diagram, suggesting these ULXs may harbor intermediate-mass black holes. We briefly discuss the important strengths and weaknesses of this interpretation.

Subject headings: accretion, accretion disks — black hole physics — galaxies: stellar content — relativity — X-rays: binaries

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are variable, off-nuclear, X-ray point sources in nearby galaxies for which the implied luminosity of the source exceeds the isotropic Eddington limit for a $10 M_\odot$ black hole (unless otherwise noted, in this work the term “luminosity” means the luminosity the source would have if it radiates isotropically). In the *Chandra* and *XMM-Newton* era, a large number of these sources have been detected (see, e.g., Fabbiano & White 2003, Miller & Colbert 2004, and Swartz et al. 2004). The X-ray spectra and variability properties of the strong majority of ULXs suggest that they are accreting sources. These sources have attracted a great deal of observational and theoretical attention, in part because their luminosities suggest that they may harbor intermediate-mass black holes (IMBHs; $M_{\text{BH}} \sim 10^2$ – $10^5 M_\odot$).

As with any new class of sources, in the case of ULXs it was initially tempting to identify the whole class as entirely one kind of source or another. The first *Chandra* study of the Antennae galaxies suggested a population of IMBHs (Fabbiano et al. 2001), but it was not long until a theoretical investigation suggested the ULXs in the Antennae are stellar-mass sources (King et al. 2001); earlier work suggested relativistic beaming in ULXs (Reynolds et al. 1997). It may be that ULXs, in particular those at the lower end of the ULX luminosity distribution, are stellar-mass black holes (or even neutron stars in rare cases). However, a growing number of ULXs have been identified that are strong intermediate-mass black hole candidates (IMBHCs). Due in part to recent observations that have obtained more sensitive spectra and light curves, cool accretion disks have been found in some of the most luminous ULXs ($L_x \geq 10^{40}$ ergs s^{-1}). Temperature is inversely related to black

hole mass ($T \propto M^{-1/4}$) in standard accretion disks; the fact that these ULXs are 5–10 times brighter than stellar-mass black hole candidates (BHCs) and yet have disks that are 5–10 times cooler than the disks in BHCs identifies them as strong IMBHCs (see, e.g., Miller et al. 2003).

In this Letter, we directly compare the luminosity and disk temperature of these IMBHC ULXs, with a number of well-known stellar-mass BHCs. This sample of ULXs indeed appears to be a distinct and perhaps rather homogeneous set of sources consistent with harboring IMBH primaries.

2. DATA SELECTION

2.1. Intermediate-Mass Black Hole Candidates

We selected ULXs for which published fluxes imply luminosities of $L_x \geq 10^{40}$ ergs s^{-1} , and for which a soft thermal component is required at the 3σ level of confidence (or higher) in the low-energy part of an X-ray spectrum that requires two continuum components. Six sources satisfy these selection criteria: NGC 1313 X-1, NGC 1313 X-2, M81 X-9 (Holmberg IX X-1), NGC 4559 X-7, Holmberg II X-1, and NGC 4038/4039 X-37 (Antennae X-37). See Table 1 for a list of references for these sources. M82 X-1 is the most luminous ULX known, and in some respects it may be the single best IMBHC ULX (see, e.g., Strohmayer & Mushotzky 2003). However, it lies in a region of significant diffuse emission, and its low-energy spectrum is poorly determined. Therefore, we have not included this source in our comparison.

2.2. Black Hole Candidates

In an effort to prevent possible biases and to ensure a representative sample, we selected stellar-mass BHCs that cover a range of binary inclinations, primary masses, companion types, distances, and absorbing columns. This sample includes LMC X-1, LMC X-3, 4U 1543–475, XTE J1550–564, 4U 1630–472, GRO J1655–40, and GRS 1915+105. These are among the best-studied stellar-mass BHCs. It should also be noted that this sample includes both persistent sources or

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TABLE 1
ULX AND BHC INFORMATION AND REFERENCES

Source Name	T/P ^a	Companion	<i>P</i> (hr)	Distance	N_{H} (10^{21} cm^{-2})	θ_i (deg)	High L_X^b	Low L_X^c
NGC 1313 X-1 .....	...	...	...	3.7 Mpc ^d	4.4 ^d	...	...	...
NGC 1313 X-2 .....	...	...	...	3.7 Mpc ^d	3.0 ^d	...	...	...
M81 X-9 .....	...	...	...	3.4 Mpc ^e	2.8 ^e	...	...	...
Ho II X-1 .....	...	...	...	3.4 Mpc ^f	1.6 ^f	...	...	...
NGC 4559 X-7 .....	...	...	...	9.7 Mpc ^g	5.1 ^g	...	...	...
Antennae X-37 .....	...	...	...	19 Mpc ^h	5.6 ^h	...	...	...
LMC X-1	P	O7 III ⁱ	101.5 ⁱ	50 kpc ⁱ	7.2 ⁱ	...	(3, 21, 25, 27, 30) ^j	...
LMC X-3	P	B3V ⁱ	40.9 ⁱ	50 kpc ⁱ	0.32 ^j	...	(5, 6, 7, 8, 9) ^j	...
4U 1543–475	T	A2 V ⁱ	26.8 ⁱ	7.5 kpc ⁱ	4.0 ^k	21 ^l	(4, 5, 6, 7, 8) ^k	(45, 46, 47, 48, 49) ^k
XTE J1550–564	T	G8 IV–K4 III ⁱ	37.2 ⁱ	5.3 kpc ⁱ	20 ^m	72 ^l	(17, 18, 19, 20, 21) ^m	(193, 195, 196, 200, 206) ^m
4U 1630–472	T	...	...	8.5 kpc	90 ⁿ	...	(28, 29, 30, 32, 34) ⁿ	...
GRO J1655–40	T	F6 III ⁱ	62.4 ⁱ	3.2 kpc ⁱ	8.9 ^o	70 ^l	(725, 801, 806, 815, 816) ^{o,p}	(729, 803, 814, 818, 825) ^{o,p}
GRS 1915+105	P	K–M III	804.0	11 kpc ^q	4.0–4.8 ^r	66 ^q	(1, 2, 3, 4, 5) ^r	...

^a Denotes whether the source is transient or persistent.

^b Denotes which high-luminosity observations were selected for BHCs.

^c Denotes which low-luminosity observations were selected. Where a value is not given, it is unknown for the given source for BHCs.

REFERENCES.—(d) Miller et al. 2003; (e) Miller et al. 2004a; (f) Dewangan et al. 2004; (g) Cropper et al. 2004; (h) Miller et al. 2004b; (i) McClintock & Remillard 2004; (j) Wilms et al. 2001; (k) Park et al. 2004; (l) Garcia et al. 2003; (m) Sobczak et al. 2000; (n) Trudolyubov et al. 2001; (o) Sobczak et al. 1999; (p) Date in MJD, minus 960,000; (q) Fender et al. 1997; (r) Ueda et al. 2002.

sources undergoing very long outbursts (LMC X-1, LMC X-3, GRS 1915+105), and transient sources (4U 1543–475, XTE J1550–564, 4U 1630–472, GRO J1655–40) with outbursts that may last as much as a year (or longer) followed by quiescent periods with fluxes 5–6 orders of magnitude lower, lasting months to years. See Table 1 for a list of references for these sources.

3. ANALYSIS AND RESULTS

The luminosity and disk temperatures we use in this Letter are those derived by the authors in the references listed in Table 1 from their spectral fits to each source using a simple and phenomenological model consisting of a multicolor disk black-

body (Mitsuda et al. 1984) and power-law spectral components (both modified by neutral interstellar absorption).

The energy range over which the spectral fits were made to the ULX sources and stellar-mass black hole sources differed considerably because of the different lower energy thresholds of *Chandra*, *XMM-Newton*, and *RXTE*. In most cases, the ULX spectra were fitted in the 0.2–10.0 or 0.3–10.0 keV range. In contrast, the stellar-mass black hole spectra were generally fitted in the 3.0–25.0 or 3.0–100.0 keV range. To perform a meaningful comparison between these sources, we converted the flux and luminosity measurements in the differing energy ranges to the 0.5–10.0 keV range. This conversion was accomplished by entering the exact spectral model for each published spectral fit into XSPEC version 11.2⁵ and measuring the “unabsorbed” flux of each model in the 0.5–10.0 keV range. For the ULXs in particular, the 0.2–100.0 keV luminosity—more representative of a bolometric luminosity—is a few times higher than the 0.5–10.0 keV luminosity. In some cases, the published disk temperatures were “effective temperatures”—converted from “color temperatures” by application of a color correction factor, which attempts to account for effects such as spectral hardening from radiative transfer through a disk (Shimura & Takahara 1995; Merloni et al. 2000; Makishima et al. 2000). In these cases, we converted the effective temperature to a color temperature. Color temperatures are compared directly to color temperatures in this work. This introduces no significant temperature bias; a recent study has shown that the correction factor for IMBHs should be very similar to that sometimes applied to stellar-mass black holes (Fabian et al. 2004).

The lower energy bound of the 0.5–10.0 keV range is somewhat higher than the present lower energy bounds of *Chandra* and *XMM-Newton*; however, history suggests that as all X-ray detectors age, the lower energy bound gradually increases. This range was chosen to be forward-looking and to avoid any biases inherent in relying too heavily on the lowest bins in the *Chandra* and *XMM-Newton* bandpasses.

To understand the properties of the ULX sources within the context of BHCs in their brightest states, we plotted the luminosity and disk temperature of each ULX and the corresponding data for the five most luminous observations of each BHC in our sample (see Fig. 1). In choosing the brightest BHC

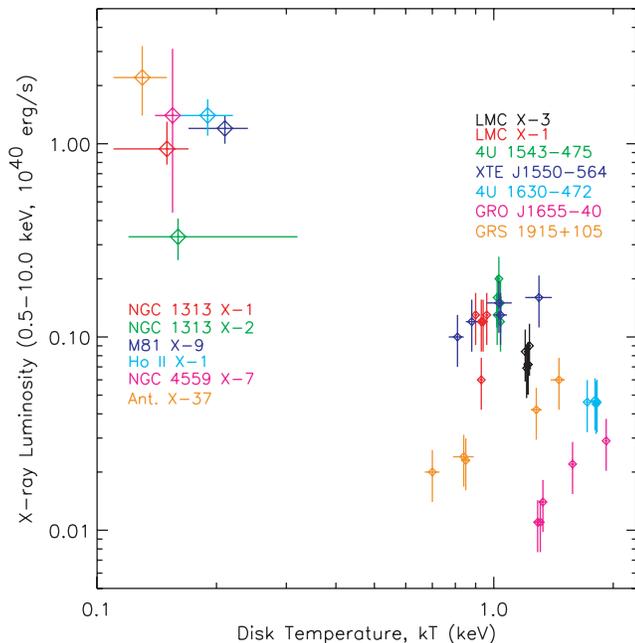


FIG. 1.—X-ray luminosity of a number of extremely luminous ULXs and stellar-mass black holes in their brightest phases are plotted against disk temperatures inferred from X-ray spectral fits. The fact that the ULXs are more luminous and yet have cooler disks than the stellar-mass black holes suggests that they may harbor IMBHs.

⁵ XSPEC is available at <http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec>.

observations, we are attempting to select those phases wherein each source is closest to its Eddington luminosity. In all cases, the errors on the disk color temperatures are 90% confidence errors. For the ULX sources, the luminosity errors are the 90% confidence errors in the measured flux. A review of the literature shows that constraints on the distance to given Galactic sources can change considerably over time with refined measurements, especially when extinction is particularly high. To be conservative, the luminosity errors on the stellar-mass black holes were set by taking the best-fit measured flux and enforcing fractional errors of $\pm 30\%$. This value is somewhat arbitrary but certainly greater than most quoted errors and represents a best-guess value based on the broad literature.

The difference between the IMBHC ULXs and standard, stellar-mass BHCs is shown clearly in Figure 1. The ULXs are generally 5–10 times more luminous than the BHCs and have inner disk color temperatures 5–10 times lower than the BHCs (it should be noted that while it is possible to make a relatively cool disk appear hotter—e.g., via Compton-upscattering in some hot material—it is not possible to make an intrinsically hot disk appear cool). Equally importantly, the ULXs in Figure 1 are clustered together, suggesting they are fundamentally similar. In those BHC sources that span a reasonable range in L_x , it is clear that kT and L_x (a trace of \dot{m}) are positively correlated. It is expected that the inner disk temperature should be positively correlated with \dot{m} (see, e.g., eq. [5.43] in Frank et al. 2002). If a BHC is to reach the luminosity window occupied by these ULXs, then it is expected that its disk temperatures should increase accordingly. Indeed, XTE J1550–564 was initially famous for flaring to 6.8 crab—a factor of a few brighter than the highest points in Figure 1. In an observation that occurred within that flare, Sobczak et al. (2000) measured an inner disk color temperature in excess of 3 keV.

It is interesting to explore the origin of the separation between the ULXs and BHCs in L_x - kT shown in Figure 1. To understand where BHCs lie in this space when their disk temperatures approach those seen in the ULXs, in Figure 2 we have added the five data points with the lowest disk temperatures from each BHC in the high-luminosity sample with such data.

Figure 2 clearly shows that when stellar-mass BHC inner disk temperatures approach those seen in the ULX sample, their luminosity has decayed to a few $\times 10^{37}$ ergs s^{-1} —generally 2 orders of magnitude (or more) below the luminosity of the ULXs. Note that there is a clear $L \propto T^4$ trend in the BHC data, as expected for standard disks. This plot also demonstrates that cool-disk components can be detected in Galactic stellar-mass black holes even with *RXTE* (which has a low-energy bound of 2 keV). It is not the case that very cool disks have not yet been detected in Galactic sources at high luminosities because of instrumental thresholds, Galactic column densities, or a combination of these. At their highest luminosities, stellar-mass black holes—regardless of companion type, orbital period, distance, or intervening absorption—do not have disks as cool as those found in IMBHC ULXs.

4. DISCUSSION

The comparison undertaken in this work demonstrates that ULXs in our sample are clearly different from our representative sample of stellar-mass BHCs. These ULXs are more luminous but have cooler thermal disk components than standard stellar-mass BHCs; these facts can be explained naturally if the ULXs harbor IMBHs. The comparison presented here makes the distinction more concrete and demonstrates that the differences are not due to instrumental effects (e.g., detector

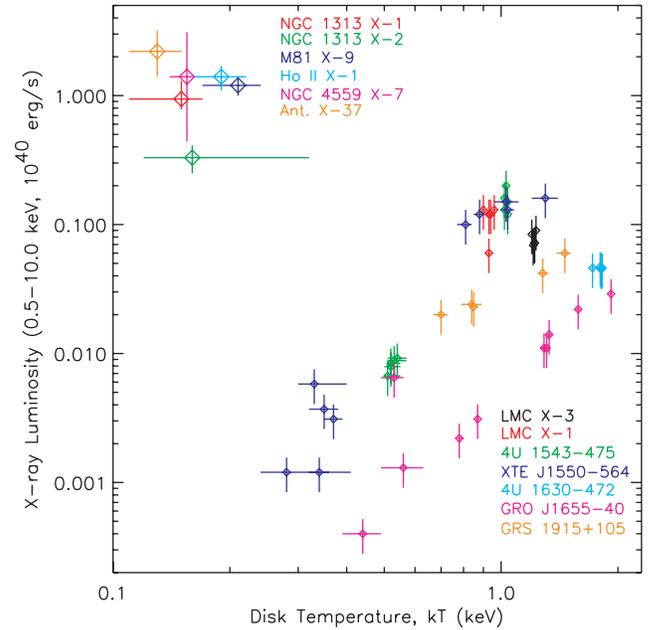


FIG. 2.—A number of low-luminosity BHC data points have been added to Fig. 1 to illustrate that BHC disk temperatures only approach those of the ULXs at luminosities that are generally 2 orders of magnitude (or more) below the ULX luminosities.

energy thresholds), observational effects (e.g., column density), or astrophysical effects (e.g., companion type or orbital period).

Optical, radio, and even X-ray data (see Pakull & Mirioni 2003; Miller et al. 2003, 2004; Strohmayer & Mushotzky 2003) suggest that the high luminosity of these ULXs cannot easily be explained through funneling in the inner disk (e.g., King et al. 2001), through relativistic beaming (e.g., Reynolds et al. 1997; Kording et al. 2002), or through alternative accretion flow geometries wherein a photosphere and shocks are postulated instead of the conventional disk and corona (King 2004).

This comparison further demonstrates the problems with present theoretical alternatives to IMBH primaries in our ULX sample. In Figures 1 and 2, it is clear that the stellar-mass BHC 4U 1543–472 ($M = 9.4 \pm 2.0 M_{\odot}$, Orosz et al. 2004) exceeds its *isotropic* Eddington limit; the source luminosity would be a factor of a few higher still if the energy band considered extended either down to 0.1 keV or up to 100.0 keV. 4U 1543–375 has an inclination of 21° (Orosz et al. 2004), and funneling might be a means to introduce sufficient anisotropy to avoid violating the Eddington limit. It is also possible that a “slim disk” solution may allow a luminosity in excess of the isotropic Eddington limit (Watarai et al. 2001; Begelman 2002). It is important to realize that although either explanation for 4U 1543–475 may hold, 4U 1543–475 is not observed to have an anomalously low inner disk color temperature.

The clustering of the ULXs in Figures 1 and 2 suggests that they may be fundamentally similar. The similarity may be that these sources harbor IMBHs with masses that lie in a rather narrow range. It is difficult to identify the mass range implied for these sources precisely: scaling the ULX luminosities to the isotropic Eddington luminosity for a $10 M_{\odot}$ black hole is sensitive to the energy range in which the luminosities are inferred, and scaling the ULX inner disk color temperatures to those seen in stellar-mass BHCs is sensitive to the temperature assumed to be typical for those sources when they accrete near to their Eddington limit. For these ULX sources, a reasonable mass range may be 100 – $3000 M_{\odot}$ (see, e.g., Miller et al. 2003,

2004; Cropper et al. 2004). If they are accreting at approximately one-tenth of their Eddington limits, lower masses implied by Eddington limit scaling would come more into line with the high-mass estimates that come from scaling the ULX inner disk color temperatures to an inner disk color temperature of 1 keV in BHCs.

The comparisons in this analysis present a strong case for IMBHs in a few ULXs, but it is worth addressing some ways in which this interpretation may ultimately be proved incorrect.

The soft thermal component in these ULX spectra have been fitted with disk models. This is because there are no compelling soft X-ray emission lines (individual lines significant at the 3σ level or higher, excluding Fe $K\alpha$ lines that are likely due to disk reflection) yet reported in any ULX spectrum. Thus, thermal plasma models are not statistically required, and simpler spectral forms are assumed. However, even in spectra with moderate sensitivity (the ULX spectra so far obtained are certainly of moderate sensitivity), it is difficult to statistically rule out thermal plasma models. Matters are further complicated by the fact that some ULXs lie near by star-forming regions, where a thermal plasma may be present but unrelated to the source (M82 X-1 is a good example; see Strohmayer & Mushotzky 2003). Although the contribution of a thermal plasma to the soft excess in these ULXs would seem to be small, improved spectra are needed to tightly constrain any such contribution.

Soft excesses have been found in a number of active galactic nuclei (AGNs), which have temperatures similar to those seen

in the ULXs in this sample when fitted with a disk model (much too hot for such massive black holes; see Gierlinski & Done 2004). The origin of the soft excess in these AGNs—and whether or not it is due to a disk—remains uncertain. The “big blue bump” would seem to be far more likely to be the primary disk contribution in these AGNs. Photosphere plus shocks models are as implausible in these sources as they are in ULXs (see Miller et al. 2004). It has also been suggested that the excess may be due to relativistically skewed soft X-ray absorption edges (Gierlinski & Done 2004) or relativistically skewed disk reflection features (Fabian et al. 2004). Although it has been suggested that ULXs in elliptical galaxies may only be background AGNs (Irwin et al. 2004), the proximity of the ULXs in this sample to their galactic nuclei, star-forming regions, or spiral arms suggests that they are properly associated with their host galaxies and not background sources. Even though these IMBHC ULXs are unlikely to be background AGNs with soft components, the difficulties found in understanding the soft X-ray excesses in a number of AGNs illustrates that the spectral continuum is not well understood in all accreting sources.

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