OBSERVATIONAL EVIDENCE FOR INTERMEDIATE-MASS BLACK HOLES IN ULTRA-LUMINOUS X-RAY SOURCES

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Evidence is mounting that some Ultra-luminous X-ray sources (ULXs) may contain accreting intermediate-mass black holes (IMBHs). We review the current observational evidence for IMBH-ULXs. While low-luminosity ULXs with $L_X \lesssim 10^{39.5}$ erg s^{-1} (assuming isotropic emission) are consistent with mildly X-ray beamed high-mass X-ray binaries, there are a considerable number of ULXs with larger X-ray luminosities that are not easily explained by these models. Recent high-S/N XMM X-ray spectra are showing an increasing number of ULXs with "cool disks" – accretion disks with multicolor blackbody inner disk temperatures $kT_{in} \sim 0.1-0.2$ keV, consistent with accreting IMBHs. Optical emission-line studies of ULX nebulae provide useful measurements of X-ray energetics, and can thus determine if the X-rays are emitted isotropically. Analysis of an optical spectrum of the Ho II ULX nebulae implies an X-ray energy source with $\sim 10^{40}$ erg s^{-1} is present, suggesting an isotropically-emitting IMBH. The spatial coincidence of ULXs with dense star clusters (young clusters and globular clusters) suggests that IMBHS formed in these clusters could be the compact objects in the associated ULXs. Quasi-periodic oscillations and frequency breaks in XMM power-density spectra of ULXs also suggest that the black hole masses are more consistent with IMBHs than stellar-mass black holes. Since *all of these ULXs with evidence for IMBHs are high-luminosity ULXs, i.e.,* $L_X \gtrsim 10^{40}$ *erg* s^{-1}, we suggest that this class of ULXs is generally powered by accreting IMBHs.

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1. Introduction

It has long been suspected that black holes of masses $\sim 10^2 - 10^4\, M_\odot$ may form in, for example, the centers of dense stellar clusters (e.g., Wyller 1970; Bahcall & Ostriker 1975; Frank & Rees 1976; Lightman & Shapiro 1977; Marchant & Shapiro 1980; Quinlan & Shapiro 1987; Portegies Zwart et al. 1999; Ebisuzaki et al. 2001). However, for many years there was no observational evidence for such a mass range. In roughly the last decade, X-ray and optical observations have revived this possibility. If such black holes exist, especially in dense stellar clusters, they have a host of implications, especially for cluster dynamical evolution and the generation of gravitational waves.

In this article, we discuss the evidence for intermediate-mass black holes (IMBHs) in Ultra-Luminous X-ray sources (ULXs). ULXs are extra-nuclear point sources that have X-ray fluxes many times the angle-averaged flux of a $M \gtrsim 20\, M_\odot$ black hole accreting at the Eddington limit. Evidence for IMBHs in globular clusters and other astrophysical objects has been discussed in several recent review articles, such as van der Marel (2003), and Miller & Colbert (2004). We focus here on the ULXs, which we regard as having the most convincing evidence for IMBHs.

2. A Brief History of ULXs

If we consider stellar-mass black holes (BHs) to have a maximum mass of $\approx$20 M$_\odot$ (e.g. Fryer & Kalogera 2001), then the Eddington luminosity (the limiting bolometric luminosity; see Eqn. 2) of an "intermediate-mass" BH is $\gtrsim 3 \times 10^{39}$ erg s^{-1}. The limiting X-ray luminosity in the 2−10 keV band, for example, will be a factor of a few−10 times smaller, and it will be dependent on the metallicity as well. The lower limit to the X-ray luminosity for a ULX is defined to be $10^{39.0}$ erg s^{-1}. In practice, this limit distinguishes the "normal" BH XRBs ($L_X \lesssim 10^{39.0}$ erg s^{-1}) found in our Galaxy from the intriguingly more luminous ULXs found in some nearby galaxies. The upper limit for L$_X$ for ULXs is not specified, but usually objects have L$_X$ $< 10^{40.5}$ erg s^{-1}, and most of them have L$_X$ $< 10^{40.0}$ erg s^{-1}. Quasars, supernovae, and other galaxy nuclei are usually omitted, although some workers (e.g. Roberts et al. 2002a) include X-ray luminous supernovae.

ULXs were named as such by several Japanese workers who analyzed spectra from the Japanese X-ray satellite ASCA (Mizuno et al. 1999, Makishima et al. 2000). Here, "ultra-luminous" is gauged with respect to "normal" X-ray binaries. Another term that is used is "Intermediate-luminosity X-ray Objects," (IXOs), which simply indicates that their X-ray luminosities are intermediate between those of "normal" stellar-mass BH XRBs, and AGNs.

ULXs were observed as early as the 1980s, when extensive X-ray observations of external galaxies were first performed with the Einstein satellite. Many of the nearby AGNs in Seyfert galaxies were expected to have very luminous X-ray nuclei, but it was a surprise to find that many "normal" spiral galaxies also had central X-ray sources (see Fabbiano 1989 for a review). These X-ray sources had X-ray luminosities $\gtrsim 10^{39}$ erg s^{-1}, well above the Eddington value for a single neutron star or a stellar-mass black hole. The spatial resolution of the most widely used instrument on Einstein (the Imaging Proportional Counter, or the IPC, FWHM $\sim 1'$) is $\gtrsim 1$ kpc for typical galaxy distances $\gtrsim 4$ Mpc, so it was not clear whether these sources were single or multiple objects, or whether they were really coincident with the nuclei. Some possibilities included a single supermassive black hole with a low accretion rate, a black hole with a normal accretion rate and super-stellar mass, hot gas from a nuclear starburst, groups of $\gtrsim 10$ "normal" X-ray binaries (e.g. Fabbiano & Trinchieri 1987), or very luminous X-ray supernovae (see Schlegel 1995). The supermassive black hole scenario was not very well supported since there was not typically any other evidence for an AGN from observations at optical and other wavelengths. Another possibility was that the errors in the galaxy distances were producing artificially large X-ray luminosities. The nearest of these interesting X-ray objects is located in the center of the Local Group spiral galaxy M33 (see Long et al. 1981). Several other Einstein observations of similar objects are reported in Fabbiano & Trinchieri (1987), and a summary of Einstein observations are given in the review article by Fabbiano (1989). Unfortunately, the X-ray spectral and imaging capabilities of the IPC instrument were not generally good enough to distinguish between the possible scenarios. Even so, it was certainly realized that these very luminous X-ray sources were not uncommon in normal galaxies, and that they certainly deserved further attention.

The ROSAT satellite was launched into orbit in 1990, and began producing X-ray images at $\sim 10-20''$ resolution. The highest resolution instrument was the High Resolution Imager (HRI; PSF $\approx 10''$). The sensitivity and spatial resolution were a significant improvement over the Einstein IPC, many more ULXs were discovered, and several surveys were done. It was soon found that some of the luminous Einstein sources were not coincident with the galaxy nucleus. For example, after registering the ROSAT image of the nearby spiral galaxy NGC 1313 with the X-ray bright supernova 1978K, Colbert et al. (1995) found that the central Einstein source (X-1) was actually located $\sim 1'$ (~ 1 kpc) NE of the center of the nuclear bar. Some Einstein X-ray sources in other galaxies, are, however, still consistent with being located in the galaxy nucleus. For example, even with Chandra accuracy ($1''$), the M33 ULX is still coincident with the nucleus of the galaxy, although is not thought to be an AGN, since the dynamic mass at that position is too small and the X-ray and optical properties are more consistent with it being an XRB-like object (Gebhardt et al. 2001, Long et al. 2002, Dubus & Rutledge 2002).

The PSPC spectrometer on ROSAT had much better spectral resolution than the Einstein IPC, but it only covered soft X-ray energies (0.2−2.4 keV), and so was of limited use for diagnosing ULX emission models. However, much progress was made from surveys done with the ROSAT HRI. Four large HRI surveys of nearby galaxies (Colbert & Mushotzky 1999, Roberts & Warwick 2000, Lira, Lawrence & Johnson 2000, and Colbert & Ptak 2002) showed that off-nuclear luminous X-ray

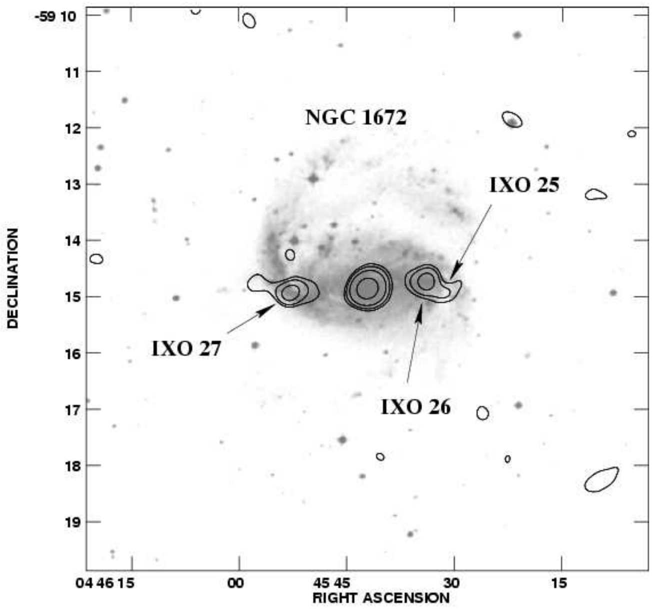

Figure 1. A sample spiral galaxy with ULXs, from Colbert & Ptak (2002). ROSAT HRI X-ray contours from the galaxy NGC 1672 are overlaid on a B-band DSS image of the galaxy, showing two ULXs straddling the nuclear X-ray source.

sources were actually quite common – present in up to half of the galaxies sampled. A sample spiral galaxy with two ULXs is shown in Figure 1 (from Colbert & Ptak 2002). At the time of the first three surveys, ULXs were not a well defined class of objects. We now know that ULXs are fairly common in galaxies. Using all of the public HRI images for nearby galaxies, Ptak & Colbert (2004) estimate that ULXs with $L_X(2{-}10\ \mathrm{keV}) \geq 10^{39}$ erg s^{-1} are present at the rate of one in every five galaxies, on average. When ROSAT survey work started showing that ULXs, and thus possibly IMBHs, were quite common, ULXs and IMBHs became a popular topic of study.

Chandra observations of spiral and starburst galaxies have revealed that many strong starburst systems have large numbers of ULXs ($\gtrsim 5$ per galaxy, e.g., the Antennae, Fabbiano, Zezas & Murray 2001; and NGC 4485/90, Roberts et al. 2002b). The starburst−ULX connection also appears to hold at cosmologically interesting ($z \gtrsim 0.1$) look-back times (Hornschemeier et al. 2004). Since the total point-source X-ray luminosity of spiral and starburst galaxies correlates very well with the star-formation rate (SFR), and the most luminous point sources dominate this luminosity (e.g., Colbert et al. 2004), many workers have argued that ULXs are merely high-mass X-ray binaries (HMXBs) created in the starburst (e.g., Grimm et al. 2003), and they emit X-rays anisotropically by mild X-ray beaming (e.g., King et al. 2001, King 2003), and thus with a lower X-ray luminosity than if isotropic. The low-luminosity ULXs ($L_X \lesssim 5 \times 10^{39}$ erg s^{-1}) are consistent with this mild-beaming HMXB model, and these sources dominate the population of all ULXs ($L_X \geq 10^{39.0}$ erg s^{-1}; see Fig 2., and Ptak & Colbert 2004). Thus, beaming models could explain the implied "artificially high" X-ray luminosities for many ULXs. However, it is not know how IMBHs form, or how IMBH-ULXs "turn on", so their numbers could also be correlated with the SFR. ULX observational diagnostics (X-ray or otherwise) have not yet progressed enough to be certain whether ULXs associated with star formation (a) have IMBHs or stellar-mass BHs, (b) are beamed or isotropic, or (c) are fed by high-mass stellar companions, or by another source.

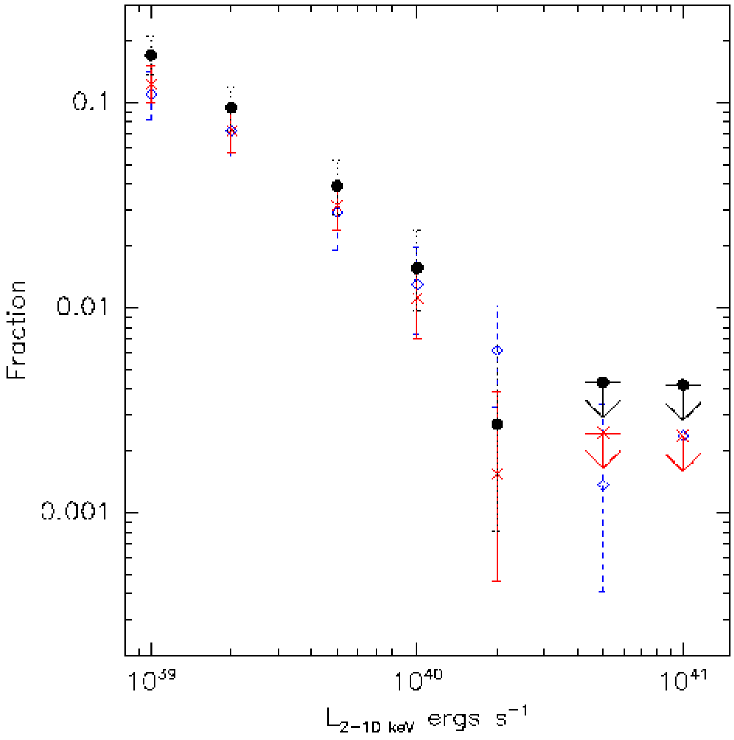

Figure 2. The frequency of ULX occurrence in galaxies (i.e., expected number per galaxy) as a function of L_X, from Ptak & Colbert (2004). Diamond symbols denote statistics for for sources within a radius of D_{25}, while crosses are for sources with $r < 0.5\ D_{25}$. Solid circular symbols are for spiral galaxies only ($r < 0.5\ D_{25}$).

3. Observational Evidence for IMBHs in ULXs

In the following six subsections, we describe the observational results that support the existence of IMBHs in some ULXs. We emphasize that we are not promoting that *all* ULXs are accreting IMBHs, but merely showing that some of them show very good evidence for having them.

3.1. *Extreme X-ray Luminosities*

Since one usually has no information about the flux radiation pattern $f_X(\Omega)$ emitted by the X-ray source, it is common to assume an "isotropic" X-ray luminosity L_X, as if the radiation pattern is uniform in all directions:

$$L_X = \iint d\Omega R^2 f_X(\Omega) = 4\pi R^2 F_X, \tag{1}$$

where F_X is the observed X-ray flux, R is the distance to the source, and $f_X(\Omega)$ is the flux emitted per unit solid angle in a particular direction. For accretion around a black hole, in which the matter is highly ionized and electron scattering is the most important form of opacity, a source of mass M that accretes and radiates *isotropically* therefore cannot have an isotropic luminosity that exceeds the Eddington luminosity

$$L_E = \frac{4\pi G M m_p}{\sigma_T} = 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{erg s}^{-1} , \tag{2}$$

assuming cosmic composition. Here, $\sigma_T = 6.65 \times 10^{-25}$ cm^2 is the Thomson scattering cross section. If the accretion or radiation is anisotropic, there is no fundamental reason why the luminosity cannot exceed L_E by an arbitrary factor (e.g., King et al. 2001, Begelman 2002). Beaming of the radiation can produce a flux $f_X(\Omega)$ in a particular direction that is much greater than the average over all angles. However, assuming isotropy holds, a given luminosity places a lower limit on the mass of an accreting black hole.

IMBHs with M $\gtrsim$20 M$_\odot$ have L$_E \gtrsim$ 3 × 10^{39} erg s^{-1}. In the Colbert & Ptak (2002) ULX catalog, 45 of 87 objects have 2−10 keV X-ray luminosities L$_X$ > 3 × 10^{39} erg s^{-1}. Eleven objects have L$_X$ > 10^{40} erg s^{-1}, which corresponds to quasi-isotropic sources with masses $M > 70\, M_\odot$. Based on the statistical results from Ptak & Colbert (2004), these "high-luminosity" ULXs are $\gtrsim$5−10% of the total ULX population. Thus, one or more high-luminosity (L$_X \gtrsim$ 10^{40} erg s^{-1}) objects are expected in every ~100 galaxies (see Figure 2), or $\gtrsim$10^7 in the Universe, assuming $\gtrsim$10^{10} galaxies. Thus, the potential for IMBHs is clearly present. Some galaxies, such as NGC 4038/9 ("The Antennae") have $\gtrsim$10 ULXs with masses $\gtrsim$10−(few)100 (by the Eddington argument), if the X-rays are not beamed (see Fabbiano et al. 2001). The brightest ULX yet observed, in the galaxy M82 (e.g., see Ptak & Griffiths 1999; Matsushita et al. 2000; Kaaret et al. 2001), has a peak X-ray luminosity of 9 × 10^{40} erg s^{-1} (Matsumoto et al. 2001), implying a mass $M > 700\,M_\odot$ by Eddington arguments. This is well beyond what is expected from stellar evolution. In addition, even a star that starts its life with a high mass may lose most of it to winds and pulsations, leaving behind a black hole of mass $M \lesssim 20\,M_\odot$ if it forms with roughly solar metallicity (e.g., Fryer & Kalogera 2001). Objects of such mass must either have accumulated most of their matter by some form of accretion, or have formed in some other epoch of the universe.

While the possibility remains that these objects are under-luminous supermassive black holes, the locations of the ULXs within the galaxies rule against masses more than $\sim 10^6\,M_\odot$ in many cases (e.g., see Kaaret et al. 2001, and Miller & Colbert 2004 for further discussion).

As mentioned, the mild beaming model of King et al. (2001) may explain some of the low-luminosity ULXs with assumed isotropic luminosities, but there are still a significant number of ULXs with $L_X \gtrsim 5 \times 10^{39}$ erg s^{-1} (see Fig. 2). Several groups have compiled large catalogs of ULXs from archival Chandra data (e.g. Swartz, Ghosh, & Tennant 2003, Swartz et. al 2003, in prog., and Ptak & Colbert, in prog.), finding ∼200−300 sources. Thus, based on a relative fraction of ∼5−10% for ULXs with $L_X \geq 10^{40}$ erg s^{-1} (Fig. 2), we have already observed $\gtrsim$10−30 "high-luminosity" IMBH-ULX candidates, consistent with counts of HRI "high-luminosity" ULXs (see section 3.1; Colbert & Ptak 2002). If this population of high-luminosity ULXs represents the *observed,* "active" IMBHs, there is likely an even larger population of "inactive" IMBHs (e.g. Madau & Rees 2001), analogous to the relationship between AGNs and "dormant" supermassive BHs in galaxy nuclei.

3.2. *X-ray Spectra: Hot and Cool Disk Temperatures*

Although ASCA had a poor PSF (FWHM ∼1′), it had far better sensitivity and spectral resolution than the Einstein IPC, and had much wider spectral coverage (0.4−10 keV) than the ROSAT PSPC. Therefore, substantial progress was made using ASCA observations of ULXs in nearby galaxies. A popular disk model for ASCA ULX spectra is the multi-color disk (MCD) blackbody model, since it was commonly used to fit X-ray spectra of "normal" BH XRBs (Mitsuda et al. 1984, Takano et al. 1994). ULX ASCA spectra are often modeled with a (soft) MCD component for the disk emission, plus a (hard) power-law component, which is presumably Comptonized disk emission (e.g. see Takano et al. 1994). As for Galactic BH XRBs, the power-law photon index Γ was noticed to be hard ($\Gamma \approx 1.8$) in ULX low-flux states, and soft ($\Gamma \approx 2.5$) in ULX high-flux states (e.g., Colbert & Mushotzky 1999, Kubota et al. 2001). In the MCD model, the inferred temperature $T_{\rm in}$ of the innermost portion of the disk is related to the mass of the black hole:

$$kT_{\rm in} \approx 1.2\,{\rm keV} \left(\frac{\xi}{0.41}\right)^{1/2} \left(\frac{\kappa}{1.7}\right) \alpha^{-1/2} \left(\frac{\dot{M}}{\dot{M}_E}\right)^{1/4} \left(\frac{M}{10\,M_\odot}\right)^{-\frac{1}{4}} \tag{3}$$

(e.g., Makishima et al. 2000, eq. 10). Here κ is the spectral hardening factor (T_{color}/T_{eff}, also known as the color correction factor), ξ is a factor that takes into account that the maximum temperature occurs at a radius larger than the radius of the innermost stable circular orbit, and $\alpha = R_{\rm in}/(6GM/c^2)$ is unity for a Schwarzschild spacetime and $\alpha = 1/6$ for prograde orbits in a maximal Kerr spacetime. Fiducial values for κ and ξ are 1.7 and 0.41, respectively. Thus, if $T_{\rm in}$ inferred from MCD fits is representative, one expects lower disk temperatures (k$T_{in} \lesssim$ 0.1−0.2 keV) from accreting IMBH, compared with accreting stellar-mass black holes. Some detailed aspects of the application of the MCD model to ULX spectra are given in Makishima et al. (2000).

The implications of the MCD model were problematic for ASCA spectra. While very large X-ray luminosities of $\sim 10^{39-40}$ erg s^{-1} are explained well by an IMBH with sub-Eddington accretion, the temperature kT_{in} (and radius r_{in}) of the inner accretion disk, derived from MCD spectral fitting, are too high (low) for IMBHs (Mizuno et al. 1999; Colbert & Mushotzky 1999; Makishima et al. 2000; Mizuno, Kubota, & Makishima 2001). BH XRBs with stellar-mass black holes in our Galaxy typically have temperatures $kT_{\rm in} \approx 0.4 - 1$ keV, while ULXs fit with ASCA have $kT_{in} \approx$ 1.1−1.8 keV, which is more consistent with LMXB micro-quasars in our Galaxy (e.g. Makishima et al. 2000). In any case, many ASCA model disk temperatures were well above the expected $\sim$ 0.1 keV.

As mentioned, one solution to this high-temperature problem is to suppose that the compact object is a stellar-mass BH in a HMXB and the X-ray emission is mildly beamed so that the radiation pattern $f_X(\Omega)$ only illuminates ~10% of the sky (King et al. 2001). This interpretation has become quite popular, since it naturally explains the ULX-starburst relationship (e.g., Grimm et al. 2003).

Mizuno et al. (1999), Makishima et al. (2000), and Ebisawa et al. (2001) offer several other potential explanations for the "high temperature" problem. For example, it is possible that the BH is a Kerr IMBH, and the resulting frame dragging can shrink the inner radius of the accretion disk up to ≈6 times less than that of a Schwarzschild BH, for which $r_{in} \gtrsim 3$ R_s. Therefore, r_{in} can be smaller, and T_{in} is larger, as implied by the MCD models. Kerr models work well for ULXs as IMBHs (e.g., Mizuno et al. 2001), but imply very high disk inclination angles (i $\gtrsim$ 80°, Ebisawa et al. 2001, Ebisawa et al. 2003).

One may also relax the assumptions of the "thin disk" model. For example, increasing κ, the ratio of the color temperature to the effective temperature, will yield higher masses (e.g. Shrader & Titarchik 1999), and so will increasing the correction factor ξ, which adjusts for the fact that T_{in} occurs at a slightly higher radius than r_{in} (see Kubota et al. 1998). The mass M is proportional to the product $\kappa^2\xi$. Makishima et al. (2000) shows that $\kappa^2\xi$ has to differ largely from values for "normal" BH XRBs for the "high-temperature" problem to be solved.

Finally, one may completely abandon the physically thin accretion disk model. Abramowicz et al. (1988) and Watarai et al. (2000) show that very high accretion rates $\dot{M} \gtrsim 10$ L_E/c^2 lead to an ADAF (Advection-Dominated Accretion Flow) solution (the so-called "slim disk" model), and that this can explain the $r_{in} \propto T_{in}^{-1}$

relationship, found for MCD fits to ASCA spectra of ULXs (Mizuno et al. 2001). The slim-disk model allows masses to be slightly larger ($\lesssim 10-30$ $M_\odot$), but not as large as ~ 100 $M_\odot$.

Much effort has gone into trying to explain why the MCD temperatures kT_{in} are so high for ULXs. However, it is possible that the ULXs are *not* well represented by a simple MCD disk model after all. For example, when simulated spectra of accretion disks are fit with MCD models, r_{in} and/or the disk accretion luminosity are very poorly estimated (e.g. Merloni et al. 2000, Hubeny et al. 2001). When the popular, but primitive MCD+power-law model is replaced by the more elaborate bulk-motion Comptonization model developed by L. Titarchuk, IMBH masses are predicted. Shrader & Titarchuk (2003) have further developed this model, and use $\kappa = 2.6$ to show its usefulness for estimating black hole masses.

In addition, since the PSF of ASCA is so large, ASCA spectra can be contaminated by diffuse X-ray emission and by X-ray emission from other point sources positioned extraction regions, so that a single MCD model is inappropriate. It was not known if this effect was significant for ULX ASCA spectra.

XMM and Chandra observations have the advantage that their spatial resolution ($\approx 1''$ for Chandra, $\approx 4''$ for the MOS2 camera on XMM) is good enough that contamination from other X-ray sources is not as problematic as it is for ASCA. They also have significantly better throughput than ASCA, which improves the signal to noise. For XMM, the bandwidth extends up to $\sim$12 keV, a few more keV than ASCA. This allows much better leverage for discriminating curved blackbody spectra from straight power-law spectra. While ASCA ULX spectral models often required both MCD and power-law components, Chandra spectra are often fit well with a single component (either MCD or power-law). In many cases, this is due to the poor quality spectra, and especially to poor spectral coverage at energies $\gtrsim 5$ keV, due to either poor sensitivity, or CCD photon pile-up problems.

An interesting recent result from the much improved XMM spectra of ULXs is that, in some cases if an MCD component is required, its inferred temperature is ~ 0.1 keV, consistent with an accreting IMBH. Some ULXs with "cool disks" were even found with ASCA, but XMM is revealing many more. XMM data are able to show the significance of the cool MCD model component much easier than ASCA data. For example, Miller et al. (2003a) analyzed XMM data of the ULX NGC 1313 X-1, and found that a two-component fit is necessary (see Figure 3), with an inferred inner disk temperature $kT_{\rm in} = 0.15$ keV. In comparison, Colbert & Mushotzky (1999) analyzed two ASCA observations of NGC 1313 X-1; one had a hard spectrum, with an MCD best fit temperature of $kT = 1.5$ keV, while the other was softer and more consistent with the recent XMM analysis. The ULX NGC 5408 X-1 is best fit with a MCD temperature $kT_{in} \approx 0.1$ keV (Colbert & Mushotzky 1999), and this is confirmed with Chandra (Kaaret et al. 2003). Similarly, the joint ROSAT+ASCA fit of the X-ray spectrum of the ULX in Ho II yields $kT_{in} \approx 0.17$ keV (Miyaji et al. 2001). We list X-ray observations of "cool disks" IMBH

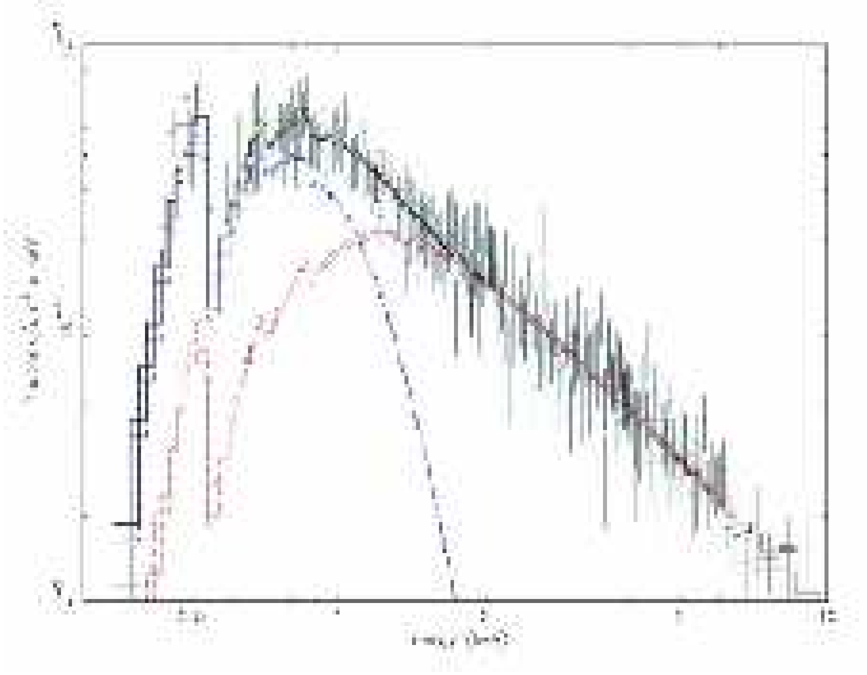

Figure 3. Unfolded XMM MOS spectrum of the ULX NGC 1313 X-1, from Miller et al. (2003a). The model components (cool MCD model and a power-law) are also shown. Absorption of soft X-rays below ∼1 keV is also modeled in the fit.

Table 1. ULXs with Cool Disks

ULX Name	kT_{in} (keV)	L_X (10^{39} erg s^{-1})	Energy Range (keV)	Comment
NGC 1313 X-1	0.12	∼10	2−10	ASCA: Colbert & Mushotzky 1999
	0.15	20	0.2−10	XMM: Miller et al. 2003a
NGC 5408 X-1	0.13	∼10	2−10	ASCA: Colbert & Mushotzky 1999
	0.11	11	0.3−8	Chandra: Kaaret et al. 2003
Ho II ULX	0.2	∼10	0.2−10	ASCA+ROSAT: Miyaji et al. 2001
Antennae (4 ULXs)	0.1−0.2	≈10−30	0.3−10	XMM: Miller et al. 2003b
Ho IX	0.2−0.3	10−16	0.3−10	XMM: Miller et al. 2003c
NGC 4559 X-7	0.12	≈20	0.3−12	XMM: Cropper et al. 2004, MNRAS

candidates in Table 1. **It is interesting to note that the cool disk candidates all have high luminosities $\gtrsim 10^{40}$ erg s^{-1}, precisely the sub-sample of ULXs that are not easily explained by the anisotropic beaming models mentioned in section 2.**

3.3. *"Type II" ULXs (?) and Globular Clusters in Elliptical Galaxies*

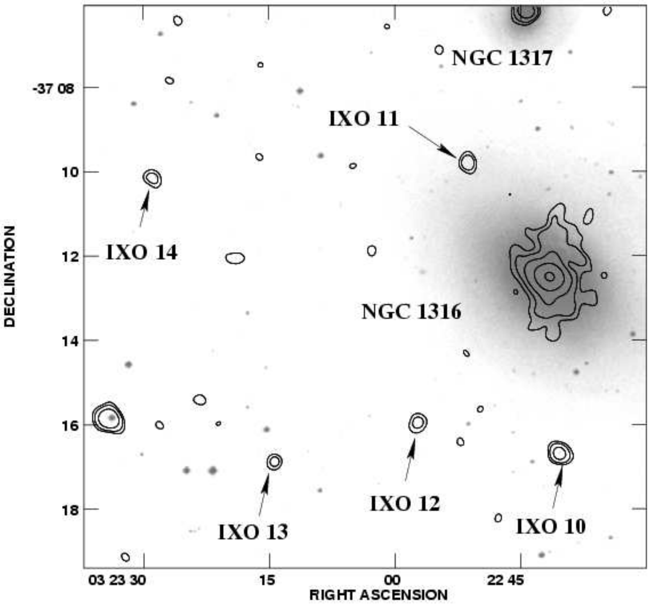

Figure 4. Contours of the ROSAT HRI X-ray emission from five of the six ULXs (IXOs) in the elliptical galaxy Fornax A (NGC 1316), from Colbert & Ptak (2002).

Now that Chandra is in full operation, its combined imaging and spectral capabilities have allowed the literature on ULXs to blossom. The excellent imaging sensitivities of Chandra and XMM ensure that one is likely to detect an ULX in observations of nearby galaxies $\gtrsim 20\%$ of the time, for integrations of more than a few hours. Even short "snapshot" observations with Chandra and XMM have detected a significant number of ULXs in both spiral and elliptical galaxies (e.g., Sipior 2003, Foschini et al. 2002). Most X-ray spectral modeling results are derived for ULXs in spiral galaxies. This is primarily due to the larger distances of the nearby ellipticals (primarily in Virgo), and thus the lack of available photons for spectral analysis. If ULXs in ellipticals are indeed a different class than those in spirals (e.g. Colbert & Ptak 2002, King 2003), we might expect a difference in their X-ray spectral properties. We know that elliptical galaxies do contain ULXs (e.g., see Fig. 4), but are these the same type of ULXs that are found in spiral and starburst galaxies? A census of ULXs using all of the public ROSAT HRI data found that if one selects *only* those galaxies with detected ULXs, the elliptical galaxies with ULXs have a larger number per galaxy than do the spiral galaxies with ULXs (Colbert & Ptak 2002). The elliptical galaxy NGC 720 has nine ULXs, which is nearly as many that are found in the "Antennae" (Jeltema et al. 2003). Since ellipticals are also generally more massive than spirals, it does not imply that they are more efficient at producing ULXs, but it does imply that the mild beaming HMXB scenario does not work for all ULXs, since elliptical galaxies have virtually no young stars being formed. Thus, ULXs in elliptical galaxies are probably associated with the older stellar population (population II).

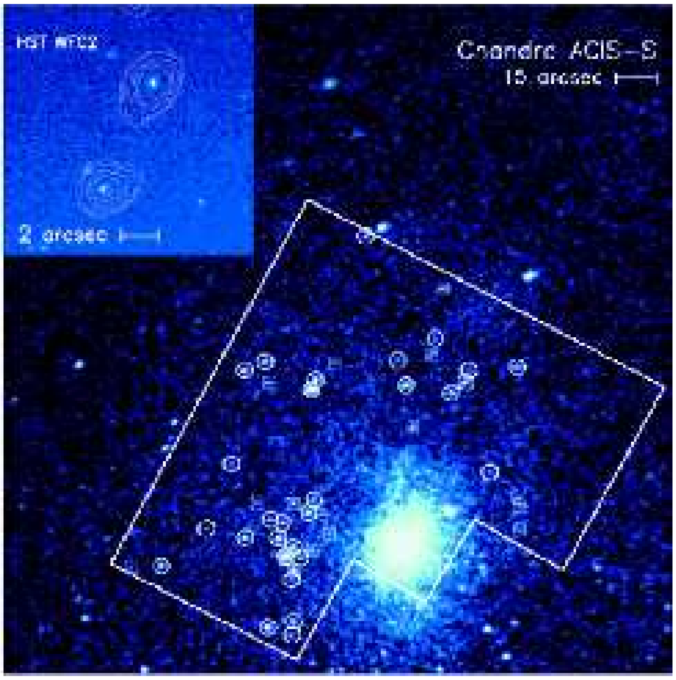

Figure 5. Grey-scale representation of the smoothed Chandra ACIS-S image of the CD elliptical galaxy NGC 1399, from Angelini et al. (2001). The HST WFPC2 FOV is overlaid. The circles show the X-ray sources positions that are associated with globular clusters.

The lack of confusing optical sources in elliptical galaxy halos allows an easier identification of unique counterparts, compared with disk galaxies. For example, Angelini, Loewenstein, & Mushotzky (2001) performed a detailed comparison between Chandra X-ray sources in the giant elliptical galaxy NGC 1399 and HST counterparts, finding that 26 of the 38 sources detected at $>3\sigma$ were obviously associated with globular clusters (Figure 5). Two of the three ULXs are associated with globular clusters. Other groups are also finding that there is a strong correlation between X-ray sources in elliptical galaxies and globular clusters (e.g. Kundu, Maccarone & Zepf 2002). Sarazin, Irwin, & Bregman (2001) find bright point sources up to $\approx 2.5 \times 10^{39}$ erg s^{-1} in the elliptical galaxy NGC 4697, and conjecture that although only 20% of these sources are currently identified with globular clusters, all the LMXBs may have originated in globular clusters. In general, low-mass X-ray binaries in early-type galaxies are strongly correlated with globular clusters (Sarazin et al. 2003). It will be exciting to learn results from follow-up optical studies to determine the age, metallicity and other derivable properties for these globular clusters, and of other globular clusters with ULXs.

These results, combined with results for ULX/young-cluster associations in starburst systems such as the Antennae (Clark et al. 2003), show that there is a strong link between ULXs and star clusters, whether they be young star-forming regions, or globular clusters, which are 100−1000 times older. It is of interest that there are dozens of sources in globular clusters around NGC 1399 with $L_X > 10^{38}$ erg s^{-1}, given that both our Galaxy (with ≈150 globular clusters, Harris 1996) and M31 (with ≈300−400 globular clusters, Hodge 1992, Fusi Pecci et al. 1993) have very few X-ray sources in globular clusters with $L_X \gtrsim 10^{38}$ erg s^{-1} (Hut 1993; Supper et al. 1997). Part of this may have to do with the high number of globular clusters per unit mass around NGC 1399 (as it typical of elliptical galaxies), which is 15 times the average specific frequency for spiral galaxies such as the Milky Way and M31 (e.g., Kissler-Patig 1997), but there may also be evolutionary differences.

As described by Miller & Hamilton (2002) and Portegies Zwart & McMillan (2002; see review article by Miller & Colbert 2004 for additional details), dense stellar clusters are likely sites for IMBH formation. There is also evidence for IMBHs in globular clusters from HST observations (e.g., Gebhardt et al. 2002, Gerssen et al. 2002, van der Marel et al. 2002), and the implied IMBH masses are consistent with the extrapolation of the tight $M_{BH}-\sigma$ relationship for galaxy bulges and supermassive BHs (e.g., see Gebhardt et al. 2002).

Although the globular-cluster−IMBH−"population II ULX" connection seems perfectly feasible, as mentioned, X-ray spectral diagnostics for these "type II" ULXs are not good enough to determine if they are observationally distinct from ULXs in spiral and starburst galaxies.

Some workers have claimed that most ULXs in elliptical galaxies are background objects (e.g., Irwin, Athey & Bregman 2003; Irwin, Bregman & Athey 2004). However, some elliptical galaxies *do have* more ULXs than is expected from background counts. A more complete analysis of the ULXs in elliptical galaxies is sorely needed, and should provide better insight to their nature.

3.4. *Implications from X-ray Variability Studies*

It is possible that objects other than a single accreting black hole system could produce X-ray luminosities $\geq 10^{39}$ erg s^{-1}. For example, some very young ($\lesssim$ 100 yr) supernovae are known to emit $\sim 10^{39}$ erg s^{-1} in X-rays. However, their X-ray emission typically fades or remains constant on timescales of $\lesssim 1$ yr (cf. Schlegel 1995). A cluster of ~10 or more "normal" luminous XRBs could also produce $\sim 10^{39}$ erg s^{-1}. However, Colbert & Ptak (2002) estimate random variability of $\gtrsim 50\%$ in over half of all ULXs, eliminating supernovae or XRB-clusters as likely scenarios. The brightest X-ray source in M82 brightened by a factor of 7 between two Chandra observations three months apart (Matsushita et al. 2000). Long-term variability of ULXs on timescales of months to years has been noted for ULXs in many nearby spiral galaxies: M81 (Ezoe et al. 2001, La Parola et al. 2001, Wang 2002, Liu et al. 2002), Ho II (Miyaji et al. 2001), M82 (Ptak & Griffiths 1999, Matsumoto & Tsuru 1999, Kaaret et al. 2001, Matsumoto et al. 2001), IC 342 (Sugiho et al. 2001, Kubota et al. 2001), Circinus (Bauer et al. 2001), NGC 4485/90 (Roberts et al. 2002b), M101 (Mukai et al. 2002), and M51 (Terashima & Wilson 2003).

Thus, variability on scales of months or longer is well-established. For periodic variability due to orbiting stars, Kepler's third law predicts very short times for orbits near the BH:

$$P = 1.73 \times 10^{-5} \frac{(a/\mathrm{km})^{\frac{3}{2}}}{(M/M_{\odot})^{\frac{1}{2}}} \mathrm{sec} = 3.65 \times 10^{2} \frac{(a/\mathrm{AU})^{\frac{3}{2}}}{(M/M_{\odot})^{\frac{1}{2}}} \mathrm{days} \tag{4}$$

where a is the semi-major axis of the stellar orbit. Measurements of both the orbital period and velocity can thus put constraints on the BH mass. Monthly X-ray monitoring can only sample orbits around ~100 $M_{\odot}$ BHs for stars at radial orbits of $\gtrsim 1$ AU (1.5×10^{8} km), where the probability of eclipsing is quite low. Thus, it is important to test for periodicity on much shorter timescales, especially when searching for evidence for IMBHs with M $\gtrsim$ 100 $M_{\odot}$.

There have been very few reports of variation on time scales less than a few weeks. There are currently three reported cases of variability on time scales of hours, all of which have been interpreted as possibly periodic. Roberts & Colbert (2003) report aperiodic variability on timescales of a few hundred seconds from NGC 6946 X-11. Bauer et al. (2001) observed one source in the Circinus galaxy to exhibit a count rate variation of a factor of 20, during a 67 ksec Chandra observation. Three peaks are seen, which are consistent with a 7.5 hour period. Bauer et al. (2001) discuss different mechanisms for this variability, including eclipses, modulation of the accretion rate, or a precessing jet. Sugiho et al. (2001) observed a ULX in the spiral galaxy IC 342 and found possible evidence for either a 31 hour or a 41 hour period, admittedly based on only two peaks. More recently, Liu et al. (2002) and Terashima & Wilson (2003) report more than 50% variation in count rate from a ULX in M51, with a time of 7620 ± 500 seconds between the two peaks seen.

It is tempting to interpret these periods as orbital periods. This would be highly constraining for the ~2 hour period of the M51 source, and would in fact imply that the companion is a $\sim 0.3\, M_{\odot}$ dwarf (Liu et al. 2002). However, it is premature to draw conclusions because at this point no source has been seen to undergo more than three cycles. This is a clear case in which sustained observations, especially of the putative 2 hour period, are essential. Only then will it be possible to separate models in which the period is orbital (in which case it should be highly coherent) from models in which the period is due to, e.g., disk modes, in which the modulation could be quasi-periodic. Furthermore, additional information (e.g. orbital velocity) is needed to constrain the BH mass.

Variability on very short timescales (seconds to minutes) can be detected to the same level of fractional RMS amplitude as variability on longer timescales, but the variability of sources from XRBs to AGN tends generally to decrease with increasing frequency. This means that variability at the few percent level would be detectable out to the Nyquist frequency of observations of the brightest ULXs (e.g., to 1 Hz in the XMM data power-density spectrum [PDS] of the M82 ULX; see Strohmayer & Mushotzky 2003). It would be well worth doing a systematic comparison of the broad-band power spectra of X-ray binaries, ULXs, and AGN, given that one expects the maximum frequency at which significant power exists to decrease with increasing mass. Although the lack of a fundamental theory of this variability limits our ability to draw rigorous conclusions (e.g., the stellar-mass black hole LMC X-3 has no detected variation at $\nu > 10^{-3}$ Hz; see Nowak et al. 2001), systematic differences in the power spectra could provide insight into the nature of ULXs.

The first, and so far only, quasi-periodic oscillation (QPO) in a ULX was reported by Strohmayer & Mushotzky (2003), based on XMM observations of the brightest point source in M82. For this high-luminosity ULX, they find a QPO at 54 mHz, with a quality factor $Q \sim 5$, with a fractional rms amplitude of 8.5%. At the time, the flux would imply a bolometric luminosity (if isotropic) of $4-5\times10^{40}$ erg s^{-1}. As discussed by Strohmayer & Mushotzky (2003), QPOs are usually thought to originate from disk emission, which if true makes this observation troublesome for a beaming interpretation. This is *not* because the frequency is low (for example, as mentioned by Strohmayer & Mushotzky 2003, a 67 mHz QPO has been observed with RXTE from GRS 1915+105, which has a dynamically measured mass of $14\pm4\,M_\odot$; see Morgan, Remillard, & Greiner 1997). The problem is instead that if the source is really a beamed stellar-mass black hole, the variability in the disk emission (which is nearly isotropic) would have to be of enormous amplitude to account for the observations. For example, even for a $20\,M_\odot$ black hole accreting at the Eddington limit, the beaming at $4-5\times10^{40}$ erg s^{-1} would need to be a factor of ~ 15, requiring intrinsic variability in the disk emission in excess of 100%. There are other sources in the XMM beam; the brightest of these sources has an equivalent peak isotropic luminosity of 3.5×10^{39} erg s^{-1}, comparable to the luminosity of 3.4×10^{39} erg s^{-1} (Strohmayer & Mushotzky 2003). For this source to produce the QPO would therefore require nearly 100% modulation, which seems unlikely. Furthermore, the QPO has a very narrow width ($\Delta\nu \approx 11$ mHz), which would be very difficult to sustain with the many photon paths from reflections from the focussing X-ray mirror in the beaming scenario. These observations therefore provide indirect evidence for the IMBH scenario, although caution is still required because the theory of black hole QPOs is not settled.

A recent XMM observation of the high-luminosity ULX NGC 4557 also shows evidence for an IMBH from X-ray timing analysis (Cropper et al. 2004). The PDS shows a break at a frequency of 28 mHz, which suggests a BH mass of $\sim$1300 $M_\odot$ if this break is associated with the upper break frequency seen in PDSs of AGNs (e.g., Markowitz et al. 2003). Note that not only does this ULX have $L_X \approx 2 \times 10^{40}$ erg s^{-1}, and is therefore not easily explained by the mild-beaming HMXB model, but it also shows evidence for a cool MCD disk (Table 1). All of these items suggest that this ULX is an accreting IMBH.

3.5. *Energetics of X-ray Source based on Optical Spectra*

Studies of the environments around ULXs have led to some interesting results. Pakull & Mirioni (2002) find that the ULX in the dwarf galaxy Holmberg II has an optical nebula around it with substantial He II 4686Å emission. This line is produced by the recombination of fully ionized helium, which requires for its excitation a high-energy source. Based on models of X-ray reprocessing where the X-ray source is located inside the nebula, Pakull & Mirioni (2002) conclude that the optical radiation is consistent with an isotropic, X-ray source and not with significant X-ray beaming, which would produce far fewer (a factor $\lesssim$ 0.1) EUV ionizing photons. However, there is substantial uncertainty in the correction factor from optical line flux to X-ray luminosity, so work of this type needs to be repeated for a number of sources in order to draw firmer conclusions. Integral field spectroscopic observations by Roberts et al. (2002a) indicate that many of the ULXs are actually located in cavities free from optical line-emitting gas, although it is not clear whether this is due to the absence of gas (e.g., gas cleared away by shocks), or to highly ionized gas irradiated by the ULX. Optical spectral analyses of some of these ULX nebulae show evidence for both shocks and photo-ionization (Pakull & Mirioni 2003). This is intriguing, as there are now at least two ULXs that are highly variable (and thus are accreting compact objects), but are directly associated with optical supernova remnants (IC 342 X-1, Roberts et al. 2003, and MF16 in NGC 6946, Roberts & Colbert 2003; note that the precise mechanism for the ionization is not rigorously established in these cases, and that jet ionization is a possible alternative to supernova shock ionization). Future multiwavelength studies of optical ULX nebulae and ULXs in SNRs may provide important clues as to how ULXs form, or at least how they become "active" X-ray sources. When emission-line spectra of individual stellar companions to ULX BHs, assuming they exist, can eventually be obtained, then this will help constrain orbital the orbital velocity, and thus the BH mass (Eqn. 4). However, high-throughput (diam. $\gtrsim$ 8 m) optical telescopes will be required to obtain single-star spectra at distances of more than a few Mpc.

3.6. *Additional Evidence*

Although Fe K lines (6.4$-$7.0 keV) are not usually strong in BH XRBs, Strohmayer & Mushotzky (2003) found that the famous M82 ULX has a very broad Fe K line in an XMM spectrum. This is not easily explained by beaming models and thus this observation provides indirect evidence for an IMBH in this high-luminosity ULX. Further Fe K line studies of ULXs will help to determine if they can be used as reliable diagnostics for the BH mass measurements, and ULX geometry.

4. Summary and Conclusions

In summary, while many of the low-luminosity ULXs with $L_X \lesssim 5 \times 10^{39}$ erg s^{-1} are consistent with mild-beaming HMXB models (e.g., King et al. 2001, King 2003), there are a significant number of ULXs that are not. The ULXs that do show evidence for isotropically-emitting sub-Eddington IMBHs – in the form of "cool disks," powerful and narrow QPOs, or suggestive breaks in their PDS – are all high-luminosity ULXs, with $L_X \gtrsim 10^{40}$ erg s^{-1}, precisely those that are not well explained by mild beaming. We emphasize that X-ray or optical/NIR observational diagnostics are not yet able to sytematically determine the mass, emission anisotropy, or fuel source of ULXs. Since the formation mechanism for IMBHs and IMBH-ULXs is not well understood, it is not absolutely certain what fraction of either the "low-luminosity" ULXs or the "high-luminosity" ULXs have IMBHs. This holds for the ULXs correlated with star-formation in spiral and starburst galaxies, as well as the "type-II" (?) ULXs in elliptical galaxies.

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