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X-ray observations of ultraluminous X-ray sources

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Abstract Ultraluminous X-ray sources (ULXs) are amongst the most intriguing of X-ray source classes. Their extreme luminosities - greater than 10^{39} erg s^{-1} in the $0.3 - 10$ keV band alone - suggest either the presence of black holes larger than those regularly encountered in our own Galaxy (the Galactic centre excepted), or sources apparently radiating well above the Eddington limit. We review the insights afforded us by studies of their X-ray emission, focussing on what this reveals about the underlying compact object. In particular, we discuss recent deep observations of ULXs by the *XMM-Newton* observatory, and how the unprecedented data quality provided by this mission is starting to discriminate between the different physical models for these extraordinary X-ray emitters.

Keywords black hole physics – X-rays: binaries – X-rays: galaxies

1 Introduction

The first imaging observations of galaxies beyond our local group were conducted by the *Einstein* observatory in the period 1978 - 1981, and revealed a somewhat unexpected result: many galaxies hosted one or more extra-nuclear sources with X-ray luminosities well in excess of those typically observed in our own galaxy and its nearest neighbours (Fabbiano 1989). At the time it was rather presciently acknowledged that if these were individual X-ray sources, their X-ray luminosity was difficult to explain without invoking massive black holes, or super-Eddington emission (Fabbiano & Trinchieri 1987).

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Throughout the 1990s the *ROSAT* mission observed hundreds of nearby galaxies, detecting many more of these sources (Colbert & Mushotzky 1999; Roberts & Warwick 2000; Colbert & Ptak 2002; Liu & Bregman 2005). These observations revealed little of the actual nature of these objects, except that a fraction can be associated with recent supernovae, for example SN 1986J in NGC 891 (Bregman & Pildis 1992). However, subsequent analysis of samples of these objects has given us some insights into their demographics, for example with estimates of between only 1 in 8 and 1 in 4 major galaxies hosting one of these X-ray bright objects with an observed luminosity in excess of 10^{39} erg s^{-1} (Ptak & Colbert 2004; Liu, Bregman & Irwin 2006). **It is this extreme luminosity threshold, in combination with an extra-nuclear location, that we use to define this class of so-called "ultraluminous X-ray sources" (ULXs)**.

A clearer insight into the nature of the majority of ULXs was provided by *ASCA* observations in the years around 2000. Most notably, the novel wide bandpass CCD spectroscopy afforded by *ASCA* allowed the spectra of many ULXs to be measured over the $0.5 - 10$ keV range for the first time. This revealed some of them to be well-fitted by the multi-colour disc blackbody model, that describes the optically-thick thermal X-ray emission of an accretion disc around a black hole (Makishima et al. 2000). Additionally, multi-epoch observations of some ULXs saw them apparently transiting between spectral states described by either the multi-colour disc blackbody model or a power-law, similar to the transition between low- and high-states seen in Galactic black hole X-ray binaries (Kubota et al. 2001). This gave the first strong corroborating evidence - on top of their extraordinary luminosities - that most ULXs are accreting black holes. However, these results were not without problems, notably that the disc temperatures measured by Makishima et al. (2000) were far too hot to be reconciled with the masses suggested by the high luminosities of the sources (see below). It was suggested that this could be explained by rapidly spinning (Kerr metric) black holes, in which the inner edge of the accretion discs are far closer to the black hole - and therefore hotter - than in the non-rotating (Schwarzschild) case.

Our understanding of the nature of ULXs has increased immensely over the last $\sim$ half decade due to the excellent capabilities of the *Chandra* and *XMM-Newton* observatories, and follow-up studies across the range of the electromagnetic spectrum. In this paper we mainly concentrate on contributions to the understanding of ULXs garnered from spectroscopic and timing studies using the European Photon Imaging Camera (EPIC) on *XMM-Newton*. However, first we will summarise some of the main arguments relating to the nature of ULXs.

1.1 A new class of black holes?

The Eddington limit for the maximum radiative luminosity possible from the spherical accretion of matter[1] on to a black hole can be expressed as

$$L_{\rm Edd} = 1.3 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1} \quad (1)$$

where M is the mass of the accreting object in solar masses (Makishima et al. 2000). Hence, for an object obeying the Eddington limit, at a luminosity of 10^{39} erg s^{-1} its mass must be $\gtrsim 7.7 M_\odot$. For an accretion rate of ~ 10 per cent of that required to reach the Eddington limit - a fairly typical accretion rate for a high-state black hole - this means that a $\sim 77 M_\odot$ black hole is required for the source to be emitting at 10^{39} erg s^{-1}. **So, if ULXs obey the Eddington limit, they must contain massive black holes.** But how massive?

Dynamical friction arguments imply that these sources cannot be misplaced super-massive black holes, sitting outside the nuclei of the host galaxies, as such massive objects should sink to the centre of the galaxies in a Hubble time (Tremaine, Ostriker & Spitzer 1975). However, the Eddington limit argument also rules out the stellar remnant black holes that we know of in our own galaxy, with masses in the range $3 M_\odot < M_{\rm BH} < 18 M_\odot$ (McClintock & Remillard 2006), for all but the mildest of ULXs ($L_{\rm X} \lesssim 2.3 \times 10^{39}$ erg s^{-1} at the Eddington limit). Indeed, Fryer & Kalogera (2001) calculate that the vast majority of black holes formed from the evolution of a single massive star will have mass $< 20 M_\odot$, clearly inadequate to power the brighter end of the ULX population (if obeying the Eddington limit).[2] These limits led to the suggestion that ULXs may be the first observational evidence for a new, $\sim 10^2 - 10^5 M_\odot$ *intermediate-mass* class of accreting black holes (IMBHs) (Colbert & Mushotzky 1999) (see also Miller & Colbert (2004) for more on IMBHs).

The strongest supporting evidence in favour of IMBHs in ULXs comes from the high signal-to-noise broad-band X-ray spectroscopy enabled by *XMM-Newton*[3]. In particular, Miller et al. (2003) showed that the spectra of two ULXs in NGC 1313 could be well fitted by the same absorbed multi-colour disc blackbody plus power-law continuum model that is commonly used as the empirical model to fit Galactic black hole binaries, with the key difference being a lower disc temperature in ULXs than Galactic black holes (0.1 – 0.3 keV versus ~ 1 keV, respectively). This is crucial because, for a fixed accretion rate, the temperature of the inner edge of a standard accretion disc scales with the black hole mass as $T \propto M^{-0.25}$, i.e. a cooler disc implies a bigger black hole. In fact, the black hole masses for the ULXs in NGC 1313 were estimated to be of the order $\sim 1000 M_\odot$. Many ULX spectra were quickly shown to agree with this result (Miller, Fabian & Miller 2004a; Cropper et al. 2004; Dewangan et al. 2004; Roberts et al. 2005), with Miller, Fabian, & Miller (2004b) demonstrating that such sources lie in a different region of disc luminosity - disc temperature space than Galactic black holes, emphasizing their potentially different natures.

Other factors also argue for the presence of IMBHs in at least some ULXs. For example, X-ray timing characteristics such as the detection of quasi-periodic oscillations (QPOs) in the X-ray fluctuation Power Spectral Densities (PSDs) of some ULXs argue that their emission is isotropic, supportive of IMBHs assuming that the Eddington limit is not exceeded (see Section 3 for more details). Similarly, simple photon counting arguments for high-excitation optical line emission regions near ULXs make the same argument (Pakull & Mirioni 2002; Kaaret et al. 2004). The source for which most evidence stacks up is M82 X-1, which through a combination of its extreme luminosity ($L_{\rm X,peak} \sim 10^{41}$ erg s^{-1}), co-location with

[1]This equation is strictly correct only for ionised hydrogen; the accretion of helium and/or heavier elements will raise this limit.

[2]Fryer & Kalogera (2001) do note that it is possible that very massive, low metallicity stars leave a sufficiently massive remnant core after the wind mass-loss phase ($\gtrsim 42 M_\odot$) to collapse directly to a massive black hole. However such objects would be comparatively rare.

[3]Although similar results have been obtained with *ASCA* (Colbert & Mushotzky 1999) and *Chandra* (Kaaret et al. 2003; Roberts & Colbert 2003; Roberts et al. 2004).

the young, dense stellar cluster MGG 11, and QPO detections is the best known candidate for an IMBH (Kaaret et al. 2001; Strohmayer & Mushotzky 2003; Portegies Zwart et al. 2004; Mucciarelli et al. 2006). However, it is possible this source is an atypical ULX; it may be the nucleus of an accreted dwarf galaxy (King & Dehnen 2005).

1.2 The problem(s) with IMBHs

Unfortunately, ULXs as a population are not trivially explained by the presence of IMBHs. There are in fact many arguments as to why the majority of ULXs cannot be IMBHs, or at least IMBHs of the size inferred from cool accretion discs ($\sim 1000 M_{\odot}$). Two arguments stand out as the principle reasons the ULX population is not dominated by (large) accreting IMBHs. Firstly, the luminosity function of X-ray sources in galaxies (XLF) has an unbroken power-law form for 5 decades up to a luminosity of $\sim 2 \times 10^{40}$ erg s^{-1} (Grimm, Gilfanov & Sunyaev 2003; Swartz et al. 2004). This break occurs at $\sim$ 10 per cent of the Eddington luminosity for the $\sim 1000 M_{\odot}$ black holes inferred from ULX spectroscopy. This is extremely troublesome for a ULX population dominated by these large IMBHs, as they would not only have to contrive to take over the XLF smoothly from Galactic black holes at $\sim 10^{39}$ erg s^{-1}, but then cease accreting at 10 per cent of Eddington. No other accreting source class behaves in this manner. This instead argues that ULXs are dominated by black holes of mass up to $\sim 100 M_{\odot}$ (or less if the Eddington limit can be exceeded).

The second strong argument against IMBHs comes from the association of ULXs with star formation. Early observations with *Chandra* revealed that starburst galaxies have populations of multiple ULXs (Fabbiano, Zezas & Murray 2001; Lira et al. 2002; Roberts et al. 2002), an unusual result given the expectation of less than one in four galaxies on average possessing even one ULX. The obvious conclusion from this is that the ULXs are intrinsically linked to the ongoing star formation occuring in those galaxies. However, the direct co-location of ULXs with the star formation, most notably seen in the Cartwheel galaxy (Gao et al. 2003), implies that they must be (relatively) short-lived, which requires successive generations of ULXs to be formed over the duration of the star formation event. King (2004) pointed out that if these ULXs were all large IMBHs, then an infeasibly large proportion of the available star forming mass would end up in the form of IMBHs. Hence the majority of ULXs in star forming regions cannot be powered by IMBHs.

1.3 The most extreme stellar-mass black holes?

If ULXs in starburst galaxies are not IMBHs, then what are they? The obvious solution is to turn to a class of objects we would expect to find there anyway: high-mass X-ray binaries. The problem then becomes one of making such objects appear as ULXs. Assuming Galactic black hole masses for these objects (i.e. $M < 20 M_{\odot}$) one then needs to either make such objects *actually* break the Eddington limit, or to make them *apparently* exceed it. Lower-luminosity and/or Eddington-limited objects could appear as bright ULXs due to beaming, either through relativistic boosting of their X-ray emission along our line-of-sight (Körding, Falcke & Markoff 2002) or through collimation of their radiation - probably by a geometrically-thick accretion disc - such that it only escapes into a fraction of the sky (King et al. 2001).[4] Alternatively, models have been suggested whereby actual super-Eddington luminosities are achieved and maintained, at factors $\lesssim 10$ above the Eddington limit (Begelman 2002; Ebisawa et al. 2003; Heinzeller & Duschl 2007).

Regardless of the processes involved, a very basic requirement of most models is that sufficient fuel is available for the super-Eddington mass transfer rates needed in ULXs. Rappaport, Podsiadlowski & Pfahl (2005) show that this is indeed the case for high-mass X-ray binary systems containing a stellar-mass black hole and a massive donor star, that can in fact sustain super-Eddington mass transfer over a very large fraction of their lifetimes. Other authors suggest that the possible hyper-Eddington mass transfer rates in SS 433-like objects fuel ULXs (Begelman, King & Pringle 2006; Poutanen et al. 2007). Furthermore, where optical stellar counterparts to ULXs have been identified, primarily by *HST*, they tend to be blue and of an appropriate magnitude for the young, massive stars required to fuel ULXs (Roberts et al. 2001; Liu, Bregman & Seitzer 2004; Kuntz et al. 2005). This provides compelling support to the argument that ULXs are high-mass X-ray binaries.

Finally, it is reassuring to know that the Eddington limit is broken in practise in Galactic black holes - McClintock & Remillard (2006) give several examples, most notably that of GRS 1915+105. This source is sufficiently luminous (at $\sim 10^{39}$ erg s^{-1}) to appear as a ULX if viewed from outside our galaxy,

[4] QPO detections and high-excitation optical line measurements argue against all but the mildest forms of beaming in some ULXs. Additionally, the lack of detectable radio emission and/or rapid, high amplitude X-ray variability in most ULXs argues against relativistic beaming - though see Krauss et al. (2005) for a possible counter-example.

and (for its known black hole mass) has consistently displayed peak luminosities in excess of the Eddington limit over the ~ 15 years of its outburst to date (Done, Wardziński & Gierliński 2004). As the Eddington limit is exceeded in known sources, there is no reason this cannot also be occuring in ULXs.

We are therefore left with the situation where most ULXs could be explained by stellar-mass black holes that are either super-Eddington, or subject to some sort of beaming. However, it is still difficult to reconcile the most extreme ULXs - those above 10^{40} erg s^{-1} - with simple stellar-mass black hole systems. Larger black holes would still provide an obvious solution. But are they really the $\sim 1000 M_{\odot}$ black holes inferred from ULX spectroscopy?

2 X-ray spectroscopy

2.1 The IMBH model, and other solutions

As we have already discussed, the strongest support for ULXs containing IMBHs comes from X-ray spectroscopy, and in particular the good fits obtained to ULX spectra using the same multi-colour disc plus power-law continuum model used for Galactic black holes. To date more than 10 ULXs with decent *XMM-Newton* spectra have been shown to have their spectral fits improved substantially (compared to, say, a simple absorbed power-law model) by the use of this model, in many cases producing a statistically acceptable fit to the data. An ubiquitous feature of these fits is a cool disc which, as we have already seen, when interpreted at face value implies the presence of an IMBH with mass of the order $\sim 1000 M_{\odot}$.

But should we take this mass at face value? There is good reason not to. The mass estimates deriving from the multi-colour disc blackbody model assume that this is the dominant emission component in the X-ray spectrum (essentially, that the black hole is in the "high" state). Unfortunately, in ULXs fit by this "IMBH model" (which here specifically refers to an empirical model composed of a cool disc plus harder power-law) it is very evidently not. We demonstrate this graphically for the IMBH candidate ($L_{\rm X} > 10^{40}$ erg s^{-1}) NGC 1313 X-1 in Fig 1, where it is obvious that the power-law dominates the flux within the *XMM-Newton* bandpass. In fact, the disc typically emits no more than 20 per cent of the $0.3 - 10$ keV flux of ULXs in this model (Stobbart, Roberts & Wilms 2006). Worse still, the power-law slopes measured by this model are somewhat on the low side for the classic high state ($\Gamma \sim 1.6 - 2.5$ for IMBH models, compared to $\Gamma \sim 2.1 - 4.8$ in Galactic high state sources; cf. McClintock & Remillard

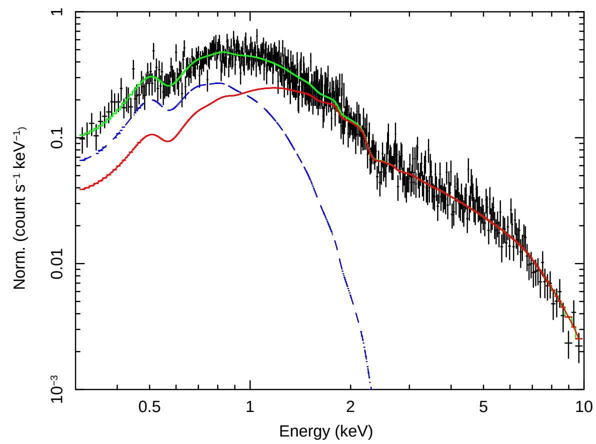

Fig. 1.— *XMM-Newton* EPIC-pn spectrum of NGC 1313 X-1, obtained on 2000 October 17, and reprocessed with SAS version 6.5.0. The data points are shown in black, with the best-fitting IMBH model in green. The contributions to this model of the multi-colour disc black body component (with $kT_{\rm in} \sim 0.2$ keV) and the power-law continuum ($\Gamma \sim 1.7$) are shown by blue (dashed) and red lines respectively. The X-ray emission detected by *XMM-Newton* is clearly dominated by the power-law component, and not the disc.

(2006)). This makes black hole masses obtained by this method (at the very least) questionable.

Furthermore, the IMBH model is not the only model that fits ULX spectra. Several sources have been identified in which a variant of this model, where the disc component fits to the hard end of the spectrum, provides a far superior fit (Stobbart, Roberts & Warwick 2004; Foschini et al. 2004; Feng & Kaaret 2005). As discussed by Roberts et al. (2005) this variant of the empirical black hole spectrum model does not provide a physical model for the X-ray emission - for example there cannot be sufficient photons present in the vicinity of the black hole to produce the dominant soft power-law through Compton up-scattering. However, the crucial point is that there is distinct curvature (which can also be described as a spectral "break") present above 2 keV in these data, for which there must be a physical explanation.

2.2 Re-evaluating ULX spectra from XMM-Newton

Given the question marks about the IMBH model, and this second, "inverted" model that fit to some ULXs, we set out to examine the best available *XMM-Newton* ULX datasets (from the beginning of 2005). Specifically, in Stobbart, Roberts & Wilms (2006) we set out to ask the questions

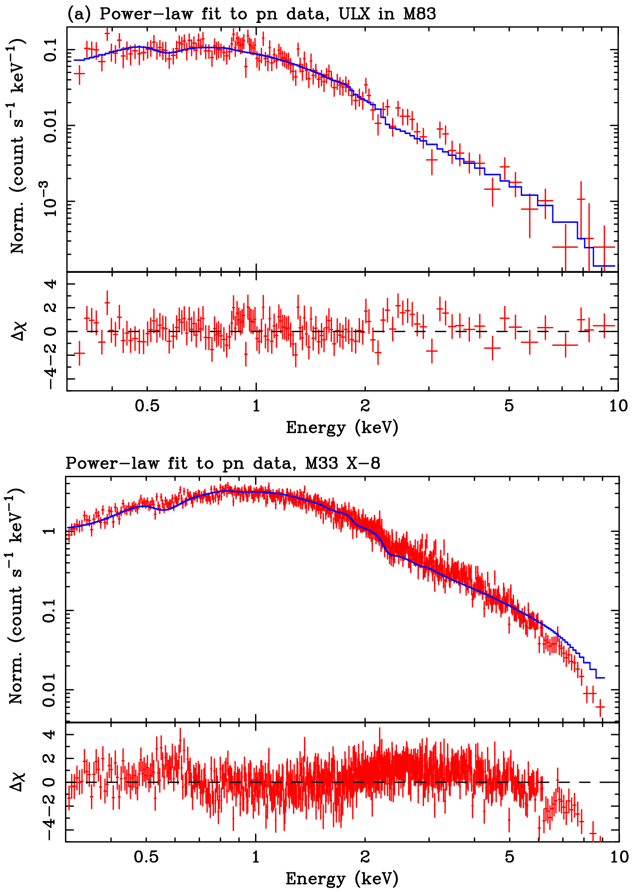

Fig. 2.— *XMM-Newton* EPIC-pn data for two ULXs in the Stobbart, Roberts & Wilms (2006) sample. In both cases we show the data (in red) and best-fitting power-law continuum model (in blue) in the top panel, with the $\Delta\chi$ residuals for the fit shown in the bottom. The ULX in M83 was adequately fit by a power-law continuum, whereas M33 X-8 was not.

- How easy is it to distinguish the IMBH and inverted models given the available quality of data?
- With what frequency do these models work for the available data?
- Can we say anything about the physics of the inverted model?

To do this we selected data sets with at least a few thousand counts (EPIC-pn and MOS combined) per ULX. We show examples of the low and high end of the data quality for ULXs in our sample in Fig 2. The data was of sufficient quality to statistically rule out simple multi-colour disc blackbody fits to all the sources, and power-law continua in 8/13 cases.

As simple models were inadequate for all but the poorest data, we next attempted empirical two-component models, beginning with the IMBH model. This provided acceptable fits to 8/13 sources, which all had the classic $\sim 0.1-0.3$ keV cool disc signature. Unfortunately, they all also displayed the problems inherent in mass measurements from this model, i.e. dominant, hard power-law continua. We then attempted fits using the inverted model. This also provided good fits to 8/13 data sets, parameterised by $\Gamma \sim 2.5-4.3$ power-law photon indices, $kT_{\rm in} \sim 0.9-2.7$ keV inner-disc temperatures, and a very roughly 50/50 split between the flux contribution of the two components in the *XMM-Newton* band. Interesting, the six lowest quality data sets provided acceptable fits to both models, demonstrating that either very high quality X-ray data, or a secondary diagnostic, is required to distinguish the models.

This key diagnostic is found at energies above 2 keV, where disc-domination leads to distinct curvature in the spectrum, whereas a dominant power-law has an unbroken spectrum. We tested for this characteristic signature by comparing power-law fits to broken power-law fits on the > 2 keV data for each ULX. In total we found 8 ULXs showing evidence for breaks, at significance levels between $3-10\sigma$. Three of these were expected, as they were from sources clearly better fit by the inverted model. However, five sources that were either ambiguous or well-fitted by the IMBH model also showed a significant break. Of the remaining (unbroken) source fits, in three cases this may be attributable to very poor data quality above 2 keV. This simple test therefore demonstrates that spectral breaks are present in the majority of ULXs (notably, across the whole range of luminosity) where the data quality above 2 keV is sufficient to detect them.[5]

In order to investigate the physics of this break further, we attempted spectral fits using a physically self-consistent accretion disc plus Comptonised corona model, specifically using an absorbed DISKPN + EQPAIR model in XSPEC. Where appropriate, parameters were tied to assumed values (based on experience with Galactic systems), so that the model had only one more degree of freedom than the empirical (two-component) models, but sufficient scope for variation within the model parameters was allowed such that the outcomes were not pre-judged. This model gave superior fits to the empirical models, with 11/13 ULXs providing statistically-acceptable fits (with one more only

[5]A by-product of this spectral break/curvature is that the best empirical fits are provided by models composed of two thermal components, in particular a combination of a blackbody with a multi-colour disc blackbody model - see Stobbart, Roberts & Wilms (2006) for more details.

marginally unacceptable). Two remarkable characteristics were common to most fits: firstly, the ULXs still showed apparently cool discs; but secondly, the coronae (in 9/12 cases) appeared **optically-thick** (with $\tau > 8$ - in several cases much higher). It is this optical thickness in the corona that is responsible for the curvature in the 2 - 10 keV spectrum. Furthermore, this distinguishes ULXs from galactic black holes, that do not *typically* show such coronae. The reason their coronae are empirically modelled by power-laws is that they are optically-thin. This therefore suggests ULXs are operating in a different accretion mode to the classic states of Galactic black holes.

2.3 Possible scenarios

So what is happening in these sources? One physical scenario that could lead to the production of both a cool disc component and an optically-thick corona is suggested by Zhang et al. (2000), based on an analogy with the solar corona. This "sandwich" model consists of a cool inner accretion disc, seeding an outer, warm (~ 1 keV) and optically-thick ($\tau \sim 10$) accretion disc layer with ~ 0.2 keV photons. This could readily provide both components we derive from our spectra, though the geometry required to see the cool photons through the warm layer is problematic. A second scenario is based on observations of a strongly-Comptonised very high state observed in the Galactic black hole XTE J1550-564 by Done & Kubota (2006). In this source they also detect a cooler-than-expected disc, alongside an optically thick corona (though neither phenomena are as extreme as detected in the ULXs), and suggest that this is due to energetic coupling of the inner-disc with the corona. In such a system, the energy released by the extreme accretion rate is sufficient to launch an optically-thick corona, which obscures (and, through extracting the launch energy, cools) the central regions of the disc. One therefore predominantly sees the cooler outer regions of the accretion disc, in addition to the optically-thick corona. As this state occurs at a very high accretion rate in XTE J1550-564, this suggests that ULXs operate at similar - or higher - accretion rates. This must be at around the Eddington limit, suggestive of black hole masses up to $\sim 100 M_{\odot}$.

Further work has now revealed this > 2 keV break in other ULXs - for example in M82 X-1 (Okajima, Ebisawa & Kawaguchi 2006) and Ho IX X-1 (aka M81 X-9) (Dewangan, Griffiths & Rao 2006). Other ideas have been also been postulated for its origin, and the full observed X-ray spectrum for ULXs. Several authors have discussed ULXs in the context of slim disc models (Watarai, Mizuno & Mineshige 2001). In particular, they note that as the Eddington limit is approached, the structure of the accretion disc should change. This would manifest itself as a change in the model disc profile, $T(r) \propto r^{-p}$, where standard discs have $p = 0.75$, and slim discs $p = 0.5$. Recent work where a variable disc profile model is fit to ULX spectra does indeed show values of $p \sim 0.6$, suggestive of slim discs (Vierdayanti et al. 2006; Mizuno et al. 2007). A second idea, put forward by Goncalves & Soria (2006), draws from observations of AGNs with outflows. In their model ULXs have an intrinsic very high state spectrum (steep power-law form, i.e. $\Gamma > 2.5$), that is modified by absorption from material in an ionised fast outflow. This effectively takes a "bite" out of the spectrum in the $\sim 1-4$ keV range, resulting in the apparent soft excess and > 2 keV spectral break features. We note that the post-break power-law slopes measured by Stobbart, Roberts & Wilms (2006) are indeed consistent with a very high state spectrum. Finally, work by Poutanen et al. (2007) has related ULX spectra to the expected spectra from super-critically accreting black holes viewed with the accretion disc close to face-on. In such sources - SS 433 may be an example, viewed edge-on - the break originates from a direct view of the spectrum of the inner-regions of a hot accretion disc.

All these models have a common theme - accretion at around or above the Eddington rate. This strongly suggests black holes of $\lesssim 100 M_{\odot}$, rather than the $\sim 1000 M_{\odot}$ IMBHs formerly proposed.

2.4 Spectral variability

Snapshot observations, though useful, can only tell us so much about accreting sources. As 10 years of *RXTE* observations have shown, for example with Galactic black holes, further progress can be made by considering how these observed spectra change with time (McClintock & Remillard 2006). As ULXs are in general too X-ray faint for monitoring missions like *RXTE* (with the exception of M82 X-1 - see Kaaret, Simet & Lang (2006)), the best one can do is to use monitoring campaigns of snapshot observations separated by days – months.

Unfortunately, to date very few campaigns have been pursued. Where they have been undertaken, sources are observed to behave in two distinct ways. Some ULXs behave as would be expected from classic Galactic black hole behaviour, i.e. they get spectrally softer as their flux increases. In contrast, other ULXs behave in the opposite fashion - they get harder (Fabbiano et al. 2003; Dewangan et al. 2004; Jenkins et al. 2004; Feng & Kaaret 2006a,b; Soria et al. 2007). We have undertaken such a campaign for the

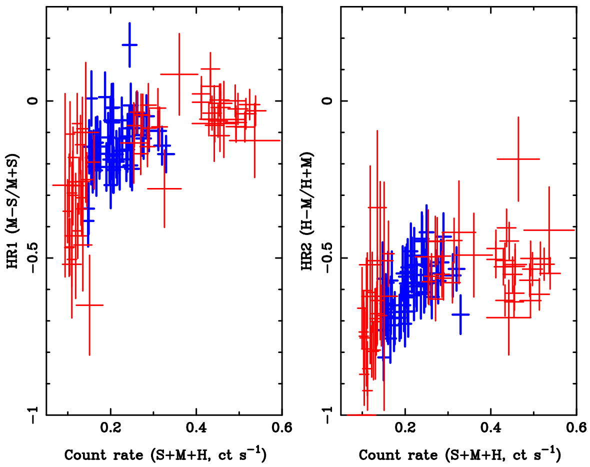

Fig. 3.— *Chandra* ACIS-S hardness ratio - count rate plots for NGC 5204 X-1. The bands used are $S = 0.3 - 1$ keV; $M = 1 - 2$ keV; $H = 2 - 8$ keV. Blue data points are from an initial 50-ks observation, with data from ten 5-ks follow-ups shown in red. The ULX spectrum clearly hardens as its flux increases.

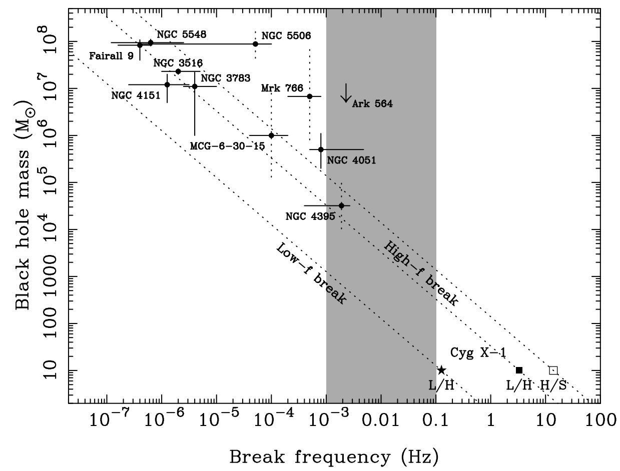

Fig. 4.— A simplified linear relationship between black hole mass and PSD break frequency for Cygnus X-1 and a number of AGN. This plot is a reasonable approximation for the $T_{\rm break} \propto M_{\rm BH}^{1.12} \dot{m}_{\rm Edd}^{-0.98}$ relationship found by McHardy et al. (2006), assuming sources at the Eddington limit (where $T_{\rm break}$ is the break timescale, $M_{\rm BH}$ is the black hole mass, and $\dot{m}_{Edd}$ is the accretion rate in Eddington units). Note that sub-Eddington accretion rates move the break to the left on this plot (and vice versa). We shade the region for which *XMM-Newton* observations are sensitive, showing that this coincides with IMBH-like masses. *Courtesy S. Vaughan.*

ULX NGC 5204 X-1 using *Chandra* data, with observations separated by days – weeks, and find that it behaves in the latter mode (Roberts et al. 2006) - see Fig 3. In particular, we show that this behaviour can be modelled as changes in the temperature of the optically-thick component of a cool accretion disc plus thick corona model, with the corona heating up as the luminosity of the ULX increases. This behaviour was also seen in the strongly-Comptonised very high state of XTE J1550-564 (Kubota & Done 2004; Soria 2007), confirming the viability of the optically-thick corona model for this ULX.

3 X-ray timing

Perhaps the most fundamental timing signal from a ULX is an X-ray periodicity, as it can be used as a first step towards establishing the orbital characteristics of the underlying binary system. However, such measurements are not very common, with the best detections coming in a couple of cases where eclipses have been found (Bauer et al. 2001; David et al 2005; Fabbiano et al. 2006). Though other claims have been made, they suffer from a lack of data - most are based on $\ll 10$ cycles, and require confirmation through further observations. In the absence of periodicities, the most useful timing diagnostic is Power Spectral Density (PSD) measurements for ULXs.

3.1 Power Spectral Densities for ULXs

The shape of the fluctuation PSD for ULXs is potentially a very powerful tool for ULXs. In particular, the characteristic frequency of breaks in the PSD slope can be used to infer masses based on a direct scaling of properties between Galactic black holes and AGN - see McHardy et al. (2006). In Fig 4 we demonstrate this concept using a simple linear scaling of black hole mass to break frequency, and show that the 10 - 1000 s timescales over which *XMM-Newton* observations are most sensitive to measuring breaks matches well with that in which one might find IMBHs.

Unfortunately, ULXs do not generally show much short-term variability (Swartz et al. 2004), with very few examples displaying sufficient variability power to establish a PSD from (Feng & Kaaret 2005). However, some measurements have been made. Cropper et al. (2004) detected a putative break at 28 mHz in the PSD of NGC 4559 X7, which they suggest supports the case that it harbours a $\sim 1000 M_\odot$ black hole, although the presence of this spectral break is now disputed (Barnard et al. 2007). Another detection of a break frequency was made by Soria et al. (2004), who found a break at 2.5 mHz in the PSD of NGC 5408 X-1. When the shape of the PSD either side of the break was considered, the authors derived a mass of $\sim 100M_\odot$ for this ULX. Finally, Dewangan, Titarchuk & Griffiths (2006) find a break at $\sim$ 34 mHz in the PSD of M82 X-1, from which they infer a mass in the $25 - 520M_\odot$ range for the underlying black hole.

In 2004 we were awarded a 100-ks *XMM-Newton* observation in order to derive a PSD for the nearby, luminous ULX Holmberg II X-1 (Goad et al. 2006). However, we found that it displayed no strong variability during the observation. In fact, through a PSD analysis we were able to demonstrate that the fractional variability amounted to less than a few per cent *rms* over time scales of minutes to hours. This variability power is less than that observed in classic high and very high state (red noise) PSDs. The PSD could instead be consistent with the low/hard state, but the energy spectrum for Ho II X-1 is closer to a very high state spectrum (in fact, it displays a cool disc plus optically-thick corona spectrum). One solution is that the source could be in a state similar to the 'χ'-class of GRS1915+105, in which the source is in a very high state, but its PSD is band-limited (i.e. all its variability power is limited to a narrow frequency band). As we do not see this band-limited variability, it is likely to be at higher frequencies than we are sensitive to in our PSD. This means the black hole must be small. In fact, we calculate a limit of $\lesssim 100M_\odot$ for Ho II X-1 from the lack of variability.

3.2 QPOs

A second feature of PSDs that has diagnostic potential for ULXs are quasi-periodic oscillations (QPOs). In fact, the detection of 3:2 ratio twin-peak high-frequency QPOs at $\sim$ 1 Hz would be strong evidence for the presence of an IMBH (Abramowicz et al. 2004) (though scaling from Galactic systems implies such a measurement is unlikely even in the medium term). Low frequency QPOs, on the other hand, have now been detected in a handful of ULXs (Strohmayer & Mushotzky 2003; Dewangan, Griffiths & Rao 2006; Mucciarelli et al. 2006; Strohmayer et al. 2007). However, this type of QPO does not provide a clear, unambiguous mass estimate. For example, the detection of a QPO in NGC 5408 X-1, even with the additional diagnostics of a break frequency and a second (4:3 ratio) possible QPO, could imply mass estimates anywhere in the range $100 - 1000M_\odot$ dependent upon the assumptions made (Strohmayer et al. 2007). Despite this, QPOs are telling us one thing - as they are a coherent signal, their detection rules out all but the mildest forms of beaming in ULXs where they are present.

4 Concluding remarks

New observational evidence is now pointing away from the interpretation of ULXs as the $\sim 1000M_\odot$ black holes inferred from simple cool disc plus power-law spectral models. Putting to one side the inherent problems with the dominant, hard power-law component derived from this model, the crucial evidence in this matter is the spectral break above 2 keV detected by Stobbart, Roberts & Wilms (2006). This is completely unexpected and inexplicable in the context of the simple $\sim 1000M_\odot$ black hole interpretation for ULXs. Indeed, it suggests physical characteristics that have more in common with Galactic sources accreting at around the Eddington limit. This implies much smaller black hole masses - of the order $\sim 100M_\odot$ or less - for ULXs.

Are ULXs then stellar-mass black holes that are radiating at super-Eddington rates, i.e. factors of $\lesssim 10$ above the Eddington limit for most ULXs, assuming masses of $< 20M_\odot$? Though this is feasible, it is perhaps not necessary. Almost all ULXs could trivially be explained (at least in luminosity terms) by accreting black holes with masses of a few tens of $M_\odot$, consistent with their spectra suggesting they are accreting at around (including slightly above) the Eddington limit. Interestingly, results based on optical observations of ULX counterparts are suggesting a similar conclusion. For example, a possible radial velocity variation in a He II line detected from the optical spectrum of NGC 1313 X-2 by Pakull, Grise & Motch (2006) suggests a small black hole mass. Furthermore, irradiation models of donor stars in ULXs, when combined with optical colours, suggest black hole masses of the order $\lesssim 100M_\odot$ (Copperwheat et al. 2007). A final piece of the puzzle is that the creation of such black holes may be possible in the young stellar populations that we generally find ULXs co-habiting with, from the merging of a binary composed of very massive early-type stars (Belczynski et al. 2006) (or, alternatively, see footnote 2). This could yield the black holes with masses of up to $\sim 100M_\odot$ that we are potentially finding in ULXs.

Hence it now appears that we can tentatively conclude that the vast majority of ULXs could harbour the slightly bigger cousins of the Galactic black holes we are familiar with, rather than their far larger distant relatives. Should we call them IMBHs? The definition of this term is somewhat indistinct, with some authors quoting $20M_\odot$ as the lower limit for this class, and others starting at $\sim 100M_\odot$. The few times larger than stellar-mass black holes that could be powering ULXs are precisely in this grey area. Perhaps a new artificial distinction between "small" ($\lesssim 100M_\odot$) and "large" IMBHs is required for clarity's sake.

However, the mass of an underlying black hole is yet to be conclusively determined for any individual ULX - this requires the measurement of a dynamical mass function, which is non-trivial for extra-galactic sources. Furthermore, a small and very rare sub-group of the most luminous ULXs - the "hyperluminous X-ray sources" with $L_X > 10^{41}$ erg s^{-1} (Gao et al. 2003; Wolter, Trinchieri & Colpi 2006; Miniutti et al. 2006) - defy easy explanation by anything other than large IMBHs, assuming they are indeed accreting black holes in the host galaxies, and not luminous supernovae or foreground/background objects. The issue of whether some ULXs could still constitute evidence for accretion onto large IMBHs is therefore far from finished with.

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