NEW INSIGHTS INTO ULTRALUMINOUS X-RAY SOURCES FROM DEEP *XMM-NEWTON* OBSERVATIONS

T.P. Roberts[1], A.-M. Stobbart[1], M.R. Goad[1], R.S.Warwick[1], J. Wilms[2], P. Uttley[3], and J.N. Reeves[3,4]

[1]X-ray & Observational Astronomy Group, Dept. of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK
[2]Astronomy & Astrophysics Group, Department of Physics, University of Warwick, Coventry, CV8 1GA, UK
[3]Exploration of the Universe Division, NASA Goddard Space Flight Center, Greenbelt Road, Greenbelt, MD 20771, USA
[3]Dept. of Physics & Astronomy, Johns Hopkins University, 3400 N Charles Street, Baltimore, MD 21218, USA

ABSTRACT

The controversy over whether ultraluminous X-ray sources (ULXs) contain a new intermediate-mass class of black holes (IMBHs) remains unresolved. We present new analyses of the deepest *XMM-Newton* observations of ULXs that address their underlying nature. We examine both empirical and physical modelling of the X-ray spectra of a sample of thirteen of the highest quality ULX datasets, and find that there are anomalies in modelling ULXs as accreting IMBHs with properties simply scaled-up from Galactic black holes. Most notably, spectral curvature above 2 keV in several sources implies the presence of an optically-thick, cool corona. We also present a new analysis of a 100 ks observation of Holmberg II X-1, in which a rigorous analysis of the temporal data limits the mass of its black hole to no more than 100 $M_\odot$. We argue that a combination of these results points towards many (though not necessarily all) ULXs containing black holes that are at most a few 10s of $M_\odot$ in size.

Key words: black hole physics - X-rays: binaries - X-rays: galaxies.

1. ULXS AND IMBHS

ULXs have garnered a great detail of attention since the launch of *Chandra* and *XMM-Newton*, as these missions have provided the first opportunity to study these remarkable objects in great detail (see e.g. Miller & Colbert 2004). The key question in these sources is whether their extreme X-ray luminosities originate in isotropic radiation from a compact object accreting below the Eddington rate - requiring the presence of an IMBH - or whether it can be explained by another means, with the prime suspects being anisotropic or super-Eddington radiation from a stellar-mass black hole.

The outstanding piece of recent evidence in support of the presence of IMBHs in ULXs derives from fitting their X-ray spectra with the same empirical model as used for Galactic black hole X-ray binaries (BHXRBs). It has been found that a number of luminous ULXs are well fitted by the combination of a soft multi-colour disc blackbody (MCDBB, representative of an accretion disc spectrum) plus a hard power-law continuum model (representative of a hot, optically thin corona). However, there is one crucial difference: the temperature of the accretion disc in these ULXs is a factor ~ 10 lower, at $\sim 0.1 - 0.2$ keV, than in Galactic systems. As the temperature of the innermost edge of an accretion disc scales with the mass of the compact object as $kT_{\rm in} \propto M_{\rm BH}^{-0.25}$, this implies very massive black holes in these ULXs, at ~ 1000 $M_\odot$ (e.g. Miller et al. 2003; Miller et al. 2004a).

However, recent analyses of high spectral quality ULX data have shown that some ULXs are best described by a variant of this empirical model where the power-law continuum dominates *at low energies* (e.g. Stobbart et al. 2004; Foschini et al. 2004), and the disc component is similar to that observed in stellar-mass black holes. Furthermore, in the case of NGC 5204 X-1 there is a clear ambiguity, with both model variants fitting the same data (Roberts et al. 2005). So a *bona fide* "alternate" empirical description for the spectra of some ULXs does exist, albeit one with serious physical challenges. In particular the origin of the dominant soft power-law is unclear - it appears too soft to originate in a jet, and cannot be disc-Comptonisation as it dominates well below the peak emissivity of the disc spectrum.

2. A SAMPLE OF BRIGHT ULXS

The existence of this second class of ULX spectral shape, and the ambiguity between this model and the "IMBH" spectrum in NGC 5204 X-1, led us to consider the following questions:

- How easy is it to differentiate the two spectral forms?
- How common is each type of spectrum?
- What are the physics underlying the alternate spectral model?

We have therefore selected and uniformly reduced a sample of 13 ULXs, comprising the highest quality EPIC spectral data available from the *XMM-Newton* archive, to address these questions. The data were primarily selected on the basis of datasets with $\sim$ 10 ks or more EPIC exposure, and a measured *ROSAT* High Resolution Imager count rate > 10 ct ks^{-1} (taken from Roberts & Warwick 2000 or Colbert & Ptak 2002). Though this sample is small, the ULXs are representative of the full range of ULX luminosity ($\sim 10^{39} - 2 \times 10^{40}$ erg s^{-1}), and with a minimum of a few thousand counts per source represent the best defined X-ray spectra of ULXs to date. More details on this work will appear in Stobbart et al. (2006).

2.1. Empirical spectral models

Our initial spectral fits were made utilising simple single component spectral models, subject only to absorption by material along the line-of-sight to the ULXs. The high definition and underlying complexity of the ULX spectra were highlighted by these fits, with none of the sources being well-fit (using a 95% probability of rejection criterion) by an absorbed MCDBB model, and only 5/13 being adequately fit by a power-law continuum (including the three lowest quality datasets).

The use of two-component models improved the fits considerably. In particular, the IMBH model (i.e. cool MCDBB + hard power-law) produced good fits to 8/13 datasets (using the same criterion as above), with an inner-disc temperature $kT_{\rm in} \sim 0.1 - 0.25$ keV and a power-law photon index $\Gamma \sim 1.6 - 2.5$. Again, the disc temperatures inferred in these sources lead to black hole mass estimates in the range ~ 1000 M$_{\odot}$. However, the anomaly in power-law slope discussed by Roberts et al. (2005) remains - though one might reasonably expect the IMBH accretion disc to be in a "high/soft" or "very high" state, given that it appears to be accreting at or above roughly 10% of the Eddington rate, these states typically (though not exclusively) show power-law continua with photon index $\Gamma > 2.4$ (McClintock & Remillard 2005). The power-law continua exhibited by these IMBH candidates therefore appear to possess photon indices that are somewhat on the low side.

The alternate empirical model (soft power-law, dominant at low energies, plus a warm MCDBB) also produced a total of 8/13 good fits. In fact, six of these sources were also well-fit by the IMBH model, hence spectral ambiguity is present in 6/13 of the ULXs even in our high data quality sample. Of the remaining sources, two apiece were uniquely well-fit by either the IMBH or alternate model, and the remaining three were well-fit by neither (though two favoured an IMBH fit, and one the alternate).

There is a potential discriminator between the two models that allows us to investigate which model the ambiguous sources prefer, namely curvature in the 2–10 keV range. This should be present in the alternate model (which is dominated by the MCDBB in this regime) but not the power-law-dominated IMBH model. We therefore examined the 2–10 keV data for each ULX by fitting both power-law and broken power-law models, and looking for a significant improvement between the two fits. This approach was vindicated by demonstrating that those sources best fit by the alternate model showed strong curvature ($> 4\sigma$ improvements in the broken power-law fit over the power-law fit, according to the F-test). Of the ambiguous sources, 3/6 also showed some evidence for curvature ($> 2\sigma$ significance) as, rather surprisingly, did two of the IMBH model sources. Hence we find at least marginal evidence for 2–10 keV curvature in $> 50\%$ of our spectra.

The above results suggests that the alternate model is at least a viable description of the spectrum of more than half of our sample. Hence we are once again faced with the problem of the dominant soft power-law. However, as there is no strong physical motivation for using a power-law to describe the soft excess apparent in these sources, we decided to test substituting another component, with the constraint that it should have morphological similarities to an absorbed power-law. We therefore attempted fits using a classical black body to describe the soft excess, and retained a MCDBB as the harder component (we describe this as a "dual thermal" model). We found this to be the most successful empirical description of the data, producing good fits to 10/13 ULXs, with typical parameters of $kT_{\rm BB} \sim 0.25$ keV and $kT_{\rm in} \sim 1 - 2$ keV. We speculate that this could describe the spectrum of the accretion disc around a stellar-mass black hole, with a related optically-thick outflow (or "black hole wind", c.f. King & Pounds 2003) producing the soft excess.

We demonstrate one interesting implication of these fits in Fig. 1. We essentially re-plot the results of Miller et al. (2004b) as elliptical regions in $kT_{\rm in} - L_{\rm X}$ space, representing the high-luminosity, low temperature IMBH candidate discs in the top left-hand corner, and the lower luminosity, warm discs of stellar-mass black holes in our own Galaxy in the bottom-right. In the left panel we demonstrate that when we model our sample of ULXs as IMBHs, we reproduce the results of Miller et al. (2004b), that is that the IMBH candidates sit in a separate part of $kT_{\rm in} - L_{\rm X}$ parameter space from stellar-mass black holes. However, the right panel demonstrates that when we use the (more successful) dual-thermal model, the ULXs appear to sit in a direct, high luminosity continuation of the stellar-mass black hole relationship (broadly $L_{\rm X} \propto T^4$ as the accretion rate increases, as expected for standard ac-

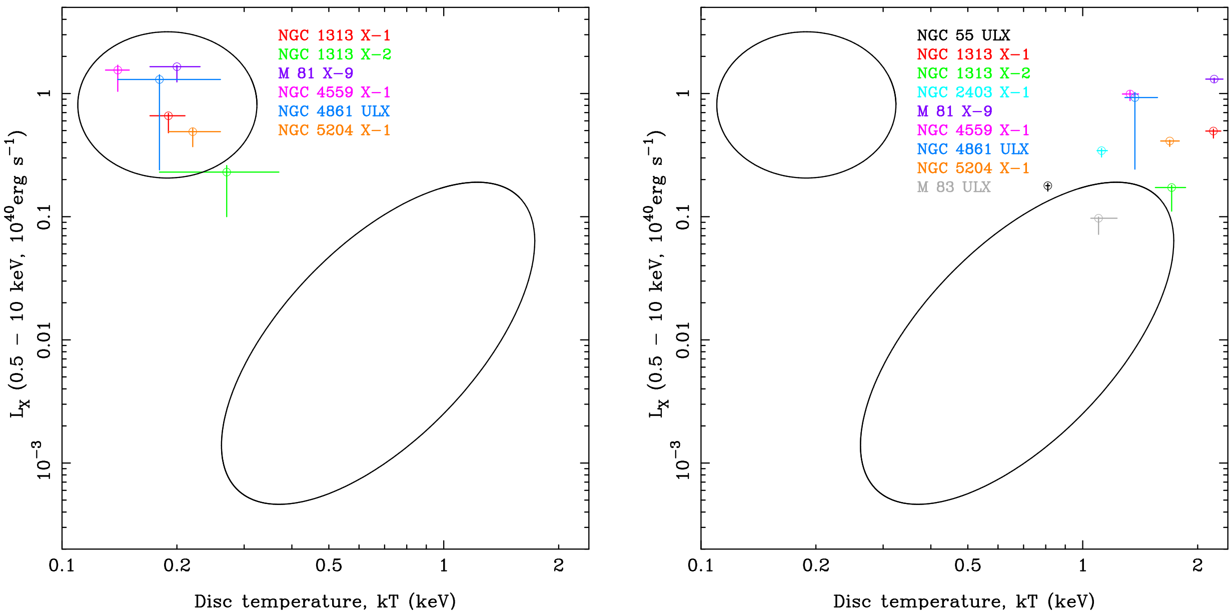

Figure 1. The relationship between accretion disc luminosity and temperature, calculated and displayed as per Miller et al. (2004b). The ellipses represent the regions in which the IMBH candidates (top left) and stellar-mass black holes (bottom right) lay in Figs. 1 & 2 of that paper. Left panel: We overlay data points from our IMBH fits (note that we only show 6 of 8 points; of the missing pair, one had a lower temperature [$\sim$ 80 eV] whilst the other had a temperature that was unconstrained). Right panel: The data points from our dual thermal model overlayed (in this case one disc was too hot to appear within the plotted range).

cretion discs). This evidence shows that, at the very least, the mass of the underlying black hole inferred from empirical spectral fitting of ULXs appears very dependent on the choice of model.

2.2. Physical spectral models

We next investigated the origin of the possible 2–10 keV curvature using more physically-motivated models. The “slim disc” model of an accretion disc (e.g. Watarai et al. 2001; XSPEC parameterisation courtesy K. Ebisawa) was only successful in fitting our spectra in 3/13 cases. Instead, we found a physically self-consistent accretion disc plus Comptonised corona model, using a `diskpn + eqpair` model in XSPEC (Gierliński et al. 2001, Coppi 2000), gave good fits to 11/13 sources (plus a further source that was only marginally rejected at the 95% criterion). All the fits display a cool disc component, with temperatures $\sim 0.1 - 0.3$ keV, as would be expected from IMBHs. However, the majority of these fits also show a second remarkable characteristic; the spectral curvature present in many sources originates in a coronal component that is optically thick, with typical optical depths of $\tau \sim 10 - 40$. This is very puzzling, because if ULXs are to be understood as direct higher-mass analogies of high-state BHXRBs, then their coronae should presumably be similarly optically thin ($\tau < 1$). This only occurs in two of our sources, leaving this pair as the best accreting IMBH candidate ULXs within our sample. For the remaining ULXs, that possess apparent optically-thick coronae, it is evident that they are not simple scaled-up Galactic BHXRBs in a classic high/soft state, and we may perhaps need new insight to explain their spectra.

3. HOLMBERG II X-1

This source is regarded as the archetypal luminous ($L_X > 10^{40}$ erg s^{-1}) nearby ULX, and has been widely studied both in X-rays (e.g. Dewangan et al. 2004) and over complementary wavebands (e.g. Kaaret, Ward & Zezas 2004; Miller, Mushotzky & Neff 2005). We were awarded a 100-ks observation of this source in *XMM-Newton* AO-3, the results of which we summarise here (see also Goad et al. 2005).

3.1. Spectra

Though more than 60% of this observation was lost to space weather, we were still able to extract the first reasonable signal-to-noise RGS spectrum of an ULX. This showed a smooth continuum shape, modelled simply as an absorbed power-law continuum ($N_H \sim 2 \times 10^{21}$ cm^{-2}, $\Gamma \sim 2.6$) with the exception of an excess of counts slightly above 0.5 keV (see Fig. 1 of Goad et al. 2005). This could be fit by an O VII triplet, but a much better solution was found by allowing the abundance of the absorbing material to drop to $\sim$ 0.6 of the solar value.

Interestingly, this result strongly affects the EPIC data modelling. In particular, using a 0.6-solar abundance

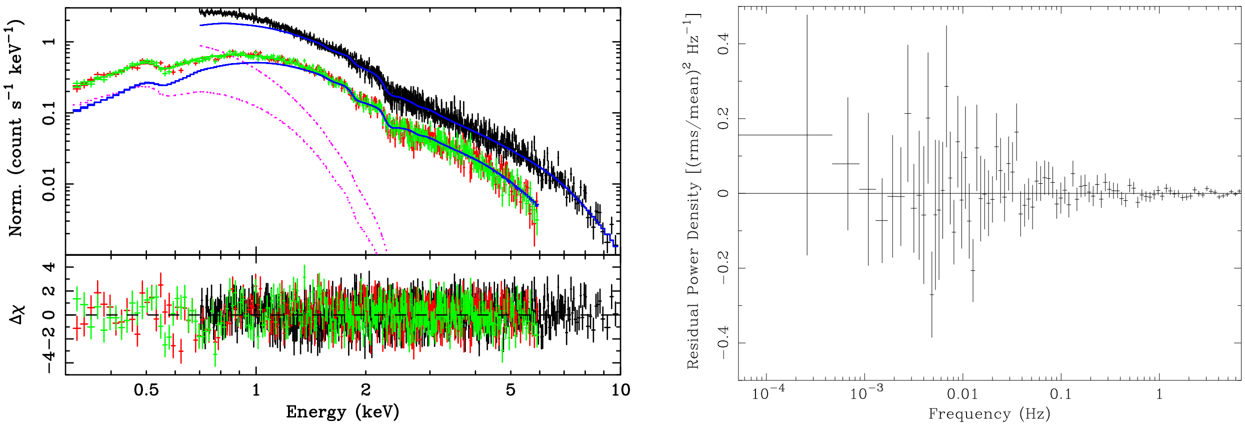

Figure 2. Left panel: EPIC X-ray spectra of Ho II X-1. The pn data points are displayed in black, and the MOS in grey. We show the modelled contributions of the accretion disc (dotted lines) and corona (solid lines) separately in the top part of the panel, and show the model fit residuals in the lower part. Right panel: the residual power density after fitting the PSD of Ho II with a constant. This demonstrates the lack of variability power in the source.

TBABS model in XSPEC (and interstellar abundances set to the values of Wilms, Allen & McCray 2000) greatly reduces the size of the apparent soft excess, and so the mass of the BH estimated from the IMBH model is reduced to $\sim 33\%$ of its value assuming a solar abundance absorber. However, the best fit to the data was again found to be the physically self-consistent accretion disc + corona model, with $kT_{\rm in} \sim 0.2$ keV and $\tau \sim 4-9$ (i.e. a cool disc and optically thick corona). The EPIC spectral data, with this best-fit model, are shown in Fig. 2. Note there is no detection of an Fe Kα line in this dataset; formally, we place a 90% upper limit of 25 eV on the equivalent width of a narrow 6.4 keV Fe Kα feature.

3.2. Timing

The EPIC timing data showed Ho II X-1 to be remarkably invariant during the observation. A power spectral density (PSD) analysis was performed, finding that no power was evident (above the Poisson noise level) in the $\sim 10^{-4} - 6$ Hz range (see Fig. 2). This likely rules out Ho II X-1 being in a high/soft state, as a comparison to Galactic black holes and AGN shows they generally have a red noise spectrum with measureable RMS variability in this state[1]. It does not rule out a state with a band-limited PSD, such as occurs in the low/hard or some very high states. However, the strong limits placed by the non-detection of power in the observed frequency interval implies any power must be present at higher frequencies. Assuming that BH timing properties scale linearly with mass (e.g. Uttley et al. 2002), we can place an upper limit on the mass of Ho II X-1 of 100 M$_\odot$ if it is in the low or certain very high states. Encouragingly, GRS 1915+105 shows very similar variability characteristics in its "χ-class" of behaviour, which is thought to occur whilst it is in the very high state.

[1]We note that dilution by photons from the accretion disc should not be a problem for Ho II X-1 if it contains an IMBH, as the 0.3–6 keV band we derive the PSD from is dominated by the putative coronal component. However, it has been brought to our attention that there may be a dimunition of intrinsic variability in the coronae of high/soft state sources at the highest luminosities (J. Homan, *priv. comm.*), which merits further quantification.

4. RADICAL SOLUTIONS

Whilst it is evident from this work that optically-thick coronae may be common in ULXs, what is their origin? One possible explanation is offered by the model of Zhang et al. (2000), that explains accretion discs as a two-layer system, with a cool ($0.2 - 0.5$ keV) interior seeding a warm, optically thick ($1 - 1.5$ keV, $\tau \sim 10$) Comptonising upper disc layer. This model therefore offers an explanation for both spectral components seen in our modelling. Crucially, it has also successfully been used to describe the X-ray spectrum of GRS 1915+105. We therefore speculate that our spectral modelling, considered along with the mass limit from Ho II X-1, argues that Ho II X-1 and many other ULXs may be analogues of GRS 1915+105. Whilst ULXs may still possess larger BH masses than GRS1915+105 (i.e. 20 - 100 M$_\odot$, so still technically IMBHs), we suggest they are operating in similar accretion states, with a key link being that the accretion is persistently at around the Eddington limit.

Obviously, we cannot rule out cool discs being the signature of a larger, $\sim$ 1000 M$_\odot$ IMBH. Indeed, a weakness of the above model is how we manage to see photons from the inner disc layer through an optically thick exterior. However, we note there are also weaknesses with a literal interpretation of cool disc parameters, most notably in the case of PG quasars. Similar soft spectral components - also modelled as cool discs - are seen in PG quasars, where their temperature has been shown to be completely independent of the mass of the BH (Gierliński & Done 2004). This implies a radically different origin for the soft excesses in PG quasars - and, by extension, ULXs - such as in an outflow (as suggested in our dual-thermal model), or perhaps even as atomic features on the accretion disc spectrum.

5. CONCLUDING COMMENTS

If ULXs do contain $\sim$ 1000 $M_\odot$ IMBHs, as suggested by empirical modelling of their spectra, then one might reasonably assume from their luminosities that they are accreting at $\sim 10\%$ of the Eddington rate, and so should behave like scaled-up versions of BHXRBs in the high-state. The detection of spectral curvature in the 2–10 keV range in the majority of our sample of ULXs, that can be physically modelled as a cool, optically-thick corona, argues that something different is happening in many ULXs. One explanation could be that these ULXs are operating in a fashion similar to GRS 1915+105, as suggested by the timing results for Ho II X-1, in which case the ULXs might harbour black holes not much more massive than in Galactic BHXRBs. This would bring X-ray spectral results more into line with other arguments on ULXs that suggest that the majority of sources do not contain IMBHs. For example, King (2004) argues that the sheer numbers of ULXs in the most extreme star-forming environments makes it very unlikely that they can all contain IMBHs, and the modelling of Rappaport, Podsiadlowski & Pfahl (2005) demonstrates many ordinary high-mass BHXRBs (that one would expect to find in these environments) have a mass transfer rate that is substantially super-Eddington, providing an adequate reservoir of fuel for ULXs. Not least, it would agree with observations of accreting sources in our own Galaxy that show many - most notably GRS 1915+105 - do experience episodes of radiating at a super-Eddington level (cf.. McClintock & Remillard 2005).

However, we certainly cannot exclude ULXs from containing $\sim$ 1000 $M_\odot$ IMBHs at the current point in time, and indeed two of the sources in our sample do appear consistent with this interpretation. Ultimately it may prove that the only measurement that can resolve the debate on the underlying nature of ULXs will be a dynamical mass limit for the black hole from its orbital motion, as is the case for Galactic BHXRBs. Until then, more and deeper X-ray observations are required to advance our knowledge of these extraordinary X-ray sources.

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