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New insights into ultraluminous X-ray sources from deep *XMM-Newton* observations†

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Abstract. The central controversy over whether or not ultraluminous X-ray sources (ULXs) contain a new *"intermediate-mass"* class of black holes (IMBHs) remains essentially unresolved. Indeed, whilst many recent X-ray spectroscopy results find evidence for a cool (100–200 eV) accretion disc – the expected signature of a ∼1000 $M_{\odot}$ IMBH – in ULX spectra, most of the circumstantial evidence (a combination of multiwavelength counterparts, theoretical modelling and the behaviour of accreting black holes in our own Galaxy) argues that the black holes underlying ULXs could be substantially less massive. I will present a new analysis of the deepest *XMM-Newton* observations of ULXs that directly addresses their underlying nature. This includes the results of a new 100-ks observation of the archetypal ULX Holmberg II X-1. Though a slight soft excess in its X-ray spectrum can be fitted by a cool accretion disc model, a rigorous analysis of the temporal data shows that the black hole cannot be larger than ∼100 $M_{\odot}$. Interestingly, we find evidence that the putative accretion disc corona is cool and optically thick in this source, unlike most Galactic binaries. We have also undertaken a detailed spectral analysis of the next 12 best ULX datasets in the *XMM-Newton* archive. Using physically self-consistent spectral modelling we show that whilst all the ULXs show possible cool accretion discs, the majority of these ULXs appear dominated by an optically-thick Comptonising medium. I will argue that this is evidence that most (though not necessarily all) ULXs contain black holes that are at most a few tens of solar masses in size.

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

1. Introduction

The key recent evidence supportive 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 this combination of a soft multi-colour disc blackbody (MCDBB) plus a hard power-law continuum model, with one crucial difference: the temperature of the accretion disc is a factor ∼10 lower, at ∼0.1–0.2 keV, than in Galactic systems. As the temperature

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of the innermost edge of an accretion disc decreases as the mass of the compact object increases, this implies very massive black holes in these ULXs, at ~1000 $M_\odot$ (e.g. Miller *et al.* 2003; Miller *et al.* 2004). However, recent analyses of high spectral quality ULX data have shown that some ULXs are best described by a variant of this model where the power-law continuum dominates *at low energies* (e.g. Stobbart *et al.* 2004; Foschini *et al.* 2004). In at least one case there is a clear ambiguity, with both variants fitting the same data (Roberts *et al.* 2005). A serious challenge for this alternate model, though, is that the physical origin of the dominant soft power-law is unclear.

2. A sample of bright ULXs

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 the following questions: how easy is it to differentiate the two spectra? How common is each type of spectrum? And what are the physics underlying the alternate spectral model? 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.

The high definition and underlying complexity of the ULX spectra were highlighted by simple spectral 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 fit by a power-law continuum (including the three lowest quality datasets). The use of two-component models improved the fits greatly. In particular, the IMBH model (i.e. cool MCDBB + hard power-law) produced good fits to 8/13 datasets, with an inner-disc temperature $kT_{in} \sim 0.1$–0.25 keV and a power-law photon index $\Gamma \sim 1.6$–2.5†.

However, the alternate empirical model also produced a total of 8/13 good fits. 6 of these sources were also well-fit by the IMBH model, hence spectral ambiguity is present in 6/13 of the ULXs in our 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). As an attempt to find which model the ambiguous sources prefer, we note that the key observable distinction between the two models is that the alternate model should show curvature in the 2–10 keV range. Therefore we fit both power-law and broken power-law models to the 2–10 keV data from each source, and looked for a statistical 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 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.

We next investigated the origin of this 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 unsuccessful in fitting our spectra in 10/13 cases. Instead, we found a physically self-consistent accretion disc plus Comptonised corona model, using a `diskpn + eqpair` model in XSPEC (Gierlinski *et al.* 2001, Coppi 2000), gave good fits to 11/13 sources (plus another only marginally rejected at the 95% criterion). All the fits display a cool disc component, with temperatures ~0.1–0.3 keV, as would be expected from IMBHs. The majority of these fits also show a remarkable

† Though see Roberts *et al.* (2005) on the anomalous flatness of this photon index if the compact object is an IMBH.

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characteristic; the spectral curvature 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 higher-mass analogies of high-state BHXRBs, then their corona should be similarly optically thin ($\tau < 1$, which only appears to be the case in two sources). Hence this model demonstrates that many ULX spectra do not appear similar to the high spectral state of BHXRBs.

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 (e.g. Dewangan *et al.* 2004). We were awarded a 100-ks observation of this source in *XMM-Newton* AO-3 (Goad *et al.* 2005, submitted to MNRAS). 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, with the exception of an excess of counts slightly above 0.5 keV. This could be fit by an O VII triplet, but a better solution was found by allowing the abundance of the absorbing material to drop to ∼0.6 of the solar value.

Interestingly, this result strongly affects the EPIC data modelling. In particular, using a 0.6-solar abundance TBABS model in XSPEC greatly reduces the size of the apparent soft excess, and so the mass of the BH estimated from the IMBH model is reduced to ∼33% of its value assuming a solar abundance absorber. However, the best fit to the data is found to be the physical accretion disc + corona model, with $kT_{in} \sim 0.2$ keV and $\tau \sim 4$–9 (i.e. a cool disc and optically thick corona).

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. This immediately ruled out Ho II X-1 being in a high BHXRB state. It does not rule out a state with a band-limited PSD, such as occurs in the low or 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 very high state. Encouragingly, GRS 1915+105 shows very similar variability characteristics in its "χ-class" of behaviour, which is thought to be typical of the very high state.

4. Conclusions

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 2-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 potentially explains both spectral components seen in our modelling. This model has also successfully been used to describe GRS 1915+105. We therefore suggest that this argues Ho II X-1 and many other ULXs may be analogues of GRS $1915 + 105$, probably with larger BH masses (10–100 $M_\odot$), accreting at around the Eddington limit.

Obviously, we cannot rule out the cool discs being the signature of an ∼1000 $M_\odot$ IMBH. However, we note that similar spectral components – also modelled as cool discs – are seen in PG quasars. In these sources their temperature has been shown to be completely independent of the mass of the BH (Gierlinski & Done 2004). This could imply a

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radically different origin for the soft excesses, such as in an outflow, or perhaps even as atomic features on the accretion disc spectrum.

The bottom line from this work is that many ULXs do not appear to be in the expected high state for a $\sim$1000 $M_\odot$ IMBH. Instead, their unusual spectra may be more consistent with $<$100 $M_\odot$ BHs in a similar mode to GRS $1915+105$ in the very high state. However, confirmation of this can only come from one source: a dynamical mass limit for the BH in an ULX derived from its orbital dynamics.

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Discussion

Miller: (Abridged) Aren't your timing results the wrong way round? Don't we expect no variability in the high state, and up to 30% RMS variation in the very high state? I also don't believe your spectroscopy results – by using specific physical models you are imprinting a limited set of assumptions on the data.

Roberts: I agree to an extent on your comment on spectroscopy, though note that our results included both optically-thin and -thick solutions so we imparted no strong bias on that parameter. The preference for optical thickness is consistent with the curvature we model empirically. On the subject of timing, the high state can have its intrinsic noise washed out if you look at the portion of the spectrum dominated by the accretion disc. We are looking predominantly at the supposed corona, and see no variation. Similarly, our point on the very high state is one would expect to see variability power at high frequencies for a stellar-mass black hole, and lower frequencies for larger black holes. As we see no variation at frequencies up to $\sim$5 Hz we can argue the black hole is no more massive than 100 $M_{\odot}$.

Ghosh: Do I understand you correctly that this high optical depth (τ greater or equal to 8) is one of the major diagnostics suggesting an unusual accretion mode? If so, one of the schematic model figures you showed is that of a "sandwich" accretion disk, wherein the top layer of the disk provides this optical depth. Such models are interesting, and their physical bases need to be understood better.

Roberts: Such high optical depths are not generally found in black hole coronae, so do suggest an unusual accretion state. I agree that a better physical understanding is very desirable!