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► **To cite this version:**

A. C. Gonçalves, R. Soria. On the weakness of disc models in bright ULXs. Monthly Notices of the Royal Astronomical Society, 2006, 371, pp.673-683. 10.1111/j.1365-2966.2006.10687.x. hal-03786414

HAL Id: hal-03786414

<https://hal.science/hal-03786414v1>

Submitted on 8 Nov 2024

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On the weakness of disc models in bright ULXs

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Accepted 2006 June 13. Received 2006 June 12; in original form 2006 April 5

ABSTRACT

It is sometimes suggested that phenomenological power law plus cool disc-blackbody models represent the simplest, most robust interpretation of the X-ray spectra of bright ultraluminous X-ray sources (ULXs); this has been taken as evidence for the presence of intermediate-mass black holes (BHs) ($M \sim 10^3 M_{\odot}$) in those sources. Here, we assess this claim by comparing the cool disc-blackbody model with a range of other models. For example, we show that the same ULX spectra can be fitted equally well by subtracting a disc-blackbody component from a dominant power-law component, thus turning a soft excess into a soft deficit. Then, we propose a more complex physical model, based on a power-law component slightly modified at various energies by smeared emission and absorption lines from highly ionized, fast-moving gas. We use the *XMM-Newton*/EPIC (European Photon Imaging Camera) spectra of two ULXs in Holmberg II and NGC 4559 as examples. Our main conclusion is that the presence of a soft excess or a soft deficit depends on the energy range over which we choose to fit the ‘true’ power-law continuum; those small deviations from the power-law spectrum are well modelled by disc-blackbody components (either in emission or absorption) simply because they are a versatile fitting tool for most kinds of smooth, broad bumps. Hence, we argue that those components should not be taken as evidence for accretion disc emission, nor used to infer BH masses. Finally, we speculate that bright ULXs could be in a spectral state similar to (or an extension of) the steep power-law state of Galactic BH candidates, in which the disc is now completely Comptonized and not directly detectable, and the power-law emission may be modified by the surrounding, fast-moving, ionized gas.

Key words: accretion, accretion discs – black hole physics – X-rays: binaries.

1 INTRODUCTION: HOW TO DETERMINE BH MASSES

Ultraluminous X-ray sources (ULXs) are point-like, accreting X-ray sources with apparent isotropic luminosities spanning a range from $\sim 10^{39}$ to $\approx 3 \times 10^{40}$ erg s⁻¹, that is, one or two orders of magnitude greater than the Eddington luminosity (L_{Edd}) of a stellar-mass black hole (BH). The main unsolved issue is whether the accreting sources are more massive than typical Galactic BH candidates (BHCs), perhaps in the intermediate-mass range ($M \sim 10^3 M_{\odot}$; Miller, Fabian & Miller 2004), or stellar-mass BHs accreting at super-Eddington rates (Begelman 2002); alternatively, their brightness could be due to beaming along the line-of-sight of the observer (Fabrika & Mescheryakov 2001; King et al. 2001; Körding, Falcke & Markoff 2002).

The standard, most reliable way to determine the mass of an accreting BH in X-ray binaries is based on phase-resolved spectroscopic and photometric studies of their optical counterparts. By measuring the orbital period and the radial velocity shifts of selected optical lines from the donor star and the accretion disc, one can constrain the mass functions of both components. Further constraints to the inclination angle and the size of the system come from the amplitude of the ellipsoidal variations in the donor star, and the presence/absence of dips and eclipses. Those techniques have been successfully applied to a growing number of BHCs (for a review, see McClintock & Remillard 2006). Attempts to apply similar techniques to ULXs have been fruitless or inconclusive, so far, mostly because of their optical faintness. At typical distances of a few Mpc (distance moduli ~ 28 – 30), most candidate optical counterparts are fainter than $V \sim 24$ mag. In many cases, crowding is also a problem: the X-ray error circle may be consistent with an unresolved group of stars. Pioneering efforts (e.g. Grisé, Pakull & Motch 2006; Pakull, Grisé & Motch 2006) may yield results for a few sources in the near

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future. Meanwhile, though, one has to rely on indirect methods to estimate the BH mass.

One such method is based on X-ray spectral fitting over the ‘standard’ 0.3–10 keV band. In Galactic BHCs, the X-ray spectrum consists of essentially two components, power law and thermal, with varying normalizations and relative contributions in various spectral states. The power-law component is scale free and without a direct dependence on BH mass. However, its slope and normalization are related to the spectral state and normalized luminosity; for instance, the slope is flatter (photon index $\Gamma \sim 1.5$ –2) in the low/hard state ($L_X/L_{\text{Edd}} \lesssim 10^{-2}$) and steeper ($\Gamma \sim 2.5$ –3) at $0.1 \lesssim L_X/L_{\text{Edd}} \lesssim 1$ (McClintock & Remillard 2006). More significantly, the thermal component, interpreted as the spectrum of an optically thick Shakura–Sunyaev disc (Shakura & Sunyaev 1973), contains, in principle, a direct dependence on disc size and BH mass.

In the standard thin-disc approximation, for a non-rotating BH,

$$\sigma T_{\text{eff}}^4(R) \approx \frac{3GM\dot{M}}{8\pi R^3} \quad (1)$$

(Shakura & Sunyaev 1973; Pringle 1981; Frank, King & Raine 2002).¹ If the disc extends to the innermost stable circular orbit, $R_{\text{in}} = 6GM/c^2$ in the Schwarzschild geometry, the inner-disc temperature scales as

$$T_{\text{in}} \equiv T(R_{\text{in}}) \propto M^{-1/2} \dot{M}^{1/4}. \quad (2)$$

The total luminosity of a standard disc, mostly emitted in the X-ray band for stellar-mass systems, is (Makishima et al. 1986)

$$L_X \approx 4\pi\sigma T_{\text{in}}^4 R_{\text{in}}^2 \approx 9.76 \times 10^{36} \left(\frac{T_{\text{in}}}{\text{keV}} \right)^4 \left(\frac{M}{M_{\odot}} \right)^2 \text{ erg s}^{-1} \quad (3)$$

which implies that $L_X \propto T_{\text{in}}^4$, varying the accretion rate along lines of constant BH mass. At the Eddington limit, assuming a standard radiative efficiency ≈ 0.1 ,

$$\dot{M}_{\text{Edd}} \approx \frac{1.3 \times 10^{39}}{c^2} \left(\frac{M}{M_{\odot}} \right) \text{ g s}^{-1}, \quad (4)$$

therefore, $T_{\text{in}} \propto M^{-1/4}$ from equation (2), and

$$L_{\text{Edd}} \approx 1.3 \times 10^{38} \left(\frac{M}{M_{\odot}} \right) \approx 4.5 \times 10^{39} \left(\frac{T_{\text{in}}}{\text{keV}} \right)^{-4} \text{ erg s}^{-1}. \quad (5)$$

There are various caveats attached to those simple relations. For example, the innermost stable circular orbit (assumed to mark the inner-disc boundary at high accretion rates) can vary between $6GM/c^2$ and GM/c^2 for a non-rotating or maximally rotating BH, respectively. The fitted temperature (‘colour temperature’) may be higher than the effective temperature by a factor as high as 2.6 (Shrader & Titarchuk 2003). On the other hand, this is approximately compensated (Fabian, Ross & Miller 2004) by the temperature drop near the inner edge, due to the zero-torque condition. The normalization of the observed spectrum, and therefore also

¹Strictly speaking, in the standard disc-blackbody approximation the disc temperature quickly drops to zero at the inner edge, due to the zero-torque condition at that boundary, after reaching a maximum at $R \approx (49/36) R_{\text{in}}$. However, equation (1) corresponds to the simplified version of the disc-blackbody spectrum more commonly used in data fitting (DISCBB model; Makishima et al. 1986), in which the temperature is assumed to increase all the way to the innermost stable circular orbit, R_{in} . This is why the fitted peak temperature of a disc-blackbody model is commonly referred to as the inner-disc temperature, T_{in} .

the inferred BH mass, depend on the viewing angle, often poorly constrained.

Nevertheless, equations (3) and (5) provide an overall good scaling and order of magnitude estimate of the BH mass in Galactic BHCs, and the DISCBB model in XSPEC (Arnaud 1996) has proved simple and successful. More complex implementations of the disc-blackbody model (e.g. DISCPN; Gierlinski et al. 1999), taking into account some of the corrective factors mentioned above, have also been used, at the cost of additional free parameters. It seems reasonable to apply the same simple tools to estimate the mass of the accreting BHs in ULXs, if they are scaled-up versions of Galactic BHCs.

2 COMPETING MODELS

2.1 Cool-disc phenomenological versus physical models

For about a dozen of the brightest ULXs, it was noted (e.g. Miller et al. 2003, 2004; Fabian et al. 2004; Roberts et al. 2004; Terashima & Wilson 2004; Feng & Kaaret 2005) that the 0.3–10 keV spectrum is dominated by a featureless broad-band component, interpreted as a power law (PO in XSPEC) plus a ‘soft excess’ significantly detected below 1 keV. The normalization of the soft excess is somewhat degenerate with the column density, metal abundance and ionization state of the absorbing medium. However, for various sources there is little doubt that an additional thermal component (BB or DISCBB in XSPEC) with $kT \sim 0.1$ –0.2 keV leads to better fits.

By analogy with Galactic BHCs, one can interpret such phenomenological fits as true physical models and use the fitted temperature as the colour temperature near the inner boundary of an accretion disc; by applying equation (3), we thus obtain characteristic mass values $\sim 10^3 M_{\odot}$ (Fig. 1). This approach has the advantage of being simple, with a minimum number of free parameters, well tested for Galactic BHCs and easy to apply as ‘common currency’ (Miller, Fabian & Miller 2006) in the comparison and classification

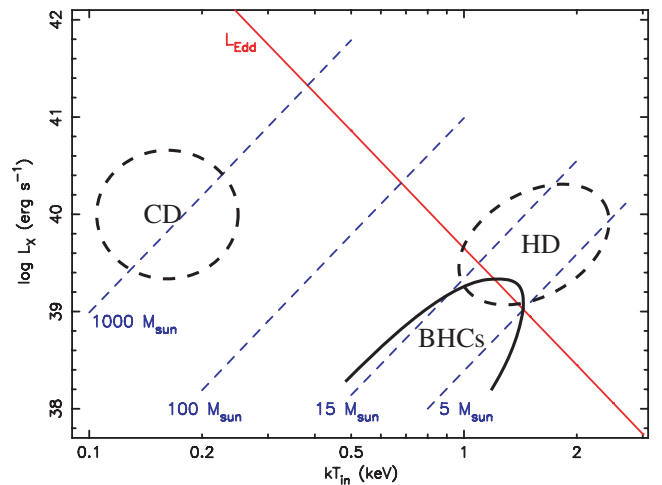


Figure 1. Schematic plot showing the location of Galactic BHCs and ULXs in an X-ray luminosity versus disc temperature plot; adapted from fig. 3 in Stobbart et al. (2006). The Eddington limit and lines of constant mass are obtained from equations (3) and (5) (see Section 1 for details). The CD model implies that ULXs are intermediate-mass BHs, emitting well below their Eddington limit. The HD model suggests that ULXs are stellar-mass objects (an extension of the Galactic BHC class), emitting above Eddington.

of different sources. It does not assume or require a specific physical model for the power-law component.

An alternative approach, also successfully applied to Galactic BHCs, is to fit the X-ray spectra with a more complex, self-consistent model (e.g. XSPEC models such as EQPAIR: Coppi 1999; BMC: Shrader & Titarchuk 1999; COMPTT: Titarchuk 1994), in which a power-law-like component arises as comptonized emission from seed thermal photons, upscattered in a corona. In this class of physical models, the thermal component (which we can still interpret as disc emission) is slightly modified from the pure DISCBB spectrum, and the power law has a low-energy truncation at the energy of the seed photons, and a high-energy break depending on the temperature of the corona. The temperature of the seed thermal component, and the optical depth and temperature of the comptonizing corona are the main fitting parameters. When such models are applied to bright ULXs, it is found (Goad et al. 2006; Stobbart, Roberts & Wilms 2006) that the emission from the inner disc may be almost completely comptonized in a warm, optically thick, but perhaps patchy, corona.

This alternative approach was critically discussed by Miller et al. (2006), who pointed out that complex comptonization models contain a larger number of additional parameters that can be adjusted to fit the data. Miller et al. (2006) simulated a DISCBB + PO spectrum and pointed out that it could also be fitted with complex comptonization models. In some cases, the same simulated spectrum could be fitted with different sets of physical parameters: either an optically thin, hot corona ($\tau \approx 0.8$, $kT_e \approx 50$ keV), or a thicker, warmer one ($\tau \approx 4$, $kT_e \approx 7$ keV). Thus, Miller et al. (2006) concluded that, because of the moderately low signal-to-noise ratio and few distinctive features in ULX spectra, comptonization models cannot give us a more solid understanding of the physical situation than simpler phenomenological models.

However, we do believe that complex physical models can be useful to draw our attention to various, apparently minor issues, which are not considered in simpler models, but can significantly affect our physical interpretation. For example, the temperature of the warm corona fitted to the spectrum of Holmberg II X-1 (Goad et al. 2006) is only ≈ 3 keV, which suggests a steepening in the spectral slope at energies $\gtrsim 5$ keV. A similar spectral steepening has also been found to be statistically significant for most of the ULXs with higher signal-to-noise ratios (Stobbart et al. 2006). Given the very small number of spectral features, such break can be an important clue to our understanding of the emission process. A phenomenological DISCBB plus PO model simply cannot reproduce that break.

We should also be careful when we attribute physical meaning to phenomenological fit parameters such as the colour temperature in the DISCBB model. For example, it is possible that the inner disc may be cooler and fainter than a standard disc-blackbody, for a given mass and accretion rate. This must happen not because the disc is truncated or replaced by an advection-dominated flow — in those cases, the total efficiency would also be low and the ULX would not be as bright, unless it was also very massive — but because most of the gravitational energy is transferred (e.g. via magnetic coupling) from the disc to the corona, before being radiated. In this scenario, the corona would draw energy from the disc and effectively cool it (e.g. see Kuncic & Bicknell 2004 for a magnetized disc/corona model based on this idea). There is no observational evidence yet to favour this scenario over the simpler DISCBB model. However, it is at least a reminder that an observed cooler disc may not necessarily be due to a higher mass.

2.2 Cool-disc versus hot-disc phenomenological models

If it is misguided directly to compare phenomenological and complex physical models, it is instead fair to compare two phenomenological models, equally simple, with the same number of free parameters, but with entirely different physical interpretations. Such a comparison can be done between the cool-disc (CD) model (Miller et al. 2004) and the hot-disc (HD) model (Stobbart et al. 2006). As extensively discussed in Stobbart et al. (2006), the latter scenario suggests that at least some bright ULXs may occupy a region of the parameter space adjacent to that occupied by Galactic BHCs (Fig. 1). The smooth spectral component, dominating in the hard band, is modelled as disc emission, with temperatures $kT_{in} \sim 1$ – 2.5 keV; the soft excess is well modelled by a simple blackbody component, and may be physically understood as downscattered emission, for example in an optically thick outflow (King & Pounds 2003). The CD and the HD models provide equally good fits to most ULXs. Here, we briefly discuss some of the strengths and weaknesses of the two scenarios.

(i) The CD model has been used as evidence of BH masses $\sim 10^3 M_\odot$, which require more complicated (and so far untested) formation scenarios. Curiously, in the CD interpretation, ULX luminosities would remain always an order of magnitude below their Eddington limit (Fig. 1), even for the brightest sources, suggesting perhaps some kind of upper limit to the mass supply. This behaviour is not observed in Galactic neutron stars and BHCs, which often reach or even slightly exceed their Eddington limit. On the other hand, the HD model suggests that ULXs could be stellar-mass BHs emitting at up to an order of magnitude above their Eddington limit. From a physical point of view, the two scenarios (stellar mass but well above Eddington, or $\sim 10^3 M_\odot$ but well below Eddington) have different kinds of drawbacks; more constraining observations in other energy bands will be necessary to rule either one out.

(ii) The standard relations between luminosity, inner-disc temperature and mass (summarized in Section 1) are well tested for systems such as Galactic BHCs in the high/soft state, when the disc contributes most of the emission. This would also be the case in the HD model, where the disc contributes ~ 70 – 90 per cent of the X-ray emission (Stobbart et al. 2006). Conversely, in the CD scenario, the disc contributes only ~ 5 – 20 per cent of the X-ray luminosity; hence, a direct scaling of the disc quantities from Galactic BHCs may not be appropriate.

(iii) In the HD model, the dominant spectral component is modelled with a simple DISCBB term, based on the standard, Shakura–Sunyaev disc. The fitted temperature and normalization imply super-Eddington luminosities. However, at those luminosities, we do not expect the accretion flow to be consistent with the standard thin disc. In fact, we already see deviations from the standard-disc spectrum in Galactic BHCs as they approach their Eddington limit (Kubota & Done 2004; Kubota & Makishima 2004; see also Kubota, Done & Makishima 2002 for an earlier ASCA study of a ULX). Taking into account those effects would require again complex physical models with various free parameters. If we want to stick to the simple DISCBB model for a phenomenological study, we need at least to be careful in attributing true physical meaning to its fit parameters.

(iv) The CD model cannot explain the observed break in the spectral slope at high energies (typically, going from a photon index $\Gamma \approx 2$ at 1.5 – 5 keV, to a slope ≈ 3 at 5 – 10 keV), as noted earlier. The HD model does predict that break; in fact, if anything, it overpredicts it, because we expect the Wien tail of the thermal emission to drop exponentially just above the fitted energy range. Spectral observations

in the $\sim 10\text{--}20$ keV region would provide a crucial test between the two phenomenological models.

(v) The inner-disc temperature in the CD model is in the same range as the characteristic temperature of the soft excess in Seyfert 1s, despite the large mass difference between ULXs and active galactic nucleus (AGN). Both kinds of spectra can formally be well fitted with a cool DISCBB component plus a power law. However, attributing the same physical meaning (disc emission) to the soft excess in both systems is problematic, and would require ad hoc modifications, for example a strong colour factor in AGN (thus, destroying the simplicity of the phenomenological model). More likely, the soft excess in AGN could be explained by a combination of blurred emission and absorption lines and reflection (Gierlinski & Done 2004; Chevallier et al. 2006; Crummy et al. 2006). This is an example of how a simple, successful phenomenological model, such as the CD model, can lead to misleading or plainly wrong physical interpretations in at least one of those two classes of objects. On the other hand, characteristic disc temperatures in the HD model fall within, or close to, the range of stellar-mass BH temperatures.

2.3 Slope of the power-law component

Most of the discussion so far has focused on the interpretation of the soft component. However, another unexplained finding of the CD model is that the slope of the dominant power law is harder ($1.5 < \Gamma < 2.5$; Roberts et al. 2005; Stobbart et al. 2006) than generally observed from bright Galactic BHCs in the high/soft or steep power-law states ($\Gamma > 2.5$; McClintock & Remillard 2006). This appears to be true both for some bright ULXs with a soft excess, and, even more so, for those whose spectra can be fitted with a simple power law; for example, NGC 4559 X-2 ($L_{0.3\text{--}10} = 1.3 \times 10^{40} \text{ erg s}^{-1}$, with $\Gamma \approx 1.8$; Cropper et al. 2004) and M99 X-1 ($L_{0.3\text{--}10} = 1.6 \times 10^{40} \text{ erg s}^{-1}$, with $\Gamma \approx 1.7$; Soria & Wong 2006). More examples of ULXs with a power-law slope $\Gamma \lesssim 2$ are discussed in Roberts et al. (2004), Terashima & Wilson (2004) and Winter, Mushotzky & Reynolds (2006). One can take at least four alternative approaches to explain this finding.

(1) It could be that such sources are intrinsically different from soft-excess ULXs because they are in the classical low/hard state (e.g. McClintock & Remillard 2006), characterized by a dominant, hard ($\Gamma \sim 1.5\text{--}2.1$) power law, $0.3\text{--}10$ keV luminosities $\lesssim 0.01 L_{\text{Edd}}$ and a disc truncated at large distances from the BH. Such a truncated disc would have a colour temperature below 100 eV (by analogy with stellar-mass BHs), thus rendering its observation with *XMM-Newton* or *Chandra* practically impossible. If those ULXs are in the low/hard state, it would imply $L_{\text{Edd}} \gtrsim$ a few $10^{41} \text{ erg s}^{-1}$, corresponding to masses \gtrsim a few $10^3 M_{\odot}$. It would support the intermediate-mass BH scenario, but again we should ask why we never see those sources reaching their Eddington limit.

(2) Alternatively, they could be in the high/soft state, with a standard disc extending down to the innermost stable orbit, and X-ray luminosities $\gtrsim 0.1 L_{\text{Edd}}$. If so, we would expect that the phenomenological CD model should apply to both classes of sources: soft excess and pure power-law ULXs. Why then is the DISCBB component not detected in the latter class of ULXs? Perhaps their BH masses are even higher ($\gtrsim 10^4 M_{\odot}$), thus pushing the disc component into the UV band, outside our detection band. This interpretation clearly carries with it many BH formation problems.

(3) Another, more likely possibility is that the DISCBB component is so tiny that it is undetectable at a given signal-to-noise ratio. As far as we know, a longer observation may turn a pure power-law source

into a soft-excess source. In other words, we have to accept that at any given signal-to-noise ratio, there is a number of bright ULXs in which the disc is not directly visible at all – perhaps because its emission is almost entirely comptonized, including that from the inner disc. But this would undermine the possibility of inferring a mass from the fitted temperature of the cool thermal component, when present: that component may simply be residual emission from the outer disc, while the hotter inner disc may not be directly visible. In this scenario, bright ULXs could be in an extreme form of steep power-law state (McClintock & Remillard 2006). The discrepancy in the power-law slope between them and bright Galactic BHCs may be due to some missing details in our band-limited spectral fitting. For example, if ULXs and Galactic BHCs have different masses, we may be comparing their power-law slopes in two different energy ranges, in scaled units. Or, we may not be considering slight broad-band modifications to the power-law flux (e.g. reflection, or smeared emission/absorption lines) that lead to a wrong estimate of the slope – for example, making it appear flatter in the $\sim 2\text{--}5$ keV range, in bright ULXs.

(4) Finally, this unexplained slope of power-law continuum may be telling us that spectral state classifications in Galactic BHCs and ULXs are totally different. In that case, phenomenological models tested for Galactic BHCs may not be directly applicable, or may not have the same physical interpretation in ULXs.

2.4 Soft excess or soft deficit?

Both the phenomenological CD and HD models share the same bias: namely, that the dominant component of the spectrum is well determined by the observed emission at $\sim 2\text{--}5$ keV. For example, in the CD model, the spectrum is more or less a true power law in that energy range. Deviations from the assumed true power law at energies $\lesssim 2$ keV are thus cast in the form of a soft excess, while deviations at energies $\gtrsim 5$ keV can be dismissed as small-count statistics, or with the introduction of an ad hoc cut-off, or by assuming a low-temperature corona if we are using a more complex comptonization model. Similarly, the HD model assumes that the spectrum is a true disc-blackbody in that range, with its emission peak falling just below or around 5 keV. Again, this choice inevitably leads us to finding a soft excess below 2 keV, modelled with an additional thermal component. A possible reason for this bias is that the continuum in the $2\text{--}5$ keV spectral range is free from line-of-sight cold or warm absorption, hardly modified by any residual soft thermal-plasma emission, and has good spectral resolution and sensitivity in *Chandra* and *XMM-Newton*. Thus, if we use a power-law model, it appears natural to adjust its slope to fit that energy range, and then take care of any deviations.

Evidence for a change in the spectral slope in the $2\text{--}10$ keV band is given by Stobbart et al. (2006), who show that a broken power-law fit provides an improvement over a single power-law fit in eight out of 13 ULXs in their sample (see their tables 6 and 7). This supports the idea that most sources cannot be described by a single power-law continuum across the whole band. Thus, instead of estimating the continuum in the $2\text{--}5$ keV range, we could equally well assume that the continuum in the region $\sim 5\text{--}10$ keV is the true expression of the power law. If we do that, we find that most bright ULXs have a distinctive ‘soft deficit’. We would then try to devise complex physical models to explain that deficit, or, more simply, we would use phenomenological models. By analogy with the CD model, where a DISCBB component is used to account for the smooth, broad-band soft excess, we could select a smooth, broad-band absorption component. In fact, we propose here to use *the same* basic

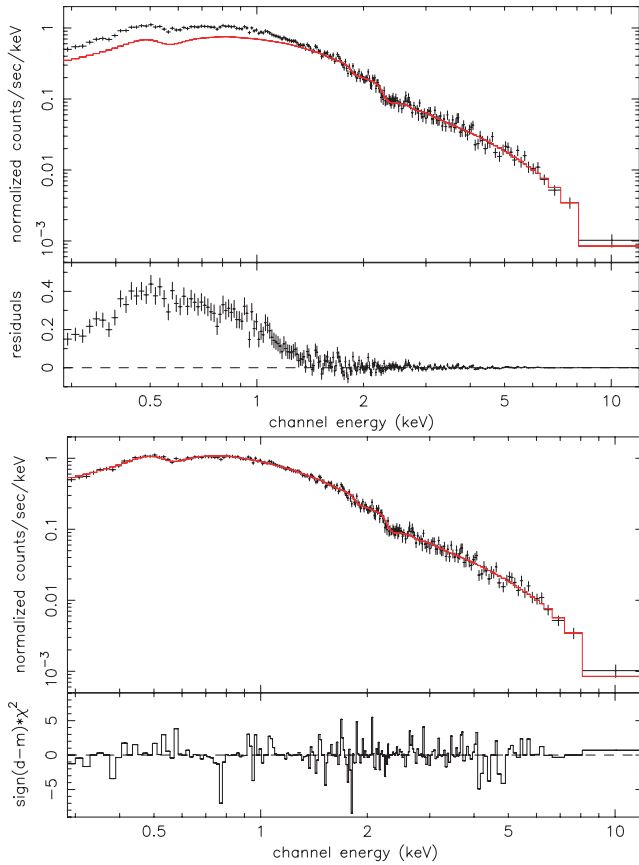


Figure 2. *XMM-Newton*/EPIC spectrum (co-added pn and MOS) and fit residuals for the Holmberg II X-1 ULX, observed on 2002 April 16 in its highest state (Dewangan et al. 2004). We have fitted the spectrum with an absorbed power law plus a *positive* disc-blackbody component (see Table 1 for the best-fitting parameters). In the top panel, we have removed the disc-blackbody component to illustrate the amount of ‘soft excess’ above the power-law flux. Taken at face value, the DISCBB temperature and normalization provide robust evidence of an IMBH.

phenomenological CD model of Miller et al. (2004), simply allowing for the DISCBB normalization to assume negative as well as positive values.

For this paper, we choose to illustrate this issue with a fit to Holmberg II X-1, leaving a more extensive analysis to further work. This is one of the sources in the Stobbart et al. (2006) sample for which a significant spectral slope change was reported ($>4\sigma$ improvement with respect to a single power-law fit); it is also one of the sources that appear to require an optically thick, low-temperature corona when fitted with comptonization models (Goad et al. 2006). The *XMM-Newton* data set studied by Goad et al. (2006) and Stobbart et al. (2006) was from 2004 April 15. Instead, the data we discuss here were obtained from an earlier 9.8-ks *XMM-Newton* observation taken on 2002 April 16, during the historically highest state for this source (Dewangan et al. 2004). To increase the signal-to-noise ratio, we co-added the European Photon Imaging Camera (EPIC) pn and MOS data, using the code of Page, Davis & Salvi (2003). We fitted the source spectrum with a $\text{WABS} \times \text{TBVARABS} \times (\text{DISCBB} \text{ plus } \text{PO})$ model to account for a (fixed) line-of-sight Galactic column as well as intrinsic, metal-poor absorption. We obtain a statistically good fit ($\chi^2_{\nu} = 222.1/214 = 1.04$), as expected, with the following parameter values (Fig. 2 and Table 1): intrinsic column density $N_{\text{H}} = (1.6 \pm 0.1) \times 10^{21} \text{ cm}^{-2}$ (at a metal abundance $\approx 0.6 Z_{\odot}$),

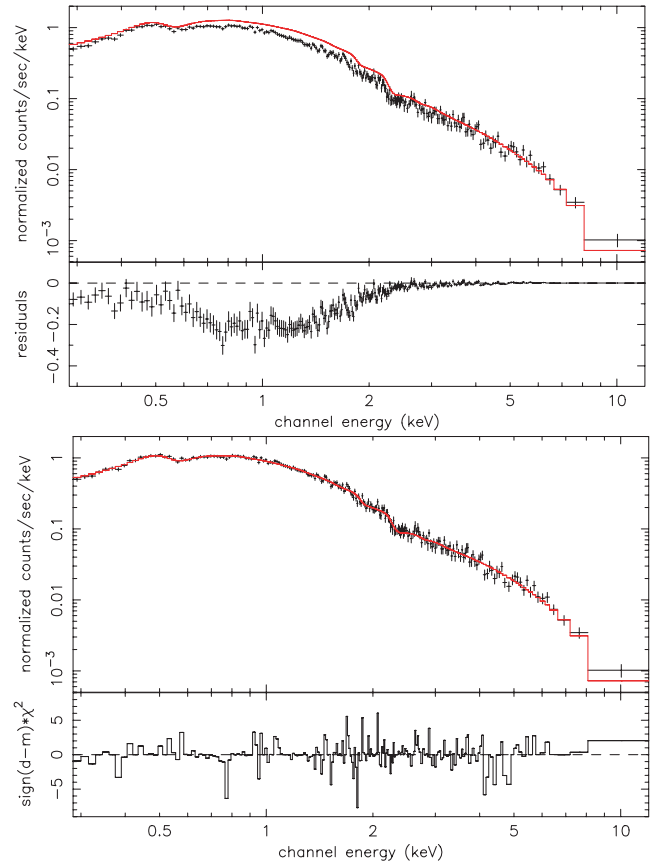


Figure 3. *XMM-Newton*/EPIC spectrum (co-added pn and MOS) and fit residuals for the Holmberg II X-1 ULX, as in Fig. 1. Again, we have fitted the spectrum with an absorbed power law plus a disc-blackbody component (see Table 1 for the best-fitting parameters). However, this time we have allowed the DISCBB normalization to be *negative*, obtaining an equally good fit, but with a power-law slope more consistent with the values found in bright Galactic BHCs. In the top panel, we have removed the disc-blackbody component to illustrate the amount of ‘soft deficit’ below the power-law flux. Taken at face value, the DISCBB temperature and normalization provide robust evidence of an iMBH.

power-law slope $\Gamma = 2.38 \pm 0.06$, inner-disc temperature $kT_{\text{in}} = 0.18 \pm 0.01 \text{ keV}$, DISCBB normalization $K = 245^{+270}_{-145}$. Taken at face value, this suggests a mass $M (\cos \theta)^{1/2} = 630^{+280}_{-230} M_{\odot}$.

However, we also obtain a good fit ($\chi^2_{\nu} = 222.3/214 = 1.04$), statistically indistinguishable from the other, with the following parameter values (Fig. 3 and Table 1): intrinsic column density $N_{\text{H}} = (1.9 \pm 0.1) \times 10^{21} \text{ cm}^{-2}$ (at a metal abundance $\approx 0.5 Z_{\odot}$), power-law slope $\Gamma = 2.67 \pm 0.09$, inner-disc temperature $kT_{\text{in}} = 0.52 \pm 0.06 \text{ keV}$, DISCBB normalization $K = -1.32^{+0.72}_{-1.27}$. Taken at face value, this suggests a mass $M (\cos \theta)^{1/2} = 45^{+19}_{-15} iM_{\odot}$, making it a robust imaginary-mass BH (iMBH) candidate.

Our preliminary investigation of other ULXs shows that a similar degeneracy is in fact common to many sources: in summary, a soft excess arises every time the power-law slope is constrained to fit the 2–5 keV range, while a soft deficit is found when the slope fits the 5–10 keV range. Either the excess or the deficit can then be accounted for, equally well, by adding or subtracting a DISCBB component. This degeneracy is a direct consequence of a change in slope at $\sim 5 \text{ keV}$ in many bright ULXs, with the spectrum becoming steeper at higher energies (Stobbart et al. 2006). If all we are looking for, in this phenomenological model, is a simple, robust ‘common

Table 1. Main best-fitting parameters for the *XMM-Newton*/EPIC spectrum of Holmberg II X-1, using a number of different phenomenological and physical models: phenomenological disc-blackbody models in emission and absorption (IMBH and iMBH, respectively), a comptonization model and our ionized outflow model; the HD model is not given here, as it does not provide an acceptable fit to this source. For DISCBB models, the characteristic mass (M_{BH}/M_{\odot}) $\times (\cos \theta)^{1/2}$ is defined as $(K_{\text{dbb}})^{1/2} \times (d/10 \text{ pc}) \times [1/(6 \times 1.5)]$. We then list the total unabsorbed flux ($f_{0.3-10}^{\text{tot}}$) and isotropic luminosity ($L_{0.3-10}$) in the 0.3–10 keV band; for the DISCBB models, we also give the unabsorbed flux that appears added ($f_{0.3-10}^{\text{em}}$) or subtracted ($f_{0.3-10}^{\text{abs}}$) to the power law in the form of soft excess or soft deficit.

Selected parameters	Model: WABS \times TBVARABS \times			
	(DISCBB + PO) ₊	(DISCBB + PO) ₋	BMC	(TABS + TEMI)
$N_{\text{H}} (\times 10^{21} \text{ CGS})$	$1.6^{+0.1}_{-0.1}$	$1.9^{+0.1}_{-0.1}$	$2.1^{+0.5}_{-0.4}$	$1.9^{+0.1}_{-0.1}$
Z/Z_{\odot}	$0.6^{+0.1}_{-0.2}$	$0.5^{+0.2}_{-0.1}$	$1.0^{+0.3}_{-0.3}$	$0.5^{+0.3}_{-0.2}$
Γ	$2.38^{+0.06}_{-0.06}$	$2.67^{+0.09}_{-0.09}$	$2.41^{+0.04}_{-0.04}$	$2.66^{+0.05}_{-0.05}$
$kT_{\text{in}} (\text{keV})$	$0.18^{+0.01}_{-0.01}$	$0.52^{+0.06}_{-0.06}$	–	–
K_{dbb}	245^{+270}_{-145}	$-1.32^{+0.72}_{-1.27}$	–	–
$kT_0 (\text{keV})$	–	–	$0.13^{+0.01}_{-0.01}$	–
$N_{\text{H}}^i (\times 10^{22} \text{ CGS})$	–	–	–	$3.2^{+0.4}_{-0.4}$
ξ	–	–	–	2740^{+750}_{-750}
χ^2_{ν}	222.1/214 (1.04)	222.3/214 (1.04)	231.2/214 (1.08)	213.5/213 (1.00)
$f_{0.3-10}^{\text{tot}} (\times 10^{-12} \text{ CGS})$	12.4	13.4	10.6	13.2
$f_{0.3-10}^{\text{po}} (\times 10^{-12} \text{ CGS})$	9.6	15.3	–	–
$ f_{0.3-10}^{\text{abs}} (\times 10^{-12} \text{ CGS})$	–	1.9	–	–
$f_{0.3-10}^{\text{em}} (\times 10^{-12} \text{ CGS})$	2.8	–	–	–
$L_{0.3-10} (\times 10^{40} \text{ CGS})$	1.8	2.0	1.6	2.0
$(M_{\text{BH}}/M_{\odot}) \times (\cos \theta)^{1/2}$	630^{+280}_{-230}	$45^{+10}_{-15} i$	$\approx 10^3$	–

currency’ modelling for the comparison of different sources, there is no need to prefer the positive rather than the negative variety. In fact, if anything, the soft-deficit scenario is more consistent with the interpretation of bright ULXs as analogous to BHCs in the steep power-law state, with additional absorption from heavily ionized metals around 1 keV. This would reconcile the power-law slope in ULXs with the typical indices seen in that spectral state for Galactic BHCs (Section 2.3).

Less phenomenological, more complex physical models would then show that the soft deficit is obviously not due to a negative DISCBB spectrum, but for example to smeared absorption lines. On the other hand, even the soft excess may not be true DISCBB emission, but instead caused by smeared emission lines and reflection. In practice, the situation is likely to be even more complicated, with a basic underlying power-law spectrum modified by a mixture of emission, absorption and reflection. Our definition of a soft excess or soft deficit is likely to have little absolute physical meaning, depending strongly on the fitting range and the detector sensitivity, in addition to real physical quantities.

3 BLURRED, IONIZED ABSORPTION AND EMISSION

3.1 Description of our model

Complex physical models based on blurred emission and absorption lines and reflection were developed, amongst others, by Ross, Fabian

& Ballantyne (2002), Gierlinski & Done (2004), Chevallier et al. (2006) and Crummy et al. (2006), initially to explain soft excess and reflection bumps in AGN. Here we develop Chevallier et al. (2006) model, based on the presence of highly ionized plasma in the line-of-sight of the primary X-ray source, and apply it to the observed spectra of bright ULXs.

In our modelling, we assume a primary source of radiation characterized by a power-law spectrum extending from 10 to 10^5 eV; we also assume that this primary emission is produced close to the BH, and we do not speculate at this stage what physical mechanism is responsible for it. Any medium surrounding this primary source will be radiatively heated and photoionized. If the ionized medium is sufficiently far from the ionizing source, we can treat it in a one-dimensional (1D) plane-parallel geometry, as a slab of gas illuminated from one side by a radiation field concentrated in a very small, pencil-like, shape centred on the normal direction. The resultant spectrum, reprocessed by such a medium, would be a combination of ‘reflection’ from the illuminated side (not a real reflection, as it includes atomic and Compton reprocessing), ‘outward emission’ (coming from the non-illuminated side of the medium) and a transmitted fraction of the incident ionizing continuum. The relative contribution of each component to the total, observed spectrum depends on parameters such as the size, density and geometry of the ionized medium. Those parameters are directly related to the covering factor: if this factor is very close to unity, only the outward emission plus the transmitted (partly absorbed) component will be observed; if it is small, then the primary source spectrum

can be observed together with the reflection and outward emission (see fig. 1 in Chevallier et al. 2006).

The models were computed using the photoionization code TITAN (Dumont, Abrassart & Collin 2000; Dumont et al. 2002; Collin, Dumont & Godet 2004), which is well suited for the study of both optically thick (Thomson optical depth up to several tens) and thin ionized media, such as warm absorbers (Gonçalves et al. 2006). Its advantage over other photoionization codes, such as CLOUDY (Ferland et al. 1998) or XSTAR (Kallman & Bautista 2001), is that it treats the transfer of both the lines and the continuum using the accelerated lambda iteration (ALI) method (see Dumont et al. 2003 for a description of the ALI method in the modelling of the X-ray spectra of AGN and X-ray binaries); in addition, it can work under constant total (gas plus radiation) pressure, thus offering a more adequate treatment of the highly ionized gas in the vicinity of a strong X-ray source (Gonçalves et al. 2006). TITAN includes all relevant physical processes from each level (e.g. photoionization, radiative and dielectronic recombination, ionization by high energy photons, fluorescence and Auger processes, collisional ionization, radiative and collisional excitation/de-excitation etc.) and all induced processes. It solves the ionization equilibrium of all the ion species of each element,² the thermal equilibrium, the statistical equilibrium of all the levels of each ion and the transfer of the lines and of the continuum. It gives as output the ionization, density and temperature structures, as well as the reflected and outward spectra. The energy balance is ensured locally with a precision of 0.01 per cent, and globally with a precision of 1 per cent; as a consequence, the total reflected and outward components, integrated over all solid angles, are constrained to be equal (within 1 per cent) to the primary ionizing spectrum, and the total output flux (leaving the gas slab from both sides) is the same as the injected flux.

All models were computed using the cosmic abundances of Allen (1973) and assuming the gas to be in total pressure equilibrium. They were then convolved with a relativistic wind (Chevallier et al. 2006) with a dispersion velocity $v = 0.1c$, which has the effect of blurring all the emission and absorption features. We have built separate grids of photoionization models for the absorption, emission and reflection components. The models in our grids are described by the following: the ionization parameter $\xi = L_i/n_H R^2$ (where L_i is the luminosity in the 0.01–100 keV range, n_H is the hydrogen number density at the illuminated side of the medium and R is the distance from the ionized plasma to the illuminating source); the column density N_H^i of the ionized gas and the spectral energy distribution of the incident X-ray flux, in our case a power-law spectrum parametrized by its photon index Γ . The ionized gas density n_H was set to 10^{11} cm^{-3} ; however, the output spectrum depends only very weakly on this parameter, which simply rescales the spatial size of the ionized gas region, for given values of ξ and N_H^i . Our grids cover the following parameter space: $1000 \leq \xi \leq 4000$, $10^{22} \leq N_H^i \leq 10^{23}$ and $2.4 \leq \Gamma \leq 3.3$. Finally, the model grids were converted into additive table models (ATABLE) in XSPEC, allowing us to fit real data. Additional neutral absorption, from cold gas further away in the local ULX environment and along the line-of-sight in our Galaxy, was also added within XSPEC. In practice, we found that the reflection component provides only a negligible improvement to our ULX fits, in agreement with a covering factor close to unity; therefore, only the absorption and emission components were taken

into account, thus reducing the number of free parameters in our models.

3.2 Fitting to real data

Once again, we fitted the *XMM-Newton*/EPIC spectrum of Holmberg II X-1 (Section 2.4), this time using our relativistically smeared ionized plasma models (labelled as TABS and TEMI in Tables 1 and 2). The best fit gives slightly better results ($\chi^2_\nu = 213.5/213 = 1.00$) than the phenomenological DISCBB fits (Fig. 4 and Table 1). The most significant best-fitting parameters are the following: an injection power-law spectrum with $\Gamma = 2.66 \pm 0.05$; a neutral absorber column density $N_H = (1.9 \pm 0.1) \times 10^{21} \text{ cm}^{-2}$ (in addition to the Galactic line-of-sight absorption), with metal abundance $Z \approx 0.5 Z_\odot$; a column density $N_H^i = (3.2 \pm 0.4) \times 10^{22} \text{ cm}^{-2}$ for the ionized plasma (ionization parameter $\xi = 2740 \pm 750$). As an aside, we also tried the HD model but it does not provide an acceptable fit to this source.

We then repeated the same exercise with the *XMM-Newton*/EPIC spectrum of another bright ULX displaying a curvature at higher energies ($>3\sigma$ improvement by using a broken power-law fit with respect to a single power law): NGC 4559 X-1. This source is often cited as an intermediate-mass BHC partly because of its cool soft-excess component (Cropper et al. 2004, where the source is identified as ‘X-7’, using the old *ROSAT* identification). In agreement with Cropper et al. (2004), we find that interpreting that component as cool disc-blackbody emission (using a positive DISCBB or any of the various comptonization models in XSPEC) leads to estimated masses $\sim 10^3 M_\odot$; the power-law index is $\Gamma \approx 2.2$ (Fig. 5, top panel, and Table 2). However, as for Holmberg II X-1, a negative DISCBB component with a steeper power-law index ($\Gamma \approx 2.7$) provides an equally good (in fact, better) fit; taken at face value, the disc-blackbody normalization corresponds to a mass $\approx 100 i M_\odot$ (Fig. 5, middle panel, and Table 2). For this source, the HD model also provides an acceptable fit to the data (Table 2); however, it is not as good as the alternative models. Finally, we obtained a good fit using our ionized plasma model,³ with $\Gamma \approx 2.7$ (Fig. 5, bottom panel, and Table 2).

It is not surprising that our relativistically smeared, photoionized plasma models provide good fits: after all, they provide broad, smooth emission and absorption bumps from the reprocessing of an injected power-law spectrum. We already know that the spectra of bright ULXs can be fitted by a steeper power law plus a broad absorption feature, or by a flatter power law plus a broad emission feature, or by a combination of both. Here, we argue that such absorption and emission bumps are easily, self-consistently produced by an X-ray irradiated plasma (i.e. not by optically thick accretion disc emission), under a plausible range of physical parameters, with the only more stringent condition that the lines be blurred by modest relativistic motions. The amount of blurring in our models (corresponding to a velocity dispersion $v/c = 0.1$) has been assumed based on the observations, so that we get smooth continuum and bumps, with no narrow features (see Chevallier et al. 2006). Such high velocities could be due, for example, to fast outflows, or Keplerian motion very close to the BH.

²Our atomic data include $\sim 10^3$ lines from ions and atoms of H, He, C, N, O, Ne, Mg, Si, S and Fe.

³In this case, the parameter ξ pegged at its lowest value of 1000; a better fit would have been obtained if our grids had extended to slightly lower values, which will be done in forthcoming works.

Table 2. As in Table 1, for the *XMM-Newton*/EPIC spectrum of NGC 4559 X-1.

Selected parameters	Model: WABS × TBVARABS ×				
	(DISCBB + PO) ₊	(DISCBB + PO) ₋	(BB + DISCBB)	BMC	(TABS + TEMI)
N_{H} ($\times 10^{21}$ CGS)	$2.5_{-0.3}^{+0.3}$	$2.6_{-0.3}^{+0.3}$	$0.9_{-0.1}^{+0.1}$	$2.1_{-0.4}^{+0.5}$	$2.6_{-0.4}^{+0.5}$
Z/Z_{\odot}	$0.5_{-0.2}^{+0.2}$	$0.3_{-0.1}^{+0.1}$	<0.1	$0.5_{-0.2}^{+0.3}$	$0.5_{-0.2}^{+0.3}$
Γ	$2.24_{-0.05}^{+0.05}$	$2.66_{-0.05}^{+0.05}$	–	$2.25_{-0.04}^{+0.04}$	$2.73_{-0.05}^{+0.10}$
kT_{in} (keV)	$0.14_{-0.01}^{+0.01}$	$0.42_{-0.03}^{+0.03}$	$1.35_{-0.05}^{+0.06}$	–	–
$K_{\text{d}bb}$	160_{-95}^{+340}	$-0.80_{-0.47}^{+0.35}$	$(9.1_{-1.7}^{+1.5}) \times 10^{-3}$	–	–
kT_0 (keV)	–	–	–	$0.11_{-0.01}^{+0.01}$	–
kT_{bb} (keV)	–	–	$0.18_{-0.01}^{+0.01}$	–	–
K_{bb}	–	–	$(4.4_{-0.01}^{+0.01}) \times 10^{-6}$	–	–
N_{H}^i ($\times 10^{22}$ CGS)	–	–	–	–	$3.7_{-0.2}^{+0.2}$
ξ	–	–	–	–	[1000]
χ^2_{ν}	216.7/208 (1.04)	199.8/208 (0.96)	229.6/208 (1.10)	215.2/208 (1.03)	205.5/208 (0.99)
$f_{0.3-10}^{\text{tot}}$ ($\times 10^{-12}$ CGS)	1.80	1.76	0.95	1.53	2.01
$f_{0.3-10}^{\text{po}}$ ($\times 10^{-12}$ CGS)	1.19	2.20	–	–	–
$ f_{0.3-10}^{\text{abs}} $ ($\times 10^{-12}$ CGS)	–	0.44	–	–	–
$f_{0.3-10}^{\text{em}}$ ($\times 10^{-12}$ CGS)	0.61	–	–	–	–
$f_{0.3-10}^{\text{hd}}$ ($\times 10^{-12}$ CGS)	–	–	0.62	–	–
$f_{0.3-10}^{\text{bb}}$ ($\times 10^{-12}$ CGS)	–	–	0.33	–	–
$L_{0.3-10}$ ($\times 10^{40}$ CGS)	2.0	2.0	1.1	1.7	2.2
$(M_{\text{BH}}/M_{\odot}) \times (\cos \theta)^{1/2}$	1400_{-500}^{+1600}	$100_{-25}^{+25} i$	11_{-1}^{+1}	$\approx 10^3$	–

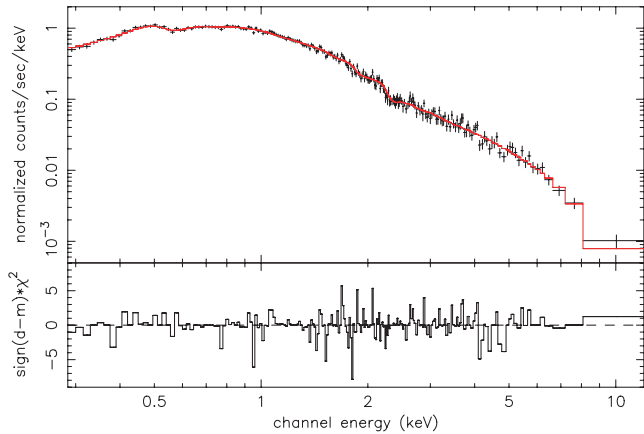


Figure 4. *XMM-Newton*/EPIC spectrum (co-added pn and MOS) and fit residuals for the Holmberg II X-1 ULX, as in Figs 1 and 2. Here, we have fitted the spectrum with a physical model based on an injection power-law spectrum, slightly modified by smeared emission and absorption lines from a slab of highly ionized gas in front of the X-ray source. See Section 3 for details of the model, and Table 1 for the best-fitting parameters. In this scenario, the disc is not directly visible.

4 SUMMARY AND DISCUSSION

4.1 The weakness of phenomenological models

Phenomenological models can successfully reproduce the observed X-ray spectral features of ULXs, and may be useful for the classi-

fication and comparison of different classes of sources, but are not necessarily more constrained, robust or reliable than complex physical models. In fact, they often introduce a dangerous bias, when we try to attribute them unwarranted physical meaning. The disc-blackbody component often used to model deviations from a pure power-law spectrum in ULXs and AGN is a classical example. We argued that the so-called soft excess can just as easily be described as a soft deficit, depending on the energy range to which we choose to fit the power-law continuum. A small change of the fitted power-law slope can turn an apparent absorption feature into an apparent emission feature. Both the excess and the deficit are well modelled with a disc-blackbody component in emission or absorption, respectively. This is simply because a disc-blackbody component is a versatile tool to model a broad, smooth bump or trough (especially if we can adjust both the temperature and the absorbing column density), regardless of its original meaning of an accretion disc spectrum. Similarly, it could be tempting to classify ULXs as stellar-mass objects, at least for those sources (see Stobbart et al. 2006) where a HD model reproduces the observed curvature around 5 keV better than a simple power law. Again, we argued that this is misleading: the curvature is likely to be unrelated to a true disc spectrum, and may instead be the signature of increasing, smeared absorption at energies below 5 keV.

A more physical model to bright ULX spectra is likely to require an injected power-law spectrum modified by the presence of an ionized medium in our line-of-sight, resulting in a combination of blurred, blended emission and absorption lines, and possibly also reflection bumps. Such kind of models would give a more natural explanation for the reason why the X-ray spectra of many bright

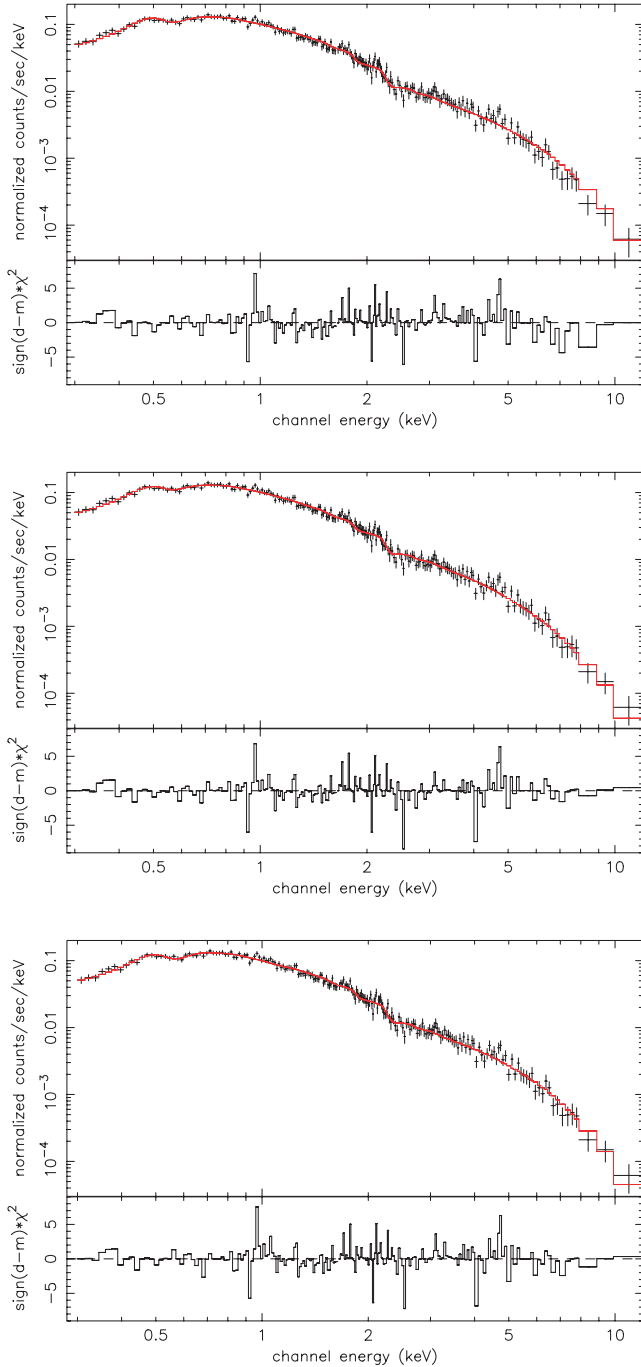


Figure 5. Three statistically good fits to the *XMM-Newton*/EPIC spectrum of NGC 4559 X-1 (Cropper et al. 2004), with three different models. Top panel: the spectrum is modelled with an underlying flatter power law ($\Gamma \approx 2.2$) plus a soft excess, approximated by a (positive) DISCBB component at 0.14 keV. Middle panel: the spectrum is modelled with a steeper ($\Gamma \approx 2.7$) power law with a broad absorption feature approximated by a (negative) DISCBB component at 0.42 keV. We argue that neither the positive nor the negative DISCBB component has any physical meaning or relation with the accretion disc; they are simply convenient, versatile components to model broad bumps. Bottom panel: the same spectrum, modelled with an underlying power law ($\Gamma \approx 2.7$) modified self-consistently by smeared emission and absorption lines caused by a layer of highly ionized gas. See Table 2 for the best-fitting parameters of all the three models.

ULXs and soft-excess AGN look somewhat similar. We have shown one recent implementation of such complex models, which we have developed thanks to the photoionization code TITAN, imported into XSPEC, and applied to two bright ULXs as an illustrative example for this paper. We are aware of the larger number of free parameters included in this kind of models, but we argue that they are less misleading than DISCBB models. Our modelling shows that it is possible to produce broad, smooth emission and absorption features when an injected power-law spectrum is seen through a highly ionized plasma with mildly relativistic motion. This may be an ad hoc condition at this stage, but it is probably less problematic than attributing those features to accretion disc emission. We do not speculate at this stage the geometry of the ionized plasma; we merely point out that such intervening medium would produce an effect consistent with what is observed. In principle, the relative contribution of the outward absorption and emission components to the observed spectrum could help us constrain the geometry of the ionized medium. However, this is not yet possible with the available X-ray data, because the true slope of the injected power-law component is not known a priori and cannot be precisely determined over the small energy range of our detectors. Further work on a more extended sample of ULXs (Soria et al., in preparation) will begin to explore this issue, at least on a statistical level. Future observations with instruments such as the Hard X-ray Telescope on *Constellation-X* will be needed to constrain the slope of the primary continuum over a larger energy range, and thus better determine the relative contribution of each component and the physical origin of the power law itself.

The uncritical use of a disc-blackbody model, interpreted as robust evidence of CD emission, has led to claims of BH masses $\sim 10^3 M_{\odot}$, skewing both observational and theoretical studies of ULXs towards the intermediate-mass BH (IMBH) scenario. The ionized-plasma model does not provide in itself evidence in favour or against IMBHs (in fact, it can also be applied to IMBHs and to even bigger BHs, in AGN); however, it implies that the deviations from a power-law spectrum seen in bright ULXs are not related to disc emission, and therefore are not a measure of their BH masses. Without this piece of information, the remaining evidence in favour of IMBHs is much weakened for the majority of ULXs (except for the brightest source in M82). Time-variability studies may provide a more critical test (e.g. Markowitz et al. 2003; Fiorito & Titarchuk 2004; Markowitz & Edelson 2004; Done & Gierlinski 2005; Uttley & McHardy 2005), at least for those few sources for which we have enough counts to investigate high-frequency quasi-periodic oscillations and breaks in the power density spectrum. In particular, the temporal behaviour of Holmberg II X-1 was studied by Goad et al. (2006), who found substantial variability on time-scales of months to years, but very little variability on time-scales of less than a day. Based on a combination of energy spectrum and power spectral density considerations, they concluded that Holmberg II X-1 was not likely to be in the disc-dominated high/soft state, and may instead have been in the steep power-law state (McClintock & Remillard 2006); this would be consistent with a BH mass $\lesssim 100 M_{\odot}$. For NGC 4559 X-1, a break in the power density spectrum was noted and discussed by Cropper et al. (2004). However, they concluded that the time-variability data available are not yet sufficient to constrain the mass range significantly: BH masses ~ 50 or $1000 M_{\odot}$ could both be consistent with the observed break frequency, if one takes different assumptions on the interpretation of that break and its scaling with BH mass. For most other ULXs, the strongest constraint to their BH mass remains their X-ray luminosity in comparison with the Eddington limit. This argument suggests an upper limit ~ 100 – $200 M_{\odot}$ if the emission is isotropic (Gilfanov, Grimm & Sunyaev

2004; Swartz et al. 2004) and even less if beamed. This may still be an order of magnitude higher than the mass of Galactic BHs, but may be accommodated with more ordinary star formation processes.

4.2 ULXs as a new spectral state?

Complex models based on ionized absorption, emission and reflection assume that the underlying X-ray spectrum is a power law, only slightly modified. This is also consistent with the detection of some bright ULXs with a pure power-law spectrum. How can the disc be not visible at all, not even as a small bump? We have argued that the brightness of those sources strongly disfavours models in which the disc is simply truncated far from the innermost stable orbit. A possible qualitative alternative is that the disc emission is completely comptonized in a non-thermal corona. This requires that most of the available gravitational power be efficiently released in the corona, or efficiently transferred from the disc to the corona – in this scenario, a magnetic disc/corona coupling could perhaps drain most of the energy from the disc at small radii (e.g. Kuncic & Bicknell 2004).

A related problem is to determine the low-energy cut-off to the power law which, we know for certain, does not extend to the optical band. In comptonization models, the low-energy cut-off identifies the characteristic temperature (or at least the lowest temperature) of the seed photons. In the ionized outflow model, the injected power-law component is assumed to extend without a break even below the *Chandra* or *XMM–Newton* energy band. This is also the case if we adopt a phenomenological disc-blackbody plus power-law model. Moreover, it appears to be the case for those bright ULXs that can be fitted with a simple power law. Taken at face value, this requires the presence of seed photons at energies $\lesssim 0.1$ keV; we speculate that UV photons from the outer disc and/or the donor star may also contribute as seed for the comptonization process. The fraction of such photons that may illuminate the comptonizing region and be upscattered depends on unknown parameters such as the radial and vertical size of the corona, the thickness and flaring angle of the disc, the spectral type and radius of the donor star, the binary separation.

A similar situation (i.e. dominant power-law component extending to energies $\lesssim 0.3$ keV and comparatively small disc component) appears to occur in the steep power-law state of Galactic BHCs (McClintock & Remillard 2006), and is not well understood in that case, either. Also, in that state, the disc contribution is already small compared to the power law. Goad et al. (2006) suggested that the temporal variability of Holmberg II X-1 is similar to that found in the Galactic BHC GRS 1915+105 in its steep power-law state (χ class). Thus, we speculate that ULXs represent a further spectral state, contiguous to the steep power-law state, in which the disc contribution is entirely negligible and, in addition, the dominant power-law component is modified by smeared emission and absorption from the surrounding, highly ionized, possibly outflowing gas. Interestingly, one of the effects of the broad absorption features at ~ 1 keV is to make the continuum appear flatter than the injected power law, over the 2–10 keV range, as we noted when comparing positive and negative disc-blackbody models (see also fig. 9 in Chevallier et al. 2006). This may be one reason why many bright ULXs in this class appear to have a flatter power-law slope, when fitted with a CD model, than Galactic BHCs in the steep power-law state (the latter presumably being less affected by highly ionized, fast outflowing plasma).

Such a spectral state could be shared by higher mass accretors such as AGN. Narrow line Seyfert 1s, in particular, display a soft X-ray excess and characteristic variability which could be associated with a steep power-law state. It has been shown (Chevallier et al. 2006) that the soft excess in AGN could be fitted with the same

relativistically smeared ionized plasma model applied here to ULXs. Thus, our approach offers a possible common explanation to the properties of ULXs, soft-excess AGN and Galactic BHs; it suggests that the main spectral features in this bright state depend on the physical parameters of the outflowing plasma, not on the mass of the accretor. A more detailed discussion of this issue is beyond the scope of this work; we shall address it in a forthcoming paper.

ACKNOWLEDGMENTS

We thank Zdenka Kuncic for discussions on the disc/corona coupling and Mat Page for pointing out the usefulness of combining EPIC spectra, and for letting us use his code. We also thank the anonymous referee for insightful comments and comparisons with previous work. ACG acknowledges support from the Fundação para a Ciência e a Tecnologia (FCT), Portugal, under grant BPD/11641/2002. RS acknowledges support from an OIF Marie Curie Fellowship, through University College London.

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