Soft-excess in ULX spectra: disc emission or wind absorption?

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Abstract. We assess the claim that Ultra-luminous X-ray sources (ULXs) host intermediate-mass black holes (BH) by comparing the cool disc-blackbody model with a range of other models, namely a more complex physical model based on a power-law component slightly modified at various energies by smeared emission/absorption lines from highly-ionized gas. Our main conclusion is that the presence of a soft excess, or a soft deficit, depends entirely on the energy range to which we choose to fit the “true” power-law continuum; hence, we argue that those components should not be taken as evidence for accretion disc emission, nor used to infer BH masses. 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 completely comptonized and not directly detectable, and the power-law emission may be modified by the surrounding, fast-moving, ionized gas.

Keywords: X-ray – Infall, accretion, and accretion discs – Black holes – X-ray binaries


1. THE NATURE OF ULXS: STELLAR-MASS BINARY SYSTEMS, OR INTERMEDIATE-MASS BLACK HOLES?

Ultraluminous X-ray sources (ULXs) are point-like, off-centre, accreting X-ray systems, with apparent isotropic X-ray luminosities up to a few $10^{40}$ erg s$^{-1}$, that is, they can be almost two orders of magnitude more luminous than the Eddington limit of typical Galactic black hole candidates (BHCs). The main unsolved issue is whether ULXs are powered by black holes (BHs) more massive than the BHCs, perhaps in the intermediate-mass range ($\sim 10^3 M_\odot$; Miller et al. 2004), or by 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 (e.g. King et al. 2001).

The standard way to determine the mass of an accreting black hole in X-ray binaries is based on phase-resolved spectroscopic and photometric studies of their optical counterparts. Attempts to apply similar techniques to ULXs have been inconclusive so far, mostly because of their optical faintness. 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 et al. 2006) may yield results for a few sources in the near future. Meanwhile, though, one has to rely on indirect methods to estimate the BH mass: either X-ray timing analysis (e.g. breaks in the Power Density Spectrum; Quasi-Periodic Oscillations), or spectral studies (e.g. X-ray data from ASCA, Chandra and XMM-Newton).
2. **THE X-RAY SPECTRA OF ULXS**

2.1. **Black hole mass determination**

One way of determining the black hole mass of ULXs 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, the slope being flatter in the low/hard state. In what concerns the thermal component, this is interpreted as the spectrum of an optically-thick Shakura-Sunyaev disc and contains, in principle, a direct dependence on disc size and BH mass. It is possible to provide a reasonable estimate of the BH mass in Galactic BHCs by modeling such a thermal component in XSPEC, through more or less complex implementations of the disc-blackbody model. 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.

2.2. **Hot-disc vs. cold-disc models**

For about a dozen of the brightest ULXs, it was noted (e.g. Miller et al. 2004) that the 0.3–10 keV spectrum is dominated by a featureless broad-band component, interpreted as a power-law plus a “soft-excess” significantly detected below 1 keV; for various sources, an additional thermal component with \( kT \sim 0.1–0.2 \) keV seems to lead to better fits. We call this interpretation the “cool disc” (CD) model. By analogy with Galactic BHCs, one can attribute true physical meaning to such phenomenological fits, interpreting the fitted temperature as the color temperature near the inner boundary of an accretion disc; this approach does not assume or require a specific physical model for the power-law component. If we apply the standard disc relation between temperature, luminosity and BH mass, we obtain characteristic mass values \( \sim 10^3 M_\odot \).

However, the CD model fitting is not unique. Good fits are also obtained, for many ULXs, using a disc with color temperature \( \sim 1.5–2.5 \) keV, which contributes most of the flux above 1 keV, plus a soft excess with characteristic blackbody temperature \( \sim 0.2 \) keV. We refer to this scenario as the “hot disc” (HD) model (Stobbart et al. 2006). A possible physical interpretation of the phenomenological HD model is that the harder emission comes from a “slim disc” (e.g. Watarai et al. 2001), typical of highly super-Eddington mass inflow rates onto stellar-mass BHs, with significant photon trapping. The softer component could be interpreted as downscattered photons in a cooler outflow or photosphere. An alternative approach, also successfully applied to Galactic BHCs,

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1 In fact, this relation may not be applicable to power-law dominated ULXs. We suggest elsewhere in these Proceedings (Soria et al. 2006) that in the framework of the CD scenario, a more accurate relation leads to a mass estimate \( \sim 50 M_\odot \). However here we stick to a discussion of the “conventional” interpretation of the CD model as a signature of intermediate-mass BHs (IMBHs).
FIGURE 1. Location of Galactic BHCs and ULXs in a disc temperature vs. X-ray luminosity plot; adapted from figure 3 in Stobbart et al. (2006). The CD (cold-disc) model implies that ULXs are intermediate-mass BHs, emitting well below their Eddington limit. The HD (hot-disc) model suggests that ULXs are stellar-mass objects (an extension of the Galactic BHC class), emitting above Eddington.

is to fit the X-ray spectra with a more complex, self-consistent model in which a power-law-like component arises as comptonized emission from seed thermal photons, upscattered in a corona. When such physical models are applied to bright ULXs, it is found (Goad et al. 2006; Stobbart et al. 2006) that the emission from the inner disc may be almost completely comptonized in a warm, optically-thick, but patchy corona.

CD and HD model make different assumptions and have been used to infer different BH masses and physical structures of the accretion flow. BH masses $\sim 10^3 M_\odot$, suggested by the CD model, require more complicated and so far untested formation scenarios; furthermore, in the CD model, ULX luminosities 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 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, and more constraining observations in other energy bands will be necessary to rule either one out. In its simplest, phenomenological form, the CD model does not explain the observed break in the spectral slope at energies $\geq 5$ keV; that can be taken into account only by more complex models in which the power-law component is replaced by comptonized emission emerging from a low-temperature corona. On the other hand, the HD model overpredicts that break. Spectral observations in the $\sim 15$–30 keV range will be crucial to determine whether that spectral feature is a change in slope or an exponential cutoff, and will provide a test between the two models. Finally, 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 Nuclei (AGN). Both kinds of spectra can formally be well fitted with a cool disc-blackbody component plus a power-law, but more likely the soft excess in AGN could be explained by a combination of blurred emission/absorption lines and reflection (Gierliński & Done 2004; Chevallier et al. 2006); this could suggest that ULXs and stellar-mass BHs are completely separate classes of sources. Instead, characteristic disc temperatures in the HD model fall within, or close to, the range of stellar-mass BH temperature; this could suggest that ULXs are simply an extension of the stellar-mass class at higher accretion rates.

2.3. Disc emission or wind absorption?

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 \( \sim 2–5\) 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 \( \leq 2\) keV are thus cast in the form of a soft excess, while deviations at energies \( \geq 5\) keV can be dismissed as small-count statistics, or with the introduction of an \textit{ad hoc} cut-off, or by assuming a low-temperature corona. 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.

Evidence for a change in the spectral slope in the 2–10 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 8 out of 13 ULXs; this supports the idea that most sources cannot be described by a single power-law continuum across the whole band (a similar degeneracy is in fact common to many ULXs). Thus, instead of estimating the continuum in the 2–5 keV range, we could equally well assume that the continuum in the region \( \sim 5–10\) 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 disc-blackbody component is used to account for the smooth, broad-band soft excess, we could select a smooth, broad-band absorption component. Figure 2 shows that both the soft deficit (left-hand panel) and the soft excess model (middle panel) account equally well for the observations.

Less phenomenological, but more complex physical models, would of course show that such a soft deficit is not due to a negative disc-blackbody spectrum, but for example to smeared absorption lines. 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 (Gonçalves & Soria 2006). Our modelling, illustrated in Fig. 2 (right-hand panel) with the spectrum of NGC 4559 X-1, 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 midly relativistic motion. This hypothesis seems less problematic than attributing those features to accretion disc emission.
FIGURE 2. Three statistically-good fits to the XMM-Newton/EPIC spectrum of NGC 4559 X-1 with 3 different models. Top left-hand panel: the spectrum is modelled with a steeper ($\Gamma \sim 2.7$) power-law with a broad absorption feature approximated by a (negative) disc-blackbody component at 0.42 keV. Top right-hand panel: the spectrum is modelled with an underlying flatter power-law ($\Gamma \sim 2.2$) plus a soft excess, approximated by a (positive) disc-blackbody component at 0.14 keV. We argue that neither the positive nor the negative disc-blackbody component has any physical meaning or relation with the accretion disc; they are simply convenient, versatile components to model broad bumps. Lower central panel: the same spectrum, modelled with an underlying power-law ($\Gamma \sim 2.7$) modified self-consistently by smeared emission and absorption lines caused by a layer of highly ionized gas. The best-fit parameters of these three models, and other pertinent information, are given in Gonçalves & Soria (2006).

3. CONCLUSIONS

The uncritical use of temperature-mass relations from the disc-blackbody model has led to claims of BH masses $\sim 10^3 M_\odot$, skewing both observational and theoretical studies of ULXs towards the IMBH scenario. We point out that this interpretation is far from unique. Specifically, we argue that: (i) the CD model may be correct, but the BH mass may be only $\sim 50 M_\odot$ (see our companion paper in these proceedings); (ii) for many ULXs, both the CD and HD models may be consistent with the observations; the latter scenario corresponds to a super-Eddington stellar-mass BH; (iii) both the CD and HD models may be incorrect: the deviations from the power-law spectrum could be due to reprocessing in an ionized outflow. This radically alternative ULX scenario is analogous to models previously applied to AGN. It implies that the deviations from a pure power-law spectrum are not related to disc emission, and therefore tell us nothing about the BH mass. Without this piece of information, the remaining evidence in favour of IMBHs is much weakened for the majority of ULXs. Both the CD and the ionized outflow models
imply that the X-ray spectrum is strongly dominated by a power-law component, with the disc emission being either comparatively small or entirely negligible.

A somewhat similar situation appears to occur in the steep-power-law state of Galactic BHCs. Goad et al. (2006) suggested that the temporal variability of Holmberg II X-1 is similar to that found in the Galactic BHC GRS J1915+105 ($M_{\text{BH}} \approx 15M_\odot$) in its steep-power-law state. We speculate that some 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 $\sim 1$ 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 (cf. Fig. 2). 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.

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