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ULTRA LUMINOUS X-RAY SOURCES: DISC MODELS AND ALTERNATIVE SCENARIOS

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Abstract. It was 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 in those sources. We assess this claim by comparing the cool disc-blackbody model with a range of other models. Using the XMM-Newton/EPIC spectra of NGC 4559 as an example, we show that 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. We also 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. 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, and that the observed deviations from such a continuum, which are usually modelled by disc-blackbody components, should not be taken as evidence for accretion disc emission, nor used to infer black hole masses.

1 Ultra-luminous X-ray sources

Ultra-luminous X-ray sources (ULXs) are point-like, off-centre, accreting X-ray sources, with apparent isotropic luminosities spanning a range from $\sim 10^{39}$ to $\approx 3\,10^{40}$ erg s^{-1}, that is, one or two orders of magnitude greater than the Eddington luminosity ($L_{\rm Edd}$). The main unsolved issue is whether these accreting sources are more massive than typical Galactic black hole candidates (BHCs), perhaps in the intermediate-mass range ($\sim 10^3 M_\odot$; Miller et al. 2004), or stellar-mass black holes 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, most reliable way to determine the mass of an accreting black hole (BH) 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 fruitless or inconclusive, so far, mostly because of their optical faintness (most candidates' optical counterparts are fainter than $V \sim 24$ mag). One has thus 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 Black hole mass determination through X-ray spectral data

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. More significantly, the thermal component, interpreted as the spectrum of an optically-thick Shakura-Sunyaev disc

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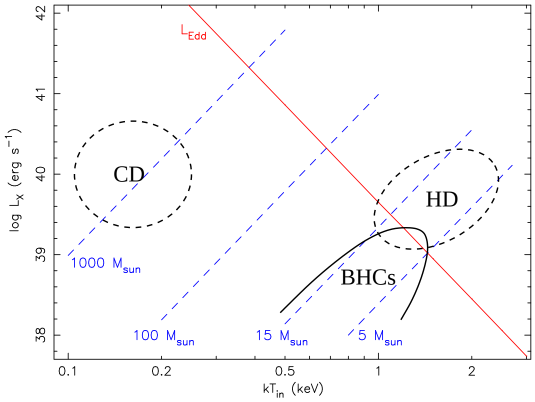

Fig. 1. Schematic plot showing the location of Galactic BHCs and ULXs in a disc temperature versus X-ray luminosity plot; adapted from fig. 3 in Stobbart et al. (2006). The CD (cold-disc) model implies that ULXs are intermediate-mass BHs, emitting well below their Eddington limit. The HD (hot-disc) model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

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.

2.1 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. By analogy with Galactic BHCs, one can interpret such phenomenological fits as true physical models and use the fitted temperature as the color temperature near the inner boundary of an accretion disc, thus obtaining 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 (Miller et al. 2006) in the comparison and classification 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 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 perhaps patchy, corona.

Although the cool-disc (CD; Miller et al. 2004) and the hot-disc (HD; Stobbart et al. 2006) models provide equally good fits to most ULXs, they make different assumptions, and arrive to very different results; here, we briefly discuss some of the strengths and weaknesses of the two scenarios: 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 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 have different kinds of drawbacks, and more constraining observations in other energy bands will be necessary to rule either one out. The standard relations between luminosity, inner-disc temperature and mass 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 contribution is important (Stobbart et al. 2006). Conversely, in the CD scenario, the disc contributes only ~ 5–20% of the X-ray luminosity; hence, a direct scaling of the disc quantities from Galactic BHCs may not be appropriate. Another drawback of the CD model is that it cannot explain the observed break in the spectral slope at high energies; the HD model predicts that

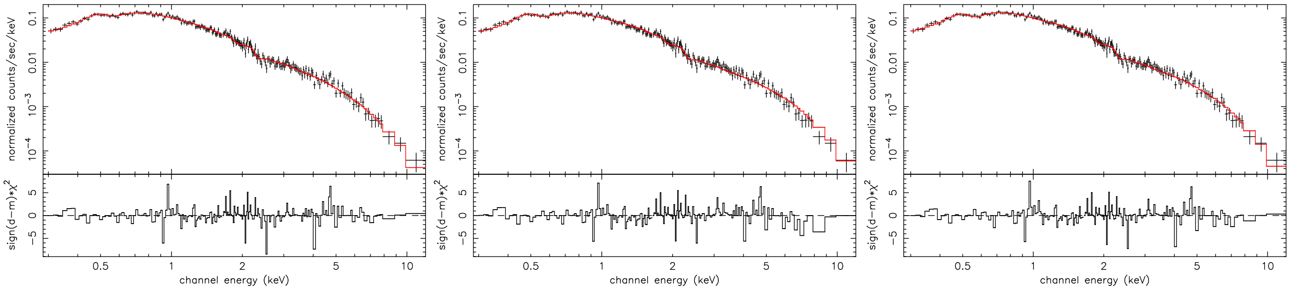

Fig. 2. Three statistically-good fits to the *XMM-Newton*/EPIC spectrum of NGC 4559 X-1 with 3 different models. Left-hand panel: the spectrum is modelled with a steeper ($\Gamma \approx 2.7$) power-law with a broad absorption feature approximated by a (negative) disc-blackbody component at 0.42 keV. Middle 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. Right-hand 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. The best-fit parameters of these three models, and other pertinent information, are given in Gonçalves & Soria (2006).

break. Spectral observations in the ~ 10–$20\,$keV region would provide a crucial 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 and absorption lines and reflection (Gierlinski & Done 2004; Chevallier et al. 2006). On the other hand, characteristic disc temperatures in the HD model fall within, or close to, the range of stellar-mass BH temperatures.

2.2 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 $\sim$ 2–5 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 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. 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. 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 components and the physical origin of the power-law itself.

3 Conclusions

The uncritical use of a disc-blackbody model, interpreted as robust evidence of cool disc 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 alternative scenario offered by 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. 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, 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.

A similar situation as observed in bright ULXs (i.e., dominant power-law component extending to energies ≤ 0.3 keV and comparatively small disc component) 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 1915+105 in its steep-power-law state. 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 (cf. Fig. 2). 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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