Astrophysics and Space Science
DOI 10.1007/sXXXXX-XXX-XXXX-X

Bridging the gap between stellar-mass black holes and ultraluminous X-ray sources

Robert Soria [1]

© Springer-Verlag ••••

Abstract The X-ray spectral and timing properties of ultraluminous X-ray sources (ULXs) have many similarities with the very high state of stellar-mass black holes (power-law dominated, at accretion rates greater than the Eddington rate). On the other hand, their cool disk components, large characteristic inner-disk radii and low characteristic timescales have been interpreted as evidence of black hole masses $\sim 1000 M_{\odot}$ (intermediate-mass black holes). Here we re-examine the physical interpretation of the cool disk model, in the context of accretion states of stellar-mass black holes. In particular, XTE J1550−564 can be considered the missing link between ULXs and stellar-mass black holes, because it exhibits a high-accretion-rate, low-disk-temperature state (ultraluminous branch). On the ultraluminous branch, the accretion rate is positively correlated with the disk truncation radius and the bolometric disk luminosity, while it is anti-correlated with the peak temperature and the frequency of quasi-periodic-oscillations. Two prototypical ULXs (NGC 1313 X-1 and X-2) also seem to move along that branch. We use a phenomenological model to show how the different range of spectral and timing parameters found in the two classes of accreting black holes depends on *both* their masses and accretion rates. We suggest that ULXs are consistent with black hole masses ~ 50–$100 M_{\odot}$, moderately inefficiently accreting at ≈ 20 times Eddington.

Keywords accretion, accretion disks — black hole physics — X-rays: binaries

Robert Soria

Harvard-Smithsonian Center for Astrophysics, 60 Garden st, Cambridge, MA 02138, USA

[1]MSSL, University College London, Holmbury St Mary, Dorking RH5 6NT, UK

1 Introduction

Black holes (BHs) are very simple systems, entirely characterized by mass and spin. However, accretion onto BHs is a much more complex process. Observationally, accreting stellar-mass BHs are found in various transient states, with different spectral and timing properties, and a different balance between mass-energy advection, radiation and outflows. For BHs in a binary system, accreting from a Roche-lobe-filling donor star, the main parameter that determines the accretion state is thought to be the mass accretion rate, or more precisely the mass inflow rate $\dot{M}$ at the outer edge of the accretion disk. This can be larger than the accretion rate through the BH horizon, if some of the gas is lost in outflows. The inflow rate depends on the nature and orbital separation of the companion star. It is convenient to rescale this rate as a dimensionless quantity, $\dot{m} \equiv \dot{M}/\dot{M}_{\rm Edd}$, where $\dot{M}_{\rm Edd} = L_{\rm Edd}/(0.1c^2)$ is the accretion rate that would be required to produce a luminosity $L = L_{\rm Edd} = 1.3 \times 10^{38}$ erg s^{-1} with a standard radiative efficiency = 0.1.

BHs accreting at a rate $\dot{m} \lesssim$ a few 10^{-2} are generally found in the low/hard state (Remillard and McClintock, 2006). Observationally, this is characterized by a cool, faint thermal disk and a hard power-law component (photon index $\Gamma \approx 1.5$–2). The power-law emission comes from the radiatively inefficient inner region of the inflow, and is probably due to inverse-Compton-scattering in a hot, optically-thin corona or at the base of a jet. The disk is sometimes truncated at a large distance from the innermost stable circular orbit. Radio studies suggest (Fender et al., 2004) that most of the accretion power is carried out by a steady jet (detected as flat-spectrum radio emission), with a possible advected component.

When $0.1 \lesssim \dot{m} \lesssim 1$, accreting BHs are typically dominated by an optically-thick, geometrically-thin disk, emitting a multicolour blackbody spectrum (Shakura and Sunyaev, 1973); this is known as high/soft state, or thermal-dominant state (Remillard and McClintock, 2006). Most of the accretion power is radiated efficiently. Advection is not significant, and jets are quenched.

What happens at $\dot{m} \gtrsim 1$ (very high state, or steep-power-law state) is less well known. Few Galactic BHs have reached this threshold, and only for short periods of time. The X-ray spectrum becomes dominated again by a non-thermal component, with the disk contributing $\sim$ 10–50% of the total flux. As in the low/hard state, the power-law emission may be due to Comptonization of the disk photons. Radiatively driven outflows are also expected, and radio flaring is observed in some sources. It is not clear whether the inner disk is covered or replaced by outflows, or by a corona. It is also not clear how the accretion power is transferred to or directly released in the upscattering medium.

A strictly related problem is the interpretation of ultraluminous X-ray sources (ULXs). Both their X-ray spectral and timing behaviour have similarities with the very high state. It was also suggested that ULXs may have high accretion rates $\dot{m} \gg 1$ (Begelman et al., 2006) or BH masses much higher than those of Galactic stellar-mass BHs (Miller et al., 2004). However, a clear understanding of the quantitative connection between ULXs and stellar-mass BHs is still missing. Here, we try to explore this comparison and determine whether ULXs are a separate class of BHs, or are stellar-mass BHs in a different accretion state.

2 Thermal disk equations for the high/soft state

We start by assuming that the disk extends all the way to the innermost stable circular orbit, so that

$$R_{\rm in} = R_{\rm ISCO} \equiv 6\alpha GM/c^2, \tag{1}$$

where α depends on the spin of the BH ($\alpha = 1$ for a Schwarzschild BH, $\alpha = 1/6$ for an extreme Kerr BH). The bolometric disk luminosity is directly related to the accretion rate, from general energy-conservation principles. Ignoring relativistic corrections,

$$L_{\rm disk} = \frac{GM\dot{M}}{2R_{\rm in}} \approx \frac{1}{12\alpha}\dot{M}c^2 \equiv \eta\dot{M}c^2, \tag{2}$$

where η is the radiative efficiency.

In the standard disk-blackbody model (Makishima et al., 1986, 2000), the bolometric disk luminosity is approximated by

$$L_{\rm disk} = 4\pi\sigma(T_{\rm in}/\kappa)^4(R_{\rm in}/\xi)^2 \equiv 4\pi\sigma T_{\rm in}^4 r_{\rm in}^2, \tag{3}$$

where: $T_{\rm in}$ is the peak colour temperature; $T_{\rm in}/\kappa$ is the peak effective temperature; κ is the hardening factor ($1.5 \lesssim \kappa \lesssim 2.6$); $r_{\rm in}$ is the "apparent" inner-disk radius. The numerical factor ξ was introduced (Kubota et al., 1998) to obtain a correctly normalized bolometric disk luminosity, taking into account that the fitted peak temperature occurs at $R = (49/36)R_{\rm in}$ because of the no-torque boundary conditions. With this approximation, and with the choice of $\kappa = 1.7$ (Shimura and Takahara, 1995), the physical inner-disk radius $R_{\rm in}$ is related to the apparent value $r_{\rm in}$ by:

$$R_{\rm in} \equiv (\xi^{1/2}\kappa)^2 r_{\rm in} \approx 1.19 r_{\rm in}. \tag{4}$$

The bolometric disk luminosity can be obtained from the observed (or extrapolated) flux:

$$L_{\rm disk} = 2\pi d^2 f_{\rm bol}(\cos i)^{-1}, \tag{5}$$

where i is the viewing angle ($i = 0$ means face-on). $T_{\rm in}$ can be directly inferred from X-ray spectral fitting[1]; $r_{\rm in}$ is derived from $L_{\rm disk}$ and $T_{\rm in}$ via Equation (3).

From Eqs. (1), (3), and (4) it follows that:

$$\begin{aligned} M &\approx \frac{c^2\xi\kappa^2\eta}{G(\sigma\pi)^{1/2}}\, L_{\rm disk}^{1/2}\, T_{\rm in}^{-2} \\ &\approx 10.0\left(\frac{\eta}{0.1}\right)\left(\frac{\xi\kappa^2}{1.19}\right)\left(\frac{L_{\rm disk}}{5\times10^{38}\ {\rm erg\ s^{-1}}}\right)^{1/2} \\ &\quad \times\left(\frac{kT_{\rm in}}{1\ {\rm keV}}\right)^{-2} M_\odot, \end{aligned} \tag{6}$$

which can also be expressed as $L_{\rm disk} \sim M^2 T_{\rm in}^4$. This is the fundamental evolutionary track of an accretion disk in the thermal-dominant state. Despite the various approximations, Eq. (6) works well (within a factor of 2) when applied to the masses of Galactic BHs, assuming radiative efficiencies $\lesssim 0.2$.

3 Tracks in the luminosity–temperature plane

3.1 Evolution along the thermal track

As its accretion rate varies, a source in the high/soft state moves along a track of constant M and $R_{\rm in}$. This track typically extends for about one order of magnitude in luminosity (e.g., Kubota and Makishima, 2004; Miller et al., 2004). At the upper end, it is truncated where the disk luminosity approaches the classical Eddington limit, $L_{\rm Edd} \approx 1.3 \times 10^{38}(M/M_\odot)$ erg s^{-1}. At

[1] the most commonly used implementation of the disk-blackbody model is `diskbb` in XSPEC (Arnaud, 1996).

the lower end, it ends as the source reverts to the low/hard state.

Another process that causes the source parameters to slide along the thermal track is the removal of a fraction of power $\epsilon > 0$, extracted from the disk at each radius (independent of radius). For example, this energy may be used to power a corona. As a result, the peak temperature $T_{\rm in} \rightarrow T'_{\rm in} = (1-\epsilon)^{1/4} T_{\rm in}$, and $L_{\rm disk} \rightarrow L'_{\rm disk} = (1-\epsilon) L_{\rm disk}$. Neither $R_{\rm in}$ nor $r_{\rm in}$ changes; the emitted spectrum is still a disk blackbody. This scenario is equivalent to changing the effective accretion rate $\dot{M} \rightarrow \dot{M}' = (1-\epsilon)\dot{M}$. In summary, changes in the accretion rate, or the (uniform) draining of power via non-radiative processes, do not affect the BH mass estimate from the fitted disk parameters via in Eq. (6).

3.2 Evolution off the thermal track

As the accretion rate approaches or exceeds the Eddington limit, an increasing fraction of the photons emitted by the disk are mildly upscattered by hot electrons at the disk photosphere. This can be modelled by increasing the hardening factor κ, typically from ≈ 1.7 to ≈ 2.5 (Davis et al., 2005; 2006). In the $(T_{\rm in}, L_{\rm disk})$ plane, the effect is to move the source horizontally to the right: higher colour temperature $T_{\rm in}$ but same effective temperature $T_{\rm in}/\kappa$ and same luminosity $L_{\rm disk}$. The true inner-disk radius $R_{\rm in}$ does not change, while the apparent disk radius decreases: $r_{\rm in} \rightarrow r'_{\rm in} = [\kappa/(\kappa+\Delta\kappa)]^2 r_{\rm in}$. This does not affect the mass estimate, which depends on $T_{\rm in}/\kappa$.

Another effect that needs to be taken into account is a partial covering of the disk surface: a fraction X of photons may be absorbed or more generally removed from the disk-blackbody spectrum by clouds or a moderately optically-thick corona. They are re-emitted in other spectral bands or components (e.g., X-ray power-law, or infrared). In a self-consistent analysis, one must account for all upscattering, downscattering and absorption effects, redistributing the (fixed) total available accretion power into the various components. But for the purpose of relating the disk emission parameters to the BH mass, we can simply consider those photons as being lost from the disk spectrum. The effect is to reduce the observed disk flux and luminosity: $L_{\rm disk} \rightarrow L'_{\rm disk} = (1-X) L_{\rm disk}$. The spectral shape is not altered. The peak colour temperature $T_{\rm in}$ is not changed. $R_{\rm in}$ stays the same but the apparent disk radius decreases: $r_{\rm in} \rightarrow r'_{\rm in} = (1-X)^{1/2} r_{\rm in}$, because $r_{\rm in}$ is indirectly derived from the flux normalization. The BH mass inferred from Eq. (6) is a factor $(1-X)^{1/2}$ less than the true mass.

The combined effect of spectral hardening and Compton upscattering is to move the location of the source to the right-hand-side of its thermal track, in the $(T_{\rm in}, L_{\rm disk})$ plane (Figure 1). Physically, it leads to lower estimates for the fitted radius $r_{\rm in}$ (sometimes much lower than the innermost stable orbit), and may lead to an underestimate of the BH mass if not properly accounted for. As expected, accreting BHs occupy this region of the parameter space when they are in their very high state (or steep-power-law state) (Remillard and McClintock, 2006), at accretion rates higher than in the high/soft state.

4 The very high state

4.1 Very high state in the stellar-mass BH H1743−322

The Galactic BH H1743−322 provides a textbook example of state transitions (McClintock et al., 2007). It showed a strong outburst between 2003 April and 2003 October (Markwardt and Swank, 2003; Miller et al., 2006). Starting from the low/hard state, it remained hard (power-law dominated) as it quickly increased in luminosity, until it reached the very high state near the peak of its outburst (as monitored by *RXTE*). It then oscillated between the very high and the high/soft state, eventually settling in the high/soft state near the high-luminosity end of the thermal track. Then, it moved downwards along the thermal track (decreasing $\dot{m}$) and finally returned to the low/hard state (McClintock et al., 2007).

Significantly, the disk parameters were always on the right-hand-side of the thermal track in the $(T_{\rm in}, L_{\rm disk})$ plane (Figures 2 and 3), suggesting that we were always seeing a full disk, partly modified by Comptonization. There is no indication that the inner boundary of the disk retreated to larger radii at any stage, either in the low/hard or in the very high state (Figure 4), even when most of the X-ray flux was carried out by the power-law component. The disk appeared subluminous for its temperature, compared to the thermal track, because some disk photons had been removed from the observed thermal component. Spectral fits give higher peak colour temperatures, and lower apparent radii, when the source was power-law dominated. This behaviour is typical of other (transient) Galactic BHs with low-mass donor stars; for example, GRO J1655−40 during the 1996 outburst (Sobczak et al., 1999).

4.2 Very high state in ULXs?

In many respects, ULXs are consistent with being in the very high state, based on their X-ray spectral and timing properties (e.g., Done and Kubota, 2006; Dewangan et al., 2006; Goad et al., 2006; Strohmayer et al., 2007). However, one of the reasons it has been difficult to interpret their nature unequivocally is that their X-ray spectra can often be fitted equally well, in our limited observing window ($\sim$ 0.3–10 keV), with a variety of phenomenological or physical models, each corresponding to a very different physical scenario. Examples of this degeneracy are discussed for example in Gonçalves and Soria (2006), Stobbart et al. (2006), Feng and Kaaret (2007). In addition, sometimes the same phenomenological fitting model can have two completely different physical interpretations. In the "standard" phenomenological model (sometimes known as the "cool disk model"), which seems to be applicable to the majority of sources, ULX spectra have a dominant power-law component, with a thermal (disk?) component contributing $\sim$ 10–50% of the X-ray flux (Stobbart et al. 2006). Their fitted temperatures are typically a few times lower than in stellar-mass BH disks, and their apparent inner-disk radii are two orders of magnitude higher. Spectral hardening and partial covering of the disk cannot explain this difference. If ULXs lie near or on the right-hand-side of their thermal tracks, their BH masses ought to be two orders of magnitude higher than in Galactic systems. This argument has been invoked in support of intermediate-mass BHs (Miller et al., 2004). This *physical interpretation of the cool disk model* may be unsatisfactory, until independent evidence is found for the formation of intermediate-mass BHs in the local Universe. We need to search for a simpler physical interpretation of the cool disk model that does not require new astrophysical objects.

5 Ultraluminous branch in XTE J1550−564

XTE J1550−564 is one of the best-known microquasars; its BH has a dynamical mass $\approx 10 M_{\odot}$ (Orosz et al., 2002). There is some evidence that the source was in a low/hard state at the beginning of the 1998 September – 1999 April outburst, just before the initial steep rise (Sobczak et al., 2000). In the early phase of the outburst, when the integrated X-ray luminosity and presumably the accretion rate were at their peaks, the X-ray spectrum was dominated by a power-law, with a relatively minor disk contribution. This, and the presence of characteristic low-frequency quasi-periodic-oscillations (LF-QPOs), are typical signatures of the very high state (Remillard and McClintock, 2006). However, there was an important difference. During the first (brightest) four weeks of the outburst, the source spent some time in the "normal" very high state, on the right-hand-side of its thermal track, and some time well to the left of that track. This is

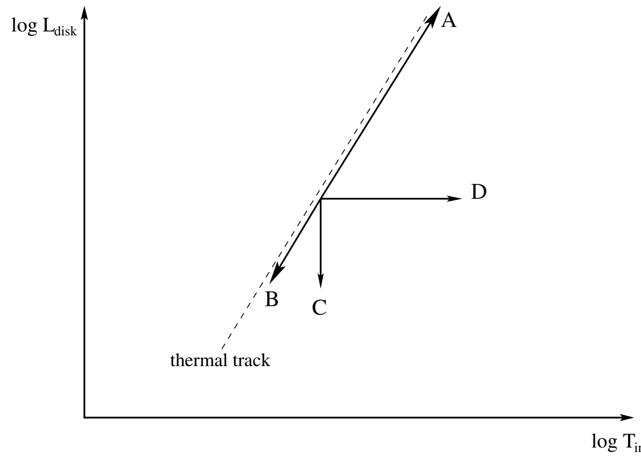

Fig. 1.— Relation between high/soft state (thermal track $L_{\rm disk} \sim T_{\rm in}^4$ marked by the dashed line) and very high state. Source parameters move up along the track (A) when $\dot{m}$ increases; move down (B) when $\dot{m}$ decreases or when a fraction of power is transferred to an optically-thin corona. Partial covering of the disk (C) and hardening of the photon spectrum (D) move the source parameters to the right-hand-side of the track (very high state). From Soria and Kuncic (2007a).

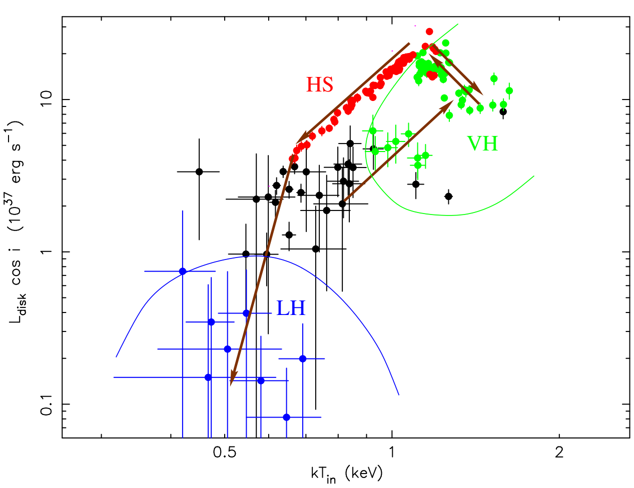

Fig. 2.— Spectral evolution of the stellar-mass BH H1743−322 in the temperature–luminosity plane, during the 2003 April–October outburst (data from McClintock et al., 2007). The source parameters are always located on the right-hand-side of the thermal track; this suggests that the disk extends to $R_{\rm ISCO}$ even when it is partly modified by a corona. Red datapoints mark the thermal-dominant state, as identified by McClintock et al. (2007); green circles are for the very high state; blue circles for the low/hard state; black circles for intermediate or transition states. We assumed a distance of 10 kpc; the viewing angle is unknown.

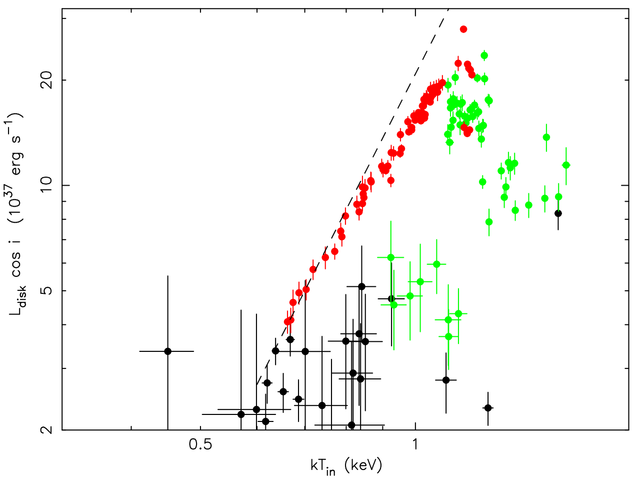

Fig. 3.— Close-up view of the high/soft and very high states in the outburst of H1743−322; colours are defined as in Figure 2. The dashed line marks the thermal track. As the accretion rate increases, the source deviates more and more from the thermal track (see also Figure 1).

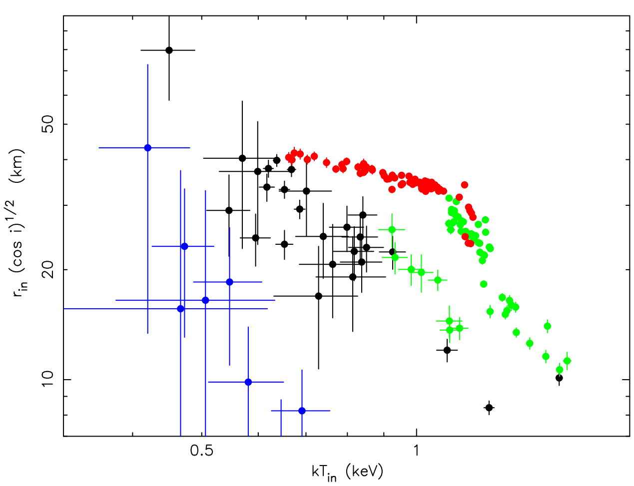

Fig. 4.— Apparent inner-disk radius for H1743−322, plotted as a function of the peak colour temperature of the disk. Colours are defined as in Figure 2. In the high/soft state, $r_{\rm in} \approx R_{\rm ISCO}$ (Eq. 4). In all other states, $r_{\rm in} < R_{\rm ISCO}$, suggesting a full disk corrected by a variable hardening factor due to Comptonization.

clearly noticeable both in the original set of spectral models (Sobczak et al., 2000, which we reproduce here in Figure 5), and in the re-analysis of the data done by Kubota and Done (2004) with more complex spectral models. When XTE J1550−564 was on the left of the track, the peak temperature of the disk was much cooler than in the normal very high state, and the fitted inner-disk radius was much larger than the innermost stable orbit. This behaviour has not been seen before in other stellar-mass BHs, but may provide a clue to understand ULXs. The new state was interpreted (Kubota and Done, 2004; Done and Kubota, 2006) as a "strong very high state" in which the disk may not extend to the innermost stable orbit or may be covered by a dominant comptonizing corona. We refer to this new state as "ultraluminous branch" (Figures 5, 6).

At a later stage of the outburst, as the mass accretion rate was probably declining, XTE J1550−564 moved back to the right-hand-side of the thermal track, and oscillated a couple of times over the following few months between this state and the high/soft state (perhaps in response to a moderatley variable but still rather high accretion rate). Eventually, the source declined, moving downwards along the thermal track. As it re-entered a low/hard state, the disk parameters moved again to the left of the thermal track (Figure 5, 6).

6 Physical interpretation of the ultraluminous branch

Spectral hardening and partial upscattering of the disk photons do not explain why the disk should appear larger and cooler, at such high X-ray luminosities; one might expect the opposite behaviour. Since the BH mass does not change, a large apparent radius is generally explained as evidence of a truncated or invisible inner disk. Indeed, it has been suggested (Done and Kubota, 2006; Dewangan et al., 2006; Goad et al., 2006) that when the source is on the ultraluminous branch, all the photons emitted from the inner disk are upscattered by an optically-thick, low-temperature corona. What we still see as direct disk emission comes from further out, beyond a transition radius $R_{\rm c} \gg R_{\rm ISCO}$, where the disk is also cooler. Another possibility is that the inner disk is disrupted or simply occulted by an optically-thick, radiatively-driven outflow (Poutanen et al., 2006; Begelman et al., 2007). Alternatively, the inner disk may still be present and directly visible, but most of its accretion power is extracted via non-radiative processes, such as mechanical outflows or Poynting flux (Kuncic and Bicknell, 2004). In this case, the peak temperature occurs much further away from the inner

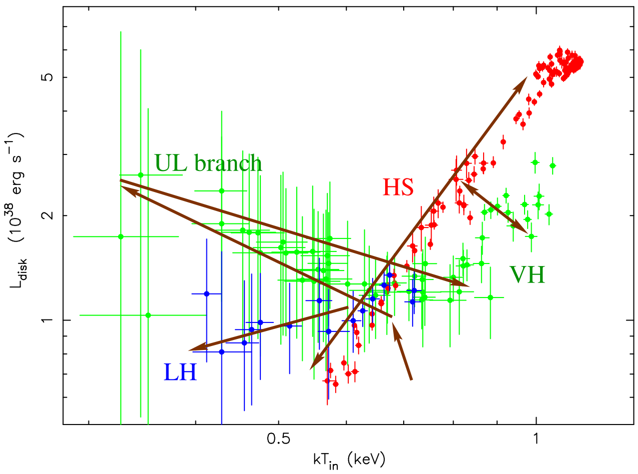

Fig. 5.— Luminosity-temperature plot for the stellar-mass BH XTE J1550−564 during its 1998 September – 1999 April outburst. Accretion states are colour-coded as in Figure 2. What was traditionally classified as the very high state (green datapoints) is split here into two states, approximately defined as being on the left (ultraluminous branch) and on the right (very high state) of the thermal track. Arrows indicate the approxime evolution track during the outburst. The fit parameters are from Sobczak et al. (2000), and we assumed a distance of 5 kpc and a viewing angle $i = 70°$.

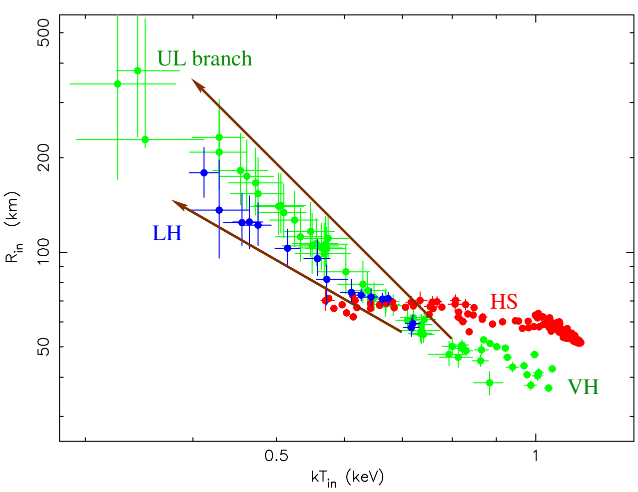

Fig. 6.— Inner-disk radius of XTE J1550−564 plotted as a function of peak colour temperature. Accretion states are colour-coded as in Figure 2. A constant conversion factor $R_{\rm in} = 1.19 r_{\rm in}$ was used for all datapoints. The radius becomes $\gg R_{\rm ISCO} \approx$ 60–70 km when the source is on the ultraluminous branch; the disk temperature decreases along the same branch. An apparently retreating disk is also found in the low/hard state.

disk edge. Some of the power released through non-radiative channels would then be converted to power-law photons. We leave a more detailed discussion of the physical interpretation of the transition radius to further work (Soria and Kuncic, 2007b).

An important question to ask is whether the ultraluminous branch corresponds to a higher or lower accretion state than the classical very high state. The detected 2–20 keV flux (*RXTE* data, Sobczak et al., 2000) was higher in the very high state. However, that is not necessarily a good indicator of the total luminosity, especially when the disk emission is very soft, nor of the accretion rate. For example, the total luminosity at the top of the thermal track is $\approx L_{\rm Edd}$, with a radiative efficiency $\gtrsim 0.1$. The non-thermal processes responsible for the dominant power-law emission in the very high and ultraluminous states are expected to have lower radiative efficiency. So, the total luminosity may still be $\approx L_{\rm Edd}$, just differently redistributed between thermal and non-thermal components, even if $\dot{m} \gtrsim$ a few. In the case of XTE J1550−564, the total disk plus power-law flux is at least as high, and probably slightly higher, along the ultraluminous branch (Soria and Kuncic, 2007b). More importantly, the disk luminosity is slightly increasing along the ultraluminous branch, for an increasing inner-disk radius. This can happen (recall Eq. 2) only if the accretion rates also increases along the ultraluminous branch (even if the total luminosity did not). The fact that XTE J1550−564 reached both the very high state and the ultraluminous branch in the first, more energetic phase of its outburst, and only (briefly) the very high state in the second, weaker phase (Sobczak et al., 2000) also suggests that the ultraluminous branch corresponds to a higher activity state. As the source started to decline, it went from very high state to high/soft state, and finally to low/hard state, consistent with this interpretation.

7 Disk parameters on the ultraluminous branch

A plausible phenomenological way to model the disk parameters on the ultraluminous branch is to assume a transition radius $R_{\rm c} \gg R_{\rm ISCO}$. For $R > R_{\rm c}$, the inflow can be approximated by a standard disk, such that

$$L_{\rm disk} \approx 4\pi\sigma T_{\rm c}^4 R_{\rm c}^2, \qquad (7)$$

where $T_{\rm c} \equiv T(R_{\rm c})$ is the maximum (observable) disk temperature. For $R_{\rm ISCO} < R < R_{\rm c}$, we assume that all the accretion power comes out in the power-law-like component, and the standard disk either is not directly visible, or is disrupted, or emits a negligible direct flux.

So, regardless of the details, R_c will appear as the inner radius when we fit the disk spectrum. In this scenario, Eq. (1) no longer holds or is no longer relevant to the observed spectrum. It is replaced by

$$R_c = F R_{\rm ISCO} \tag{8}$$

with $F = F(\dot{m}) > 1$. The visible disk radiates only the accretion power released from the outer radius to R_c. The effective radiative efficiency of that part of the inflow $\sim M/R_c \sim 1/(12\alpha F) < 0.1$. Therefore, we have (cf. Eqs. 2 and 6):

$$L_{\rm disk} \approx \frac{GM\dot{M}}{2R_c} \approx \frac{1}{12\alpha F}\dot{M}c^2 \equiv \frac{\eta}{F}\dot{m}Mc^2 \tag{9}$$

$$\begin{aligned} M &\approx \frac{10.0}{F}\left(\frac{\eta}{0.1}\right)\left(\frac{\xi\kappa^2}{1.19}\right)\left(\frac{L_{\rm disk}}{5\times10^{38}\ {\rm erg\ s^{-1}}}\right)^{1/2} \\ &\quad \times \left(\frac{kT_{\rm in}}{1\ {\rm keV}}\right)^{-2} M_\odot \\ &\approx \frac{790}{F}\left(\frac{\eta}{0.1}\right)\left(\frac{\xi\kappa^2}{1.19}\right)\left(\frac{L_{\rm disk}}{5\times10^{39}\ {\rm erg\ s^{-1}}}\right)^{1/2} \\ &\quad \times \left(\frac{kT_{\rm in}}{0.2\ {\rm keV}}\right)^{-2} M_\odot, \end{aligned} \tag{10}$$

where the first expression for M is scaled to the typical values observed in stellar-mass BHs, and the second one is scaled to typical ULX parameters. An estimate of the BH mass based only on the disk luminosity and temperature, without taking into account the truncation factor F, will necessarily over-estimate the BH mass. We argue that this is the main reason why the intermediate-mass BH hypothesis is probably incorrect.

Hence, to estimate the BH mass and accretion rate of a source on the ultraluminous branch (Eqs. 9 and 10), we need to measure $F = R_c/R_{\rm ISCO}$ directly, or model its dependence on $\dot{m}$. For XTE J1550−564, we see that the apparent radius increases by a factor $F \approx 6$–8 along that branch (Figure 6). For ULXs, we do not have a complete coverage of state transitions, and we do not know the BH mass independently. The simplest way to estimate F, at least as an order of magnitude, is to assume that all of the accretion power released at $R > R_c$ is radiated by the disk, and some or most of the power released at $R_{\rm ISCO} < R < R_c$ is eventually radiated as power-law photons, without contributing to the thermal disk component. From Eqs. (2) and (9), we get $F \gtrsim L_{\rm tot}/L_{\rm disk}$. The inequality sign takes into account the fact that the radiative efficiency of the non-thermal processes in the inner region is less than the efficiency of blackbody emission in a standard disk. For the most luminous nearby ULXs, extrapolating from the relative fluxes of the power-law and thermal components in the 0.3–10 keV band, the luminosity ratio $L_{\rm tot}/L_{\rm disk} \sim 3$–20; in a few other, more distant ULXs, there is only a lower limit $\gtrsim 10$ for this ratio (Stobbart et al., 2006; Winter et al., 2006). Hence, we infer that $F \gtrsim 10$ for typical ULXs.

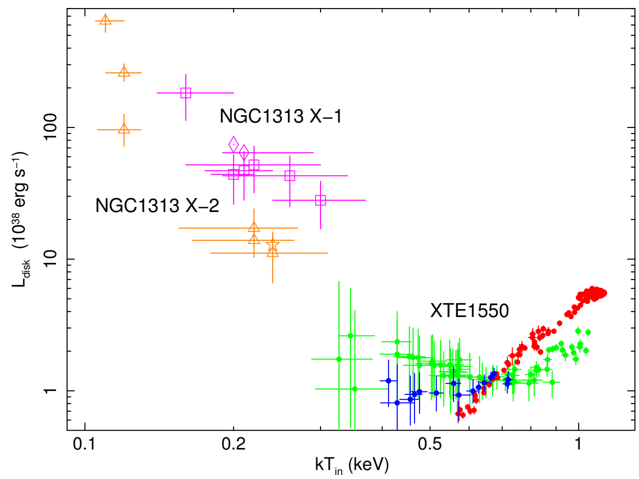

Fig. 7.— As in Figure 5, but with two ULXs (NGC 1313 X-1 and X-2) plotted alongside the stellar-mass BH XTE J1550−564. Both ULXs show an anticorrelation between disk luminosity and temperature. This suggests that they are also on their respective ultraluminous branches. Unlike XTE J1550−564, they never occupy any other accretion state. The colour coding of the XTE J1550−564 datapoints is the same as in Figure 2. Datapoints (and, where available, error bars) for NGC 1313 X-1 are plotted in magenta; squares are for the *XMM-Newton* data (Feng and Kaaret, 2006, 2007), and diamonds for the *Suzaku* data (Mizuno et al., 2007). Datapoints for NGC 1313 X-2 are plotted in orange (triangles for the *XMM-Newton* data and a star for the *Suzaku* data).

8 Observational predictions

From the fitted disk luminosities and temperatures (e.g., Miller et al., 2004; Feng and Kaaret, 2005; Stobbart et al., 2006), typical values of $R_c \gtrsim 5000$ km are found for many ULXs, i.e., ~ 100 times larger than typical inner-disk radii in stellar-mass BH. If, as we speculate, ULXs are accreting BHs on the ultraluminous branch, with $F \gtrsim 10$, it means that their BH masses are only required to be $\lesssim 10$ times larger than typical BH masses in Galactic systems. This simple argument suggests that ULX masses are $\lesssim 100 M_\odot$. At the same time, masses ~ 50–$100 M_\odot$ are still sufficiently high to guarantee that the apparent ULX luminosity is comparable or only a factor of a few higher than the Ed-

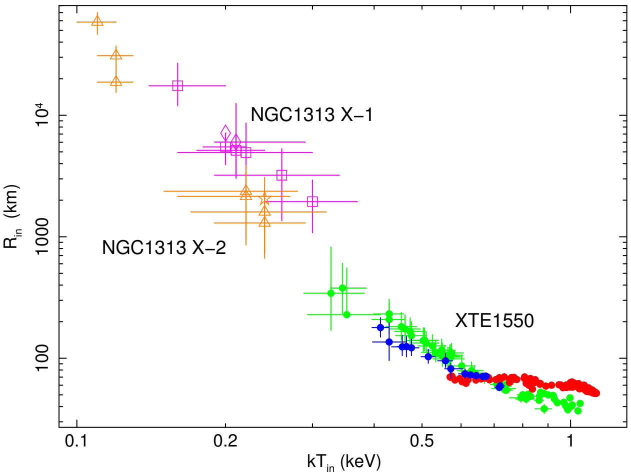

Fig. 8.— As in Figure 6, but with two ULXs (NGC 1313 X-1 and X-2) plotted alongside the stellar-mass BH XTE J1550−564. A constant conversion factor $R_{\rm in} = 1.19 r_{\rm in}$ was used for all datapoints. A viewing angle $i = 60^{\circ}$ was assumed for NGC 1313 X-1 and X-2, for consistency with the flux/luminosity conversion of Feng and Kaaret (2006, 2007). The colour coding is the same as in Figures 7. The anticorrelation of radius and temperature seen in the two ULXs is very similar to (in fact, almost the direct extension of) the ultraluminous track of XTE J1550−564.

dington limit, and therefore they do not require strong collimation of their emission.

The location or evolutionary track of a source in the $(T_{\rm c}, L_{\rm disk})$ plane provides another observational constraint. To predict the displacement of a source from its thermal track when $F > 1$, we need to understand how F, $T_{\rm c}$ and $L_{\rm disk}$ vary as a function of $\dot{m}$. For a fixed BH mass, the radiative flux equation of a standard disk tells us that $T_{\rm c} \sim R_{\rm c}^{-3/4} \dot{m}^{1/4}$. It was suggested (Poutanen et al., 2007; Begelman et al., 2007) that $R_{\rm c} \sim \dot{m}$, based on plausible physical processes that may form such a transition radius. If so, from Eq. (7) we expect that, as the accretion rate $\dot{m}$ increases, a source will move along a track parameterized by $L_{\rm disk} \approx$ constant, $T_{\rm c} \sim \dot{m}^{-1/2}$. This is not exactly what is found in the *RXTE* spectra of XTE J1550−564, because, there, $L_{\rm disk} \sim T_{\rm c}^{-1}$. However, the luminosity track is very sensitive to the radial temperature distribution on the disk, at $R > R_{\rm c}$. Disk models with a distribution flatter than $R^{-3/4}$ are sometimes used. For example, it was found (Kubota et al., 2005) that $T \sim R^{-0.7}$ may provide a more accurate fit to the X-ray spectral data of Galactic BHs. In that case, we expect $L_{\rm disk} \sim T_{\rm c}^{-0.44}$, with $T_{\rm c} \sim \dot{m}^{-0.45}$. For a disk dominated by X-ray irradiation (as may be the case if $R \gg R_{\rm ISCO}$), $T \sim R^{-0.5}$. In that case, $L_{\rm disk} \sim T_{\rm c}^{-4}$, with $T_{\rm c} \sim \dot{m}^{-0.25}$. Another way to reproduce the observed anticorrelation of disk luminosity and peak temperature is to parameterize $R_{\rm c} \sim \dot{m}^{\beta}$ with $\beta < 1$. For example, $L_{\rm disk} \sim T_{\rm c}^{-0.8}$ for $R_{\rm c} \sim \dot{m}^{3/4}$ and a standard temperature profile.

Regardless of the precise functional forms of $F(\dot{m})$ and $T_{\rm c}(R_{\rm c})$, the significant result is that we expect a source to move *to the left-hand-side of its thermal track*, as the accretion rate increases to $\dot{m} \gg 1$. Along that track, the luminosity of the disk component stays constant or increases, even if the observed peak temperature decreases. Thus, it appears that in order of increasing accretion rates, the spectral states of an accreting BH are: high/soft (thermal track); very high (to the right of that track); ultraluminous (to its left). Along this sequence, we also expect the source to become more and more dominated by non-thermal emission components.

9 Testing the ultraluminous scenario with fitted ULX parameters

Let us consider an accreting BH with $M \approx 50 M_{\odot}$. If $\dot{m} \approx 1$ and $F = 1$, we expect its spectrum to be dominated by the disk component, with a peak temperature ≈ 0.8 keV, a characteristic size of the X-ray emitting region $\sim 6GM/c^2 \sim 500$ km, and a disk luminosity $\approx 5 \times 10^{39}$ erg s^{-1} $\approx L_{\rm Edd}$. This luminosity is consistent with those found in average ULXs, but the other fit parameters are not. Let us now suppose that $F \approx \dot{m} \approx 20$, for the same source on the ultraluminous branch. In that case, we expect that the source will still have $L_{\rm disk} \approx L_{\rm Edd} \approx 5 \times 10^{39}$ erg s^{-1} or slightly higher, but a peak temperature $\approx 0.8 \times 20^{-0.5}$ keV ≈ 0.18 keV, a characteristic radius $\sim 20 \times 6GM/c^2 \sim 10^4$ km, and an X-ray power-law component with a luminosity $> 5 \times 10^{39}$ erg s^{-1}. These are more typical ULX parameters. If we had observed such a source, and had directly inserted the fitted values of $L_{\rm disk}$ and $T_{\rm c}$ into Eq. (6) instead of Eq. (10), we would have incorrectly interpreted the source as an intermediate-mass BH with $M \approx 1000 M_{\odot}$. The same mistake would have occurred if we had only observed XTE J1550−564 at the end of its ultraluminous branch. In that case, we might have estimated a mass $\approx$ 60–80$M_{\odot}$ from Eq. (6), instead of $10 M_{\odot}$.

We want to test whether at least some ULXs show evidence of spectral evolution along the ultraluminous branch, with a predicted (and observed in XTE J1550−564) anticorrelation between disk luminosity and temperature. For this, we consider the two "classical" sources, NGC 1313 X-1 and X-2; *XMM-Newton* and *Suzaku* observations of those sources were recently studied by Feng and Kaaret (2006, 2007) and Mizuno et al. (2007). Their works show that both sources admit at least two alternative fitting models: a cool-disk and a hot-disk scenario. The hot-disk model was considered more physical, partly because it would place those ULXs close to the extrapolation of a thermal track ($L_{\rm disk} \sim T_{\rm c}^4$), while the cool-disk model place them to its left and would imply an anticorrelation between disk temperature and luminosity[2]. However, based on the comparison with XTE J1550−564 (Figure 7), this is precisely what we expect to find. Therefore, we argue that the spectral evolution of those two ULXs *strongly supports the cool-disk model*. The physical interpretation of the cool disk is *not* based on intermediate-mass BHs, but on a receding inner radius $R_{\rm c}$, when the sources are moving along their ultraluminous branches at accretion rates $\dot{m} \gtrsim 10$. The increase in the apparent inner-disk radius $R_{\rm c}$ is even more obvious when it is plotted against $T_{\rm c}$ (Figure 8). We suggest that this is further evidence of a fundamental similarity between the ultraluminous branch seen in XTE J1550−564 and the ULX behaviour. Note that, unlike XTE J1550−564, neither NGC 1313 X-1 nor X-2 have shown evidence of ever reaching their thermal tracks (Figures 7, 8), which remain undetermined. This makes it more difficult to disentangle the effects of higher masses and higher accretion rates, and hence to estimate the values of F and of their BH masses. We will discuss these issues quantitatively and in greater details in a forthcoming paper (Soria and Kuncic, 2007b).

10 Evidence from X-ray timing: low-frequency QPOs

Some nearby, luminous ULXs show LF-QPOs in their power-density-spectra (Strohmayer et al., 2007; Dewangan et al., 2006; Strohmayer and Mushotzky, 2003).

[2]A caveat about the cool-disk fitting model for NGC 1313 X-1 and X-2 is that the disk temperature also appears to be anticorrelated with the column density (see in particular Fig. 1 of Feng and Kaaret 2007). Thus, it has been suggested that the apparent increase in the disk luminosity at lower disk temperatures could be a spurious effect, if the anticorrelation between column density and disk temperature has no physical basis. However, we argue that an increase in the intrinsic absorption as the accretion rates increases to more than one order of magnitude above Eddington, along the ultraluminous branch, is in fact very plausible. Other transient X-ray binaries show higher absorption near their outburst peaks. So, we do not think this is a serious reason to consider the disk luminosity-temperature anticorrelation unphysical. It is, however, possible that the luminosity increase at lower temperatures is partly due to uncertainties in the column density, and therefore that the slope of the ultraluminous branch is flatter than it appears in Figure 7.

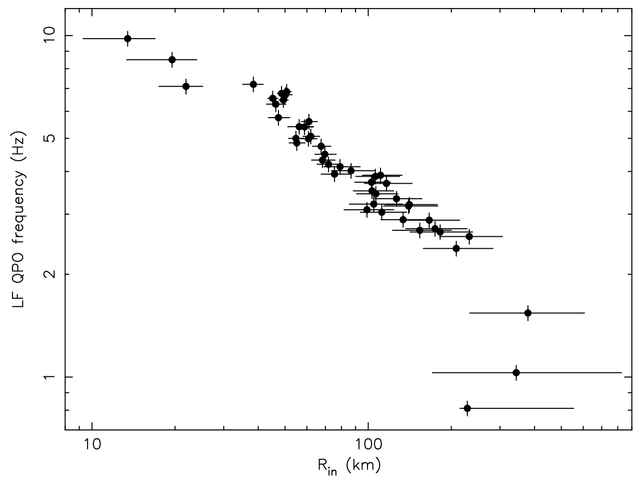

Fig. 9.— Frequencies of the LF-QPOs detected (only) in the very high and ultraluminous states of XTE J1550−564 during its 1998 September – 1999 April outburst, as a function of fitted inner-disk radius. A constant conversion factor $R_{\rm in} = 1.19 r_{\rm in}$ was used for all datapoints. The anticorrelation of frequency and radius (and hence, of frequency and accretion rate) provides an independent constraint to ULX masses and their accretion rates.

Such oscillations are more strongly associated with the power-law photons (Strohmayer et al., 2007). A similar behaviour is observed in stellar-mass BHs, including XTE J1550−564, in their very high and ultraluminous states (Remillard and McClintock, 2006). This has been interpreted (e.g., Done and Kubota, 2006) as further evidence of a connection between those luminous, power-law dominated states in ULXs and stellar-mass BHs, also consistent with their spectral properties. Moreover, it was suggested that LF-QPO frequencies scale as $1/M$ across the whole range of BH masses, from stellar-mass objects to AGN (McHardy et al., 2006).

LF-QPO frequencies in ULXs are a factor ≈ 20–100 lower than in stellar-mass BHs; for example, one of the most notable cases is the 20-mHz QPO in NGC 5488 X-1 (Strohmayer et al., 2007). At face value, this appears to strengthen the intermediate-mass BH hypothesis (Strohmayer et al., 2007). However, just as we discussed for the large inner-disk radii, there may be a more physical interpretation, which becomes apparent from a comparison with the LF-QPOs in XTE J1550−564. From the timing analysis of Sobczak et al (2000), it is clear (Figure 9) that the LF-QPO frequency in this stellar-mass source decreased as the apparent radius increased, during the 1998–1999 outburst. That is, for a fixed BH mass, the frequency decreased as the accretion rate increased along the proposed ultraluminous branch. The relation is not linear; however, it can be roughly approximated as $\nu_{\rm QPO} \sim \dot{m}^{-0.5}$ over most of the parameter range. More generally, taking into account the expected $(1/M)$ scaling between sources of different masses, we can write

$$\nu_{\rm QPO} \sim \dot{m}^{-\delta}\,(1/M) \qquad (11)$$

with $0.5 \lesssim \delta \lesssim 1$.

This suggests that the lower frequencies found in ULXs may also be the result of higher accretion rates, not only of higher masses, in agreement with our proposed interpretation of the spectral data. The different dependence of spectral and timing parameters on $\dot{m}$ and M suggests that it is in principle possible to disentangle the two effects. Preliminary back-of-the-envelope calculations suggest that accretion rates $\dot{m} \approx 20$ and masses $M \sim 50$–$100 M_\odot$ are consistent with both the spectral and timing data of typical ULXs.

In addition to providing an independent constraint on the effects of accretion rate and BH mass, the observed anticorrelation between a disk parameter (inner radius) and the frequency of oscillation of the power-law emission component is also a fundamental clue to understand the origin of such oscillations. One can speculate that LF-QPOs originate at the interface of outer disk and inner flow, at the transition radius $R_{\rm c}$. We will present a more detailed analysis of the timing results, in the framework of our ultraluminous branch model, in Soria and Kuncic (2007b).

11 Conclusions

It is often noted that ULXs and stellar-mass BHs share X-ray spectral and timing properties typical of the luminous, power-law dominated accretion state (very high state). If we plot the spectral evolution of typical accreting BHs in the $(T_{\rm in}, L_{\rm disk})$ plane, the very high state is located on the right-hand-side (higher disk temperatures) of the thermal track characteristic of the disk-dominated high/soft state. This would imply that ULXs and stellar-mass BHs are entirely separate species, with a two-order-of-magnitude gap in BH masses between them (intermediate-mass BH scenario). However, *RXTE* spectral fits to the stellar-mass BH XTE J1550−564 in its 1998–1999 outburst (Sobczak et al. 2000; Kubota and Done 2004) clearly show that the very high state can in fact be divided into two substates, located to the right (higher temperature) and to the left (lower temperature) of the thermal track, respectively. In the latter state (ultraluminous branch), the fitted inner-disk radius is much larger than the innermost stable circular orbit, and the peak colour temperature much cooler than in the high/soft state. This is consistent with a standard outer disk truncated or obscured beyond a transition radius $R_{\rm c} \gg R_{\rm ISCO}$. The inner region of the inflow contributes mostly to the power-law component, perhaps through upscattering in a moderately optically-thick corona, or in a magnetized wind (Kuncic and Bicknell, 2004). The observed anticorrelation between bolometric disk luminosity and peak colour temperature, and the observed sequence of spectral state transitions imply that the ultraluminous branch occurs at even higher accretion rates than the classical very high state, hence probably at $\dot{M} >$ a few $M_{\rm Edd}$.

The ultraluminous branch provides *a bridge between stellar-mass BHs and ULXs*. It supports the cool-disk spectral model for ULXs, but not its interpretation in terms of intermediate-mass BHs. At the other end of the bridge, we showed that two prototypical ULXs (NGC 1313 X-1 and X-2) also move along a track consistent with the ultraluminous branch, with anticorrelations between disk luminosity and temperature, and between inner-disk radius and temperature. If this interpretation is correct, all the main spectral and timing properties of accreting BHs (including their characteristic LF-QPO frequencies) depend simultaneously on two factors: a mass scaling and an accretion rate scaling, at least when $\dot{M} >$ a few $M_{\rm Edd}$. We suggest that the observed ULX parameters may be best explained with BH masses ~ 50–$100 M_\odot$ and $\dot{M} \approx 20 M_{\rm Edd}$. This also implies that the radiative efficiency of the non-thermal medium is $\lesssim 0.02$.

In this scenario, ULXs persistently occupy the high-accretion-rate ultraluminous branch, whereas stellar-mass BHs would only rarely reach such rates, and only near the peak of their outbursts (for example, we showed in Section 4 that the stellar-mass BH H1743−322 never does). We are currently investigating whether brief transitions to an ultraluminous branch may have occurred in other historical outbursts of Galactic BHs; and whether other variable ULXs move along similar tracks. A significant difference between the two classes of objects may be caused by the different types of Roche-lobe mass transfer. ULXs may accrete a few $M_\odot$ over $\lesssim 10^6$ yr from B-type donor stars, while transient Galactic BHs accrete from older solar-mass stars, which do not persistently fill their Roche lobes.

I thank Zdenka Kuncic, Geoff Bicknell, Mark Cropper, Jeroen Homan and Jeff McClintock for useful discussions and suggestions. In particular, I thank Hua Feng and Phil Kaaret for private communications and comments about their study of NGC 1313 X-1 and X-2, and the anonymous referee for various appropriate suggestions. I also thank Z. Kuncic for funding my visit to

Sydney University, where part of this work was done. I am grateful to the organizing committee of the 5th Stromlo Symposium for their great efforts, that led to a very enjoyable and successful meeting. I also thank Jeff McClintock for kindly sharing his *RXTE* data of H1743−322 well ahead of publication. I acknowledge financial support from a Marie Curie Outgoing International Fellowship (No. 509329), from a *Chandra*/NASA grant (No. 07620718), and from the 2006 RSAA AFL footy tipping competition.

References

Arnaud, K.A.. In: Jacoby G. and Barnes J. (eds.) Astronomical Data Analysis Software and Systems V, ASP Conf. Series vol. 101, p. 17 (1996)

Begelman, M.C., King, A.R., Pringle, J.E.: **MNRAS** 370, 399 (2006)

Davis, S.W., Blaes, O.M., Hubeny, I., Turner, N.J.: **ApJ** 621, 372 (2005)

Davis, S.W., Done, C., Blaes, O.M.: **ApJ** 647, 525 (2006)

Dewangan, G.C., Griffiths, R.E., Rao, A.R.: **ApJ** 641, L125 (2006)

Done, C., Kubota, A.: **MNRAS** 371, 1216 (2006)

Fender, R.P., Belloni, T.M., Gallo, E.: **MNRAS** 355, 1105 (2004)

Feng, H., Kaaret, P.: **ApJ** 633, 1052 (2005)

Feng, H., Kaaret, P.: **ApJ** 650, L75 (2006)

Feng, H., Kaaret, P.: **ApJ** 660, L113 (2007)

Goad, M.R., Roberts, T.P., Reeves, J.N., Uttley, P.: **MNRAS** 365, 191 (2006)

Gonçalves, A.C., Soria, R.: **MNRAS** 371, 673

Kubota, A., Tanaka, Y., Makishima, K., Ueda, Y., Dotani, T., Inoue, H., Yamaoka, K.: **PASJ** 50, 667 (1998)

Kubota, A., Done, C.: **MNRAS** 353, 980 (2004)

Kubota, A., Makishima, K.: **ApJ** 601, 428 (2004)

Kubota, A., Ebisawa, K., Makishima, K., Nakazawa, K.: **ApJ** 631, 1062 (2005)

Kuncic, Z., Bicknell, G.V.: **ApJ** 616, 669 (2004)

McClintock, J.E., Remillard, R.A., Rupen, M.P., Torres, M.A.P., Steeghs, D., Levine, A.M., Orosz, J.A.: **ApJ** submitted, preprint: arXiv:0705.1034 (2007)

McHardy, I.M., Koerding, E., Knigge, C., Uttley, P., Fender, R.P.: **Nature** 444, 730 (2006)

Makishima, K., Maejima, Y., Mitsuda, K., Bradt, H.V., Remillard, R.A., Tuohy, I.R., Hoshi, R., Nakagawa, M.: **ApJ** 308, 635 (1986)

Makishima, K., et al.: **ApJ** 535, 632 (2000)

Markwardt, C.B., Swank, J.H.: **ATel** 133, 1 (2003)

Miller, J.M., Fabian, A.C., Miller, M.C.: **ApJ** 614, L117 (2004)

Miller, J.M., et al.: **ApJ** 646, 394 (2006)

Mizuno, T., et al.: **PASJ** 59, 257 (2007)

Orosz, J.A., Groot, P.J., van der Klis, M., McClintock, J.E., Garcia, M.R., Zhao, P., Jain, R.K., Bailyn, C.D., Remillard, R.A.: **ApJ** 568, 845 (2002)

Poutanen, J., Lipunova, G., Fabrika, S., Butkevich, A.G., Abolmasov, P.: **MNRAS** 377, 1187 (2007)

Remillard, R.A., McClintock, J.E.: **ARA&A** 44, 49 (2006)

Shakura, N.I., Sunyaev, R.A.: **A&A** 24, 337 (1973)

Shimura, T., Takahara, F.: **ApJ** 445, 780 (1995)

Sobczak, G.J., McClintock, J.E., Remillard, R.A., Bailyn, C.D., Orosz, J.A.: **ApJ** 520, 776 (1999)

Sobczak, G.J., McClintock, J.E., Remillard, R.A., Cui, W., Levine, A.M., Morgan, E.H., Orosz, J.A., Bailyn, C.D.: **ApJ** 544, 993 (2000)

Soria, R., Kuncic, Z.: **AdSpR** in press, preprint: arXiv0705.1374 (2007a)

Soria, R., Kuncic, Z.: **MNRAS** submitted (2007b)

Stobbart, A.-M., Roberts, T.P., Wilms, J.: **MNRAS** 368, 397 (2006)

Strohmayer, T.E., Mushotzky, R.F.: **ApJ** 586, L61 (2003)

Strohmayer, T.E., Mushotzky, R.F., Winter, L., Soria, R., Uttley, P., Cropper, M.: **ApJ** 660, 580 (2007)

Winter, L.M., Mushotzky, R.F., Reynolds, C.S.: **ApJ** 649, 730 (2006)

This 2-column preprint was prepared with the AAS LaTeX macros v5.0.