Black Holes from Stars to Galaxies – Across the Range of Masses
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Chilled disks in ultraluminous X-ray sources

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Abstract. If the standard disk-blackbody approximation is used to estimate black hole (BH) masses in ultraluminous X-ray sources (ULXs), the inferred masses are $\sim 1000 M_{\odot}$. However, we argue that such an approximation cannot be applied to ULXs, because their disks are only radiating a small fraction of the accretion power, and are therefore cooler than they would be in a thermal-dominant state, for a given BH mass. Instead, we suggest that a different phenomenological approximation should be used, based on three observable parameters: disk luminosity, peak temperature, and ratio between thermal and non-thermal emission. This method naturally predicts masses $\sim 50 M_{\odot}$, more consistent with other theoretical and observational constraints.

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

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1. Mass estimates from thermal disk spectra

The masses of the accreting BHs in ULXs, and hence their nature and physical origin, are still unknown. In the absence of direct kinematic measurements, indirect methods based on X-ray spectral modelling have been used, by analogy with stellar-mass BH X-ray binaries in our Galaxy. For stellar-mass BHs in the high/soft state, most of the accretion power is radiated by the disk, and the X-ray spectrum is well fitted by a multicolour blackbody (Shakura & Sunyaev 1973; Frank, King & Raine 2004). The fitted peak temperature T_0 and the integrated disk-blackbody luminosity L_0 are simply related to the mass accretion rate $\dot{M}$ and the size of the inner disk $R_{\rm in}$ (Makishima *et al.* 1986):

$$L_0 \approx 4\pi\sigma T_0^4 R_{\rm in}^2 \tag{1.1}$$

$$L_0 = \eta \dot{M} c^2 \tag{1.2}$$

$$\sigma T_0^4 \approx \frac{3GM\dot{M}}{8\pi R_{\rm in}^3}, \tag{1.3}$$

where we have ignored a factor related to the no-torque condition at $R_{\rm in}$ and a hardening factor, whose combined effect is ≈ 1.35 (Fabian, Ross & Miller 2004). The radiative efficiency $\eta \approx 0.1$–0.3 for a source in a high/soft state.

¿From (1.1), (1.2), and (1.3), one can estimate the BH mass:

$$M \approx \frac{c^2 \eta L_0^{1/2} T_0^{-2}}{3G(\sigma\pi)^{1/2}} \approx 5.6 \left(\frac{\eta}{0.2}\right) \left(\frac{L_0}{5 \times 10^{38}\ {\rm erg\ s^{-1}}}\right)^{1/2} \left(\frac{T_0}{1\ {\rm keV}}\right)^{-2} M_{\odot}. \tag{1.4}$$

Studies of Galactic stellar-mass BHs show that the spectroscopic mass estimate (1.4) is in agreement (within a factor of 2) with the kinematic mass.

2. Spectroscopic mass estimates for power-law-dominated ULXs

Let us assume that the "soft-excess" component in ULXs is indeed thermal emission from a disk (see Gonçalves & Soria 2006 for an alternative scenario). Direct application to (1.4) of the observed values of their X-ray luminosity ($L_0 \sim 10^{40}$ erg s^{-1}) and colour temperature ($kT_0 \approx 0.15$ keV) has led to the suggestion that ULXs may contain intermediate-mass BHs with masses $\sim 1000 M_\odot$ (Miller, Fabian & Miller 2004).

However, the thermal component is only a small fraction ($\sim 10\%$) of the X-ray emission in ULX spectra. In the inner region, at $R_{\rm in} \leqslant R \leqslant R_{\rm c}$, most of the accretion power is released via non-thermal processes. This implies that the inner disk is *cooler than a standard disk*, because it radiates only a flux

$$\sigma T(R)^4 \approx \frac{3GM\dot{M}}{8\pi R^3} - F_{\rm nr}(R) < \frac{3GM\dot{M}}{8\pi R^3} \tag{2.1}$$

where $F_{\rm nr}(R)$ is the energy flux released via non-radiative processes, for example transferred to a corona or outflow via magnetic stresses (Kuncic & Bicknell 2004). If $T(R)$ increases more slowly that $R^{-1/2}$ for $R \to R_{\rm in}$, the maximum contribution to the disk emission occurs at $R \approx R_{\rm c}$, $T \approx T(R_{\rm c})$ (peak in the fitted spectrum). For simplicity, here we assume that $T = T(R_{\rm c}) =$ constant inside $R_{\rm c}$; only a fraction $\beta < 1$ of the disk emission from the inner region is directly visible, depending on the optical depth of the scattering region. We can now re-write (1.1), (1.2), (1.3) as:

$$L_0 = 4\pi R_{\rm c}^2 \sigma T_0^4 + 2\pi (R_{\rm c}^2 - R_{\rm in}^2)\sigma T_0^4 \times \beta \approx 4\pi R_{\rm c}^2 \sigma T_0^4 \times (1 + \beta/2) \tag{2.2}$$

$$L_0 = f\eta \dot{M} c^2 \tag{2.3}$$

$$\sigma T_0^4 \equiv \sigma T(R_{\rm c})^4 \approx \frac{3GM\dot{M}}{8\pi R_{\rm c}^3}. \tag{2.4}$$

where L_0 is the total radiative luminosity of the disk, $T_0 \equiv T(R_{\rm c})$ is the peak temperature, and $f \sim 0.1$ is the fraction of accretion power radiated by the disk; f cannot be directly measured, but we can estimate it based on the fitted ratio of soft thermal emission over total X-ray luminosity. We can then solve (2.1), (2.2), (2.3) for M, $\dot{M}$ and $R_{\rm c}$ as a function of the observable quantities f, T_0 and L_0. In particular, for the BH mass we obtain:

$$M \approx \frac{49.8}{(1+\beta/2)^{3/2}} \left(\frac{\eta}{0.2}\right) \left(\frac{f}{0.1}\right) \left(\frac{L_0}{2 \times 10^{39}\ \text{erg s}^{-1}}\right)^{1/2} \left(\frac{T_0}{0.15\ \text{keV}}\right)^{-2} M_\odot \tag{2.5}$$

We conclude that the fitted spectral features of ULXs (X-ray luminosity, temperature and ratio of thermal/non-thermal contribution) suggest masses $\sim 50 M_\odot$. This is at the extreme end of, but still consistent with models of stellar evolution. If that is the case, the emitted luminosity is a few times the Eddington luminosity $L_{\rm Edd}$, but the disk radiative contribution alone is $\lesssim L_{\rm Edd}$. The rest is generated outside the disk by non-thermal processes, which dominate at radii $\lesssim R_{\rm c} \sim 100$ gravitational radii.

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