

Ultra-luminous X-ray sources: X-ray binaries in a high/hard state?

Z. Kuncic,¹ R. Soria,² C. K. Hung,¹ M. C. Freeland¹
and G. V. Bicknell³

¹School of Physics, University of Sydney, Sydney NSW 2006, Australia

²Mullard Space Science Laboratory, University College London, Holmbury St Mary,
Dorking, Surrey RH5 6NT, UK

³Research School of Astronomy and Astrophysics, Australian National University,
Mount Stromlo Observatory, Cotter Road, Canberra ACT 2611, Australia
email: z.kuncic@physics.usyd.edu.au, rs1@mssl.ucl.ac.uk, geoff@mso.anu.edu.au

Abstract. We examine the possibility that Ultraluminous X-ray sources (ULXs) represent the extreme end of the black hole X-ray binary (XRB) population. Based on their X-ray properties, we suggest that ULXs are persistently in a high/hard spectral state and we propose a new disk–jet model that can accommodate both a high accretion rate and a hard X-ray spectrum. Our model predicts that the modified disk emission can be substantially softer than that predicted by a standard disk as a result of jet cooling and this may explain the unusually soft components that are sometimes present in the spectra of bright ULXs. We also show that relativistic beaming of jet emission can indeed account for the high X-ray luminosities of ULXs, but strong beaming produces hard X-ray spectra that are inconsistent with observations. We predict the beamed synchrotron radio emission should have a flat spectrum with a flux density $\lesssim 0.01$ mJy.

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

1. Introduction

The exceptionally high X-ray luminosity of ULXs, $L_{0.5-8\text{ keV}} \approx (0.2-10) \times 10^{40} \text{ erg s}^{-1}$, emerges almost entirely as a hard power-law with photon indices $1.5 \lesssim \Gamma \lesssim 2.5$ (Irwin, Bregman & Athey 2004; Swartz *et al.* 2004; Liu & Bregman 2005; Stobbart, Roberts & Wilms 2006). ULXs are statistically consistent with representing a sub-population of XRBs (Swartz *et al.* 2004). However, known Galactic black hole XRBs have never been observed to enter a spectral state in which they simultaneously have an X-ray luminosity that is at least Eddington and a power-law spectrum that is harder than $\Gamma \approx 2.5$. The XRB spectral state that perhaps most closely resembles ULXs is the short-lived steep power-law (or very high) state, in which $L_x \approx L_{\text{Edd}}$, but $\Gamma \gtrsim 2.5$ (see McClintock & Remillard 2006). ULXs therefore appear to be in a persistently high/hard state.

It is unclear whether existing models for XRBs can explain a high/hard spectral state. ULXs appear to require a model with both a high \dot{M}_a and strong corona and/or jet. Furthermore, it is clear that most of the accretion power in ULXs is not being dissipated in a standard accretion disk. This implies that we cannot use the standard Multi-Colour Disk (MCD) model to fit any soft spectral component that might be present. We summarize the main results of the model proposed by Freeland *et al.* (2006) and we examine further the implications of a strong, accretion-powered jet for spectral fitting of accretion disk models to soft components evident in some ULX spectra.

2. Model Outline and Results

The details of our ULX model can be found in Freeland *et al.* (2006). It is based on the generalized theoretical framework of Kuncic & Bicknell (2004), which specifically addresses vertical angular momentum transport by a magnetic torque on the the accretion disk surface. This magnetic torque is identified as the mechanism responsible for jet/corona formation. It results in a modified radial structure of the accretion disk and hence, a modified disk spectrum, which we refer to as an Outflow Modified Multi-Colour Disk (OMMCD). Let us assume here that the total power extracted by the torque is injected into a relativistic jet and partitioned into magnetic and kinetic energies.

Modified disk spectrum. The radiative energy flux of an accretion disk modified by a magnetized jet is

$$\sigma T^4 = F(r) = \frac{3GM_{\bullet}\dot{M}_a}{8\pi r^3} [f_{ss}(r) - f_j(r)], \quad (2.1)$$

where $f_{ss} = 1 - (r/r_i)^{-1/2}$ is the small- r correction factor for a standard disk and where the jet correction factor is directly related to the magnetic torque acting on the disk surface:

$$f_j(r) = \frac{1}{M_a r^2 \Omega} \int_{r_i}^r 4\pi r^2 \frac{B_{\phi} B_z}{4\pi} dr. \quad (2.2)$$

Thus, the jet drains energy from the disk and modifies the radial temperature profile. As a result, the total disk spectrum is modified in the soft X-ray bandpass for stellar-mass black holes (see also Soria, Kuncic & Gonçalves 2006, this volume). This means that unusually soft spectral components seen in some bright ULXs may be interpreted as an accretion disk spectrum modified by a jet that is responsible for the dominant power-law spectral component.

Figure 1 shows the *XMM-Newton*/EPIC spectrum of ULX X-7 in NGC 4559. The spectrum of this bright ULX cannot adequately be fitted with a single power-law model. A broken power-law plus MCD model provides an acceptable fit. The low inner disk temperature required by the MCD fit to the soft component implies a black hole mass $M_{\bullet} \sim 1.4 \times 10^3 M_{\odot}$. We also show in Fig. 1 an almost identical spectral fit to the data using a similar broken power-law plus an OMMCD model. The best fit model parameters are listed in Table 1. The OMMCD parameters correspond to a $M_{\bullet} \approx 155 M_{\odot}$ black hole accreting at $\dot{M}_a \approx 3\dot{M}_{\text{Edd}}$, but with only $L_d \approx 0.3L_{\text{Edd}}$ being emitted by the disk. According to this model, the bulk of the accretion power is removed from the disk and injected into a jet, which is responsible for the hard power-law spectral component. However, only a small fraction of the jet power is dissipated in the form of radiation, since jets are highly inefficient emitters. Relativistic beaming is then responsible for boosting the X-ray emission to the high observed levels.

Jet emission. We calculated the jet spectral energy distribution for two different relativistic beaming scenarios (Körding, Falcke & Markoff 2002): 1. the microblazar scenario, where the jet is pointing close to our line-of-sight and the observed emission is thus strongly beamed; and 2. the microquasar scenario, where the jet is directed at larger angles and hence, there is less contribution from relativistic beaming to the observed X-ray emission. We used a simple radiative transfer model to take into account the synchrotron optical depth. The details of the microblazar and microquasar spectral models can be found in Freeland *et al.* (2006).

The spectral modelling results shown in Figure 2 confirm that both the microblazar and microquasar scenarios can produce X-ray luminosities sufficiently high to be consistent with ULXs. The microblazar model, however, predicts strong deviations from a power-law in the 0.2–10 keV bandpass resulting from strongly beamed nonthermal Comptonization.

Table 1. Best fit parameters for the spectral models used in Figure 1.

broken power-law+MCD model		broken power-law+OMMCD model	
$N_{\text{H}}(\times 10^{21} \text{ cm}^{-2})$	2.3	$N_{\text{H}}(\times 10^{21} \text{ cm}^{-2})$	2.3
$kT_{\text{in}} \text{ (keV)}$	0.16	$M_{\bullet} (M_{\odot})$	155
normalization	162.2	$\dot{M}_{\text{a}}(\times 10^{-5} M_{\odot} \text{ yr}^{-1})$	1.3
Γ_1	2.11	$L_{\text{d}}/L_{\text{Edd}}$	0.3
$E_{\text{break}} \text{ (keV)}$	4.66	normalization ($\times 10^{-6}$)	1.0
Γ_2	3.11	Γ_1	2.04
normalization ($\times 10^{-4}$)	2.2	$E_{\text{break}} \text{ (keV)}$	4.05
χ^2/dof	202.6/195	Γ_2	2.79
		normalization ($\times 10^{-4}$)	1.99
		χ^2/dof	264.7/196

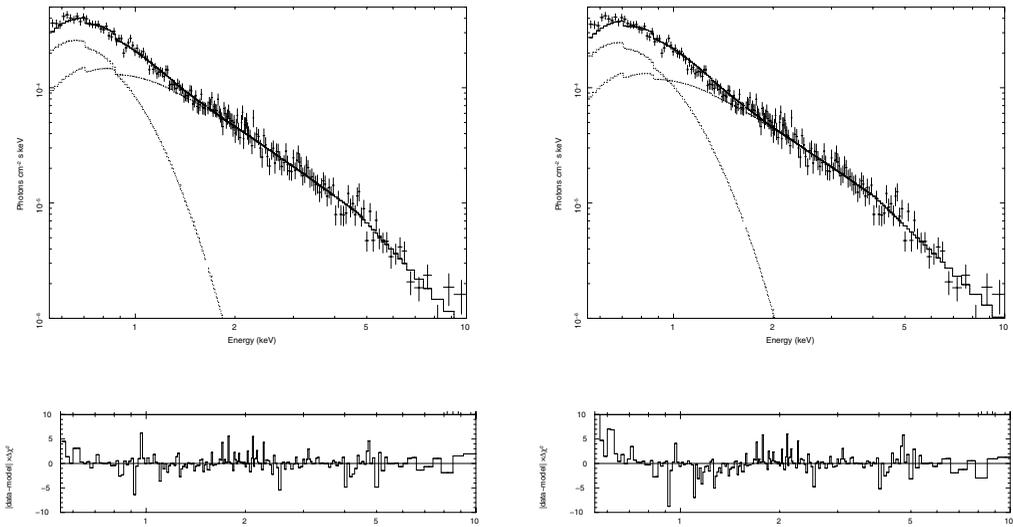


Figure 1. *XMM-Newton*/EPIC unfolded spectra of ULX NGC 4559 X-7. The solid line is the total model spectrum. The dotted lines are the broken power-law plus MCD models (left) and the broken power-law plus OMMCD models (right). χ^2 residuals are shown underneath. Best fit model parameters are shown in Table 1.

This is inconsistent with the observational data to date. The microquasar model, on the other hand, predicts an approximately power-law hard X-ray spectrum.

Both models predict similar radio properties. The synchrotron radio spectra are approximately flat at 5 GHz and the specific radio power is $L_{\nu} \approx 10^{22} \text{ erg s}^{-1} \text{ Hz}^{-1}$. This corresponds to a flux density $S_{\nu} \approx 10 \mu\text{Jy}$ at a distance of 1 Mpc. This is more than two orders of magnitude below the levels measured for the few cases where radio sources have been found associated with ULXs. Our theoretical results support other pieces of evidence ruling out beamed jet emission as the origin of ULX radio counterparts. Our results are also consistent with the overwhelming excess of non-detections over detections found in the deepest ULX radio counterpart search to date, down to detection limits $\approx 60 \mu\text{Jy}$ with the VLA (Körding, Colbert & Falcke 2005). Note that a typical Galactic XRB placed at a distance of 1 Mpc would have a flux density of only $\approx 1 \mu\text{Jy}$.

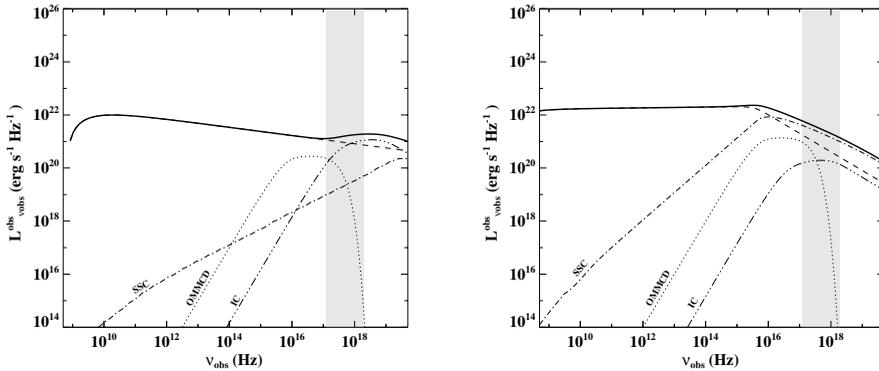


Figure 2. The predicted spectral energy distributions for the microblazar (left) and microquasar (right) scenarios for ULXs. The microblazar model has $M_{\bullet} = 5M_{\odot}$, $\dot{M}_a = \dot{M}_{\text{Edd}}$, $\delta = 8.4$ and $L_{0.5-8\text{ keV}} \approx 3 \times 10^{39} \text{ erg s}^{-1}$. The microquasar model has $M_{\bullet} = 20M_{\odot}$, $\dot{M}_a = \dot{M}_{\text{Edd}}$, $\delta = 1.6$ and $L_{0.5-8\text{ keV}} \approx 5 \times 10^{39} \text{ erg s}^{-1}$. The shaded region indicates the 0.5 – 8 keV bandpass.

3. Summary

We have argued that ULXs appear to be in a persistently high/hard spectral state and that they may represent an extreme sub-population of XRBs. According to this interpretation, ULXs must be accreting at very high rates (at least Eddington) and must possess a strong corona and/or jet. We have outlined a theoretical model that satisfies these criteria and that explicitly identifies the disk-jet coupling mechanism as a magnetic torque. The model predicts that ULXs should possess an accretion disk that is substantially cooler at small radii than a standard disk at the same \dot{M}_a . This offers a viable explanation for the unusually soft component seen in the spectra of some bright ULXs. We fitted the *XMM-Newton* spectrum for ULX X-7 in NGC 4559 and found that the modified disk fit to the soft component requires a much lower black hole mass ($M_{\bullet} \approx 155M_{\odot}$) than a standard disk fit ($M_{\bullet} \simeq 1400M_{\odot}$). We also presented theoretical spectral modelling results showing that relativistic beaming can account for the observed X-ray luminosities of ULXs without resorting to extreme black hole masses. If ULXs are indeed relativistically beamed, we predict they should exhibit unresolved, flat-spectrum radio cores with fluxes $\lesssim 0.01$ mJy. Such radio counterparts have not yet been detected.

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