New insights into ultraluminous X-ray sources from XMM-Newton/EPIC observations

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ULXs and IMBHs

ULXs – discrete X-ray sources with $L_X > 10^{39}$ erg s$^{-1}$. But at these luminosities $L_X > L_{\text{Edd}}$ for a ~ 10 M black hole – a new class of ~ 100 – $10^4$ M intermediate-mass black holes (IMBHs) required?

Supporting evidence from “soft excess” in XMM-Newton ULX spectra (e.g. Miller et al. 2003). Now 10+ examples.

$T \propto M^{-0.25}$

cf. $kT_{\text{in}} \sim 1 – 2$ keV for stellar BHs
But.....

Multiple ULXs (10+) are found in Starburst galaxies – e.g. Cartwheel galaxy (Gao et al. 2003). Ongoing star formation → ULXs are intrinsically short-lived.

Requires an infeasibly large underlying population of IMBHs (King 2004).

**Alternative:** are ULXs in Starbursts high-mass X-ray binaries (HMXBs)?

NB – no comparable population in ellipticals (Irwin et al. 2004).
Stellar-mass BHs as ULXs

Possible mechanisms for breaking Eddington limit:
- Beaming by relativistic jets (e.g. Körding et al. 2002).
- Anisotropic radiation patterns (King et al. 2001).

Podsiadlowski et al. (2003), Rappaport et al. (2005) – super-Eddington mass transfer rates in HMXBs – account for most ULXs.

Blue stellar counterparts to several ULXs.
At least three stellar mass BHs (albeit LMXBs) in our galaxy have been seen to reach super-Eddington luminosities – GRS1915+105 does so frequently (McClintock & Remillard 2003).

Some ULXs do have stellar-mass disc temperatures (∼1 – 2 keV).

But not much recent observational evidence from ULX X-ray
The NGC 55 ULX

• Source exhibits temporal variability including dipping.
• Dips most prominent at high energies.

\( kT_{in} \approx 0.9 \) keV

\( ? \approx 4 \)
A problematic spectrum

Dominance of power-law continuum at soft energies not seen before in Galactic systems – e.g. GRS 1915+105 high state extrapolates below 2 keV to this spectrum.

Dis parameters extreme (high $kT_{in}$, low $R_{in}$) but plausible for slim disc accretion onto a stellar-mass (or slightly bigger) BH.

Problem is dominant soft power-law – cannot be disc-Comptonisation (too few photons below peak in disc emissivity). $\sim 3 - 4$ vs $\sim 1.5 - 2$ for jet – inconsistent with thermal footpoint? Unsolvable problem?


From Zhang et al. (2000)

$kT \sim 0.2 - 0.5$ keV

$kT \sim 1 - 1.5$ keV, $\sim 10$

$kT \sim 100$ keV

VHS of GX 339-4

NGC 55 ULX

Outflow
Other examples of “new” spectrum

This spectrum is seen in second $L_X \sim 10^{39}$ erg s$^{-1}$ ULX – M33 X-8 (Foschini et al. 2004).
More luminous ($L_X \sim 5 \times 10^{39}$ erg s$^{-1}$) NGC 5204 X-1 data well fit by both “IMBH model”, i.e. cool accretion disc ($kT_{in} \sim 0.2$ keV) + hard power-law continuum ($\Gamma \sim 2$), and “non-standard” description ($\Gamma \sim 3.3$, $kT_{in} \sim 2.2 - 2.8$ keV).

From Roberts et al. (2005)
A sample of bright ULXs

How prevalent is the “new” spectrum in ULXs? Particularly in comparison to an IMBH spectrum? Select 13 (predominantly archival) ULXs observed by XMM-Newton/EPIC with (a) ~20 ks or more EPIC exposure, and (b) > 10 ct/ks in ROSAT HRI. Expect ~ few thousand counts per source. Full range of $L_X$ covered ($10^{39} – \text{few} \times 10^{40}$ erg s$^{-1}$).

Uniform reduction to produce clean spectra for comparison of empirical models and state-of-the-art physical models.

Analysis ongoing…
Empirical models

Absorbed multi-colour disk blackbody spectrum (disk bb in XSPEC) rejected at high significance for all data.

Absorbed power-law continuum not rejected at 95% confidence in only 4 datasets (including 3 lowest quality).

IMBH model produces “good” ($\chi^2 \sim 1$) fits in 7 sources (“better” in 2 more). Find $kT_{in} \sim 0.1 - 0.25$ keV, $\sim 1.6 - 2.5$. Masses circa. 1000 M for IMBH.

Problem: too small? Theory and observations show $\sim > 2.5$ for high-state black hole accretion discs.
2-10 keV curvature

From Roberts et al. (2005)
Physical models (1)

Slim disc model (e.g. Watarai et al. 2001; Ebisawa et al. 2004); XSPEC parameterisation courtesy of K. Ebisawa.

At \( \sim L_{\text{Edd}} \) expect advection-dominated optically-thick discs – differences to “standard accretion disc, e.g. \( R_{\text{in}} \) decreases below ISCO as Mdot increases.

Provides poor fits in most cases; problems with degeneracy between \( \dot{M} \) and \( M_{\text{BH}}, \dot{M} \).

\( M_{\text{BH}} \) typically 10 – 50 M\(_{\odot}\) and < 100 M\(_{\odot}\) in all but one case. Gives Mdot in 0.1 – 10 in Eddington units.
Other fits have cool discs ($kT \sim 0.2 – 0.5 \text{ keV}$) but are optically thick ($\ell \sim 6 – 10$). INCONSISTENT WITH IMBHs!

cf. Zhang’s 3-layer model…
Holmberg II X-1

Holmberg II X-1, combined EPIC MOS light curve, 100s binning

Background in source region

Count rate (ct s⁻¹)

Time from start of obs (s)

0 2\times 10^4 4\times 10^4 6\times 10^4 8\times 10^4

Helmberg II X-1
Conclusions

Detailed spectroscopy – some ULXs just don’t look like IMBHs with “standard” accretion disc + corona spectra extrapolated from Galactic BHs (2 – 10 keV curvature/flat ?).

Highly compton-thick layer may be key evidence – ionised surface of bloated accretion disc fed by super-Eddington inflow of material from high-mass secondary. BH mass few 10s of M⊙.

Lack of short-term variability supports Compton-thick layer.

However, only conclusive means of ending this debate is to derive a dynamical mass limit on the BH from orbital dynamics...and that’s another story!