The ultraluminous state refined: spectral and temporal characteristics of super-Eddington accretion

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ULXs as super-Eddington accretors

**KEY QUESTION:**
What’s the physics of this new accretion state – how does super-Eddington accretion work?

NuSTAR data for NGC 1313 X-1
(Bachetti et al. 2013)

Spectrum is NOT analogous to common sub-Eddington states – implies super-Eddington ‘ultraluminous’ state (Gladstone et al. 2009)
Starting point

- Spectral sequence:
  - Broadened disc regime
  - Hard ultraluminous regime
  - Soft ultraluminous regime

- In Gladstone et al. we attributed this sequence to increasing accretion rate: is this true? Or are other factors at play?

Gladstone, Roberts & Done (2009)
How do we say more about ULX physics?

- X-ray spectral states in BHs show related timing & spectroscopy characteristics
- Is this true of ULXs?
- Empirical study
  - Classify 89 obs from 20 ULXs into 3 distinct regimes based on empirical spectral model
  - Recover deabsorbed fluxes, hardness
  - Calculate fractional variability on 200 s timescale in broad, soft & hard bands

Sutton, Roberts & Middleton (2013)
Below $\sim 3 \times 10^{39}$ erg s$^{-1}$ broadened discs dominate: $\sim$ Eddington stellar mass BHs?

Soft & hard ultraluminous (UL) found at similar $L_X$

Higher $L_X$ discs – massive stellar BHs or hard UL with weak soft component?
Hardness-variability diagrams

- Low $F_{\text{var}} (< 10\%)$ in most disc & all hard UL
- High $F_{\text{var}}$ mainly seen in some soft UL; stronger above 1 keV; not persistent
What are the broadened discs?

- Dominate at \( \sim L_{\text{Edd}} \) for 10 \( M_\odot \) BHs
- Best data: not well fit by disc models
- 2 component models work well, e.g. advective disc plus thick corona
- Same 2 components as UL state – emergent UL spectra?

Left: XMM data for M31 ULX, fit with BHSPEC model (Middleton et al. 2012)

Below: 2 component fits to same data – advective disc (left) and cool, thick corona (right)
Do we understand accretion disc spectra?

- But: similar residuals in TD state CCD spectra of Galactic BHs?
- Sutton et al. (submitted) – reprocessing fraction same as TD state – same geometry?
- Broadened discs simply most luminous TD objects?
- Are disc spectra well understood?

*GX339-4 – EPIC pn & RXTE spectrum at ~ 10% $L_{\text{Edd}}$ (Kolehmainen et al. 2011)*
Super-Eddington models

- Super-Edd models naturally explain 2-component spectra as optically thick wind + inner disc
- Poutanen et al. (2007) – inclination critical for observed spectrum: so on-axis HUL, off-axis SUL
Origin of variability

- Variability seen predominantly in wind-dominated ULXs
- Face-on systems show little variability
- Explanation: extrinsic hard variability imprinted by edge of clumpy wind passing through line of sight

Takeuchi et al. (2013)

Middleton et al. (2011)
Regime change

- Do ULXs switch between different regimes?
- King (2009) – $\dot{m}$ goes up, funnel opening angle decreases
- For constant line-of-sight expect to see switch from hard to soft – seen in two ULXs
Winds

☐ Interpretation predicated on presence of wind

☐ Any direct evidence for presence of wind material?

☐ No narrow emission lines around Fe K in deep Suzaku observation of a hard ULX, Ho IX X-1

☐ But hard – so not viewed through wind!

*Top: change in $\chi^2$ statistic for addition of narrow Gaussian feature; bottom: limits on line equivalent width*
More winds

- Long known that soft ULXs can have extensive fit residuals
- Can be fitted by thermal plasma
- But also explained by absorption from broadened, partially ionised and blueshifted ($v \approx 0.1c$) material – outflowing wind!

*Combined NGC 5408 data – left: continuum model; right: continuum model plus broad, partially ionised absorber*

 Middleton et al. (2014).
Refining the UL state

Return to model predictions (e.g. Poutanen et al. 2007) to find new tests

Qualitatively consider: effects of inclination on photon propagation; damping of intrinsic disc variability
New predictions/better explanations

- Possible dependence of variability on mass accretion rate – at higher rates, increased wind so greater damping of intrinsic variability & effect of clumps averages out

- Evolution of spectra with inclination angle and mass accretion rate better justified; type 1 (HUL) to type 2 (SUL) if off-axis

- Type 3 (close to edge-on): should be faint & spectrally soft, and likely bright UV sources
Some examples of evolution

- Predictions seem to be justified by data

Best fitting models for multiple epochs of XMM data – green spectra when also variable. Red/blue are soft/hard components for least (dotted) and most (solid) luminous epochs.
Conclusions

- Not just spectra: also *behaviour* of most ULXs inconsistent with sub-Eddington IMBHs!

- Can explain properties of most ULXs in framework of super-Eddington accretion

- We can now qualitatively explain the range of ULX spectra in terms of 2 properties: accretion rate and inclination