Ultraluminous X-ray sources in the nearby Universe

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Introduction

- What are ultraluminous X-ray sources (ULXs)?
- Intermediate mass black holes or super-Eddington accretion?
- A new super-Eddington accretion state: the 'ultraluminous state'
What are ultraluminous X-ray sources?

- Extra-Galactic (distances of ~ 5 – 100 Mpc)
- Non-nuclear - they are not supermassive black holes
- Bright X-ray point sources
  - $L_X \sim 10^{39} – 10^{41}$ erg s$^{-1}$
    - Exceeds the Eddington limit ($\sim 1.3 \times 10^{38}$ erg s$^{-1} M_\odot^{-1}$) for stellar remnant black holes
- Implying they are intermediate-mass black holes (IMBHs)
  - Which could be the remnant seeds of the SMBHs
- Or, they are in a new, extreme accretion state
Sub-Eddington disks

- Sub-Eddington accretion disk spectra can be approximated as a sum of black bodies
- Stellar remnant black holes peak in X-rays
- AGN peak at lower energies
4 classic sub-Eddington states

- Differentiated by mass accretion rate, to first-order
- 2-components: accretion disk and 'power-law': \( (kE^{-\alpha}) \)

Done et al. 2007
ULX spectra

- Many ULXs are well fitted by the same model
- They have a soft excess
  - Disk emission?
- And a hard power-law

Gladstone et al. 2009
Soft excess: disk emission?

- Accretion disk luminosity - temperature relation:
  - \( L \propto MT^4 \)
- ULXs and BHBs occupy different regions of parameter space
  - Implies \( 10^3 M_\odot \)
  - IMBHs
Soft excess: disk emission?

- Inconclusive - ULX $L-T$ relation depends on assumptions

$L \propto T^4$ - disk

Miller et al. 2013

$L \propto T^{-3.5}$ - outflow

Kajava & Poutanen 2009
The ultraluminous state

- The highest quality XMM-Newton ULX spectra differ from sub-Eddington states
- ULXs are in a new 'ultraluminous' state
  - Characterized by a soft excess
  - And a high energy break

Gladstone et al. 2009
The ultraluminous state

- 3 types of ultraluminous spectra
  - Broadened discs
  - Hard-ultraluminous
  - Soft-ultraluminous

Gladstone et al. 2009
Hardness-luminosity diagram

Sutton et al. 2013

Soft ultrauminous

Hard ultraluminous

Broadened disks below $\sim 3 \times 10^{39}$ erg s$^{-1}$

Hardness $(f(1-10 \text{ keV})/f(0.3-1 \text{ keV}))$

Sutton et al. 2013
Broadened disk ULXs

- A few of the faintest ULXs are transients
- A ULX in M31 is seen in a sub-Eddington state when at low $L_X$
  - Confirmed by radio data
  - $M_{BH} < 17 M_{\odot}$

Middleton et al. 2013
Broadened disk spectra

- Another transient: M33 X-8
  - It may have a geometrically slim accretion disk
  - Or an emerging 2-component spectrum

Middleton et al. 2011

Straub et al. 2013
X-ray reprocessing

- X-rays irradiate the outer-disk and are re-emitted as optical/UV photons
- ULX reprocessing fractions are similar to thin disks (Sutton et al. 2014)
  - This may be inconsistent with slim disks

Modified from Dotan & Shaviv 2011
X-ray reprocessing

- Scattering in an optically thin phase of an outflow may oppose the obscuration by the disk bulge
- But it seems highly contrived for these effects to cancel out

Modified from Dotan & Shaviv 2011
A comparison of BHB and ULX disk spectra

- Sutton et al. In prep.: some sub-Eddington BHB disk spectra are also broader than expected
- ULX-like phenomenological models can reproduce the broad sub-Eddington disk spectra
- Broad disk spectra do not necessarily imply slim disks

Kolehmainen et al. 2011: GX 339-4 with XMM and RXTE
Hardness-luminosity diagram

Sutton et al. 2013

Soft ultrauminous

Hard ultraluminous

Broadened disks below \( \sim 3 \times 10^{39} \) erg s\(^{-1}\)

Sutton et al. 2013

Hardness (f(1—10 keV)/f(0.3—1 keV)

\[ L_X \text{ (erg s}^{-1}) \]

\[ L_X \text{ (erg s}^{-1}) \]
Fractional variability

- High levels of variability seen in **soft ultraluminous ULXs**
- Variability $\leq 10\%$ in **hard ultraluminous sources**

$F_{\text{var}} (0.3-10\text{ keV}, \text{per cent})$

Sutton et al. 2013
Fractional variability

- Soft ultraluminous ULXs are more variable
- The variability is significantly greater in the hard band

\[ F_{\text{var}} \text{ (1—10 keV, per cent)} \]

\[ F_{\text{var}} \text{ (0.3—1 keV, per cent)} \]

Sutton et al. 2013
Covariance

- Confirms that the variability is consistent with originating in the hard spectral component

Middleton et al. 2015

*Top:* spectral model and contributing components (lines), and 3 – 200 mHz (black points) and 0.9 – 3 mHz (red points) covariance relative to 1.5 – 3 keV band;

*Bottom:* ratios from re-normalizing the spectral model to the covariance data, with component ratios fixed (black), free (green) and hard component only (blue)
4 classic sub-Eddington states

- Differentiated by mass accretion rate, to first-order
- 2-components: accretion disk and 'power-law': \((kE^{-\alpha})\)

Done et al. 2007
Interpreting the X-ray properties

- Inclination is key in determining the X-ray spectra
  - Funnel shaped wind
  - Face on: hard ultraluminous
  - Off-axis: soft ultraluminous
- Variability supports this
  - Clumpy wind imprints variability
  - Suppressed variability if wind is out of line-of-sight
- State transitions could be due to changes in the wind opening angle

Kawashima et al. 2012

Middleton et al. 2011
Interpreting the X-ray properties

Hard ultraluminous

Soft ultraluminous

Variable soft ultraluminous

Hard ultraluminous

Soft ultraluminous
Potential soft absorption features

- ULXs can have soft residuals
- Absorption by a partially ionised, blue-shifted (0.1 c) material – such as a wind
- But, they can also be well-fitted by thermal plasma emission models
  - Diffuse emission related to star-formation

Soft residuals in NGC 5408 X-1
Middleton et al. 2014
NGC 5408 X-1 with Chandra

- The ULX is not resolved from star-formation regions with XMM-Newton
- But it can be resolved by Chandra
- >2/3 of the putative plasma emission remains unresolved

Sutton et al. 2015
An evolving wind

- Residuals are seen in both hard- and soft-ultraluminous sources
- The absorption strength is anti-correlated with spectral hardness in NGC 1313 X-1
  - which is consistent with a wind

Middleton et al. 2015
Ultraluminous super-soft X-ray sources (ULSs)

- ULGs have super-soft thermal disk spectra
- A cool disk may imply an IMBH
- Or the photosphere of an edge-on super-Eddington ULXs may peak in soft X-rays (e.g. King & Muldew 2015)
A Galactic ULS?

- SS 433 is a Galactic binary with an extreme accretion rate of $\sim 10^4$ times the Eddington rate
  - It is edge-on, so we do not see a ULX
  - The photosphere peaks below X-rays so we do not see a ULS

(Kyoto University)
Conclusions

- Most ULXs are stellar remnant black holes in a new, extreme accretion state.
- At around the Eddington limit ULXs have broadened disk spectra.
- At even higher, super-Eddington accretion rates ULXs are characterized radiatively driven outflows, and inclination is key in determining the observed X-ray properties.
- ULXSs may be the same class of source, but observed edge-on.
The brightest ULXs may still be IMBHs

Most famous: ESO 243-49 HLX-1

Sub-Eddington state transitions

But at $L_X \sim 10^{40} - 10^{42}$ erg s$^{-1}$

Webb et al. 2014

Servillat et al. 2011
IMBH ULXs

- ULXs more luminous than $\sim 5 \times 10^{40}$ erg s$^{-1}$ have hard power-law spectra and $\sim 10\%$ fractional variability.

- Reminiscent of the low hard state ($L/L_{Edd} \sim 0.1$)
  - $10^3 - 10^4 \ M_{\odot}$ IMBHs

- But cannot completely rule out ultraluminous state spectra

Sutton et al. 2012
IMBH ULXs

- NGC 2276-3c peaks at $L_X \sim 6 \times 10^{40}$ erg s$^{-1}$
- Low/hard state-like in X-rays and radio
- Its position on the X-ray – radio fundamental plane implies a $5 \times 10^4 M_\odot$ black hole

Mezcua et al. 2015
A neutron star ULX

- 0.7 Hz pulsed flux detected in M82 with *NuSTAR* indicating a pulsar
- Most likely from a ULX M82 X-2
  - With peak $L_X \sim 1.8 \times 10^{40}$ erg s$^{-1}$
  - Or 100 $L_{\text{edd}}$ for a 1.4 $M_\odot$ neutron star
Conclusions

- Most ULXs are stellar remnant black holes in a new, extreme accretion state
- At around the Eddington limit ULXs have broadened disk spectra
- At even higher, super-Eddington accretion rates ULXs are characterized radiatively driven outflows, and inclination is key in determining the observed X-ray properties
- ULSs may be the same class of source, but observed edge-on
- A sub-set ULXs may still contain IMBHs, and at least one even contains a neutron star primary
Problems with IMBHs 1

- The X-ray luminosity function normalized by star-formation is a power-law over 5 decades in $L_X$
- Breaks at $\sim 10^{40}$ erg s$^{-1}$
- $10^3 M_\odot$ IMBHs would have to switch off at $\sim 0.1 L_{\text{Edd}}$

Mineo et al. 2012
Problems with IMBHs 2

- IMBHs need a supply of mass to accrete
  - The best option: a companion star
- But, models under-predict IMBH ULXs by a factor ~ 10 – 100 (Madhusudhan et al. 2005)
Problems with IMBHs 3

- Cartwheel galaxy
- Unfeasibly high fraction of mass in black holes, if all ULXs are IMBHs
- Most ULXs must contain stellar-remnant black holes

Chandra, GALEX, Hubble, Spitzer - Composite: NASA/JPL/Caltech/P.Appleton et al.