The scaling of X-ray variability with luminosity in Ultra-luminous X-ray sources

(Gonzalez-Martin et al. 2010, A&A submitted)

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Ultra Luminous X-ray sources (ULX) are compact objects out of the center of the galaxies with luminosities log(Lx)>39. These luminosities imply intermediate mass black holes (IMBHs, 1000-100000M\(_{\odot}\) Colbert & Mushotzky 1999) between Galactic binary systems and SMBHs. However, there nature is uncertain and other explanations as anisotropic emission (King et al. 2001) or super Eddington rates (Begelman 2002) have also been proposed.

We need to determine the BH mass:

1. From the spectral fitting, with temperature and luminosity (Stobbart, Roberts & Wilms 2006).

2. From timing methods:
   - QPO detections (e.g. Strohmayer & Mushotzky 2009).
   - Scaling relationships of the characteristic time scales with the BH mass and accretion rate (Mc Hardy et al. 2006).
   - Anticorrelation of the variability amplitude with the luminosity in AGN (Nandra et al. 1997; Leighly 1999; Turner et al. 1999).

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Our aims are:

1. Study the correlation of the normalised excess variance (as an estimate of the variability amplitude) with the luminosity of ULX.

2. Compare this correlation with that for AGN.

3. Compare it with the expected correlation assuming a Power Spectral Density (PSD) shape.
Sample

We considered all the ULXs reported in the literature (in particular those reported by Gladstone et al. 2009 and Heil et al. 2009) with net exposure times > 30 ksec observed with XMM-Newton/pn data. The final sample comprises 14 ULXs and 18 observing files. We also added the low BH mass AGN POX 52 for comparison purposes.

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Normalised excess variance

We construct light curves of 1000 sec bins.

We chose segments of 40 ksec excluding large background flares.

Therefore we sample variations with frequency between:

\[ \nu(\text{min}) = 1/40000 \text{ Hz} \]
\[ \nu(\text{max}) = 1/2000 \text{ Hz}. \]

\[ \sigma_{\text{NXS}}^2 = \frac{S^2 - \langle \sigma_{\text{err}}^2 \rangle}{\langle x \rangle^2}, \]
\[ \text{err}(\sigma_{\text{NXS}}^2) = \sqrt{\frac{2}{N} \left( \frac{\langle \sigma_{\text{err}}^2 \rangle}{\langle x \rangle^2} \right)^2 + \frac{4 \sigma_{\text{NXS}}^2}{N} \langle x \rangle^2}, \]

This error is only based on Poisson error (Vaughan 2003), where:

\[ S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \langle x \rangle)^2. \]
Log($\sigma_{NXS}$) = (49 ± 14) - (1.31 ± 0.36) x log L(2-10 keV)
Normalised excess variance versus Luminosity

\[ \log(\sigma_{\text{NXS}}) = (49 \pm 14) - (1.31 \pm 0.36) \times \log \text{L}(2-10 \text{ keV}) \]

Heil et al. (2009)
Comparison with AGN

ULXs follow the same relation than AGN but about 4 orders fainter.
Comparison with AGN

For a given luminosity the variability amplitude of ULXs is at least 10 times lower than expected.

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Model 'variability-luminosity' relations:

Can ULXs be similar to AGN? i.e.:

- Same variability mechanism (i.e. same PSD shape).
- Same scaling of the $v_{\text{br}}$ with the BH mass and accretion rate (Mc Hardy et al. 2006).

$$v_{\text{br}} \propto \frac{\dot{m}_{\text{edd}}}{M_{\text{BH}}}$$

- Same X-ray to L$_{\text{bol}}$ conversion factor.
Model 'variability-luminosity' relations:

Case A

\[ \nu \propto \alpha \dot{m}_{edd} / M_{BH} \]
Model 'variability-luminosity' relations: Case A

\[ \nu_{\text{br}} \propto \dot{m}_{\text{edd}} / M_{\text{BH}} \uparrow \]

\[ P(\nu) = A(\nu/\nu_{\text{br}})^\alpha \]

\[ \alpha = -2 \]

\[ \nu(\text{min}) \quad \nu(\text{max}) \]
Model 'variability-luminosity' relations:

Case A

$\nu \propto \dot{m}_{\text{edd}} / M_{\text{BH}}$

$P(\nu) = A(\nu/\nu_{\text{br}})^\alpha$

$\nu_{\text{br}} \propto \dot{m}_{\text{edd}} / M_{\text{BH}}$

$\nu_{\text{min}} < \nu < \nu_{\text{max}}$
Model 'variability-luminosity' relations:

Case A

\[ \dot{m}_{\text{edd}} = 0.2 \]
\[ \dot{m}_{\text{edd}} = 0.1 \]
\[ \dot{m}_{\text{edd}} = 0.05 \]

POX 52 follow the predicted Case A correlation for AGN with low BH mass. However, ULX are far from this correlation.
Model 'variability-luminosity' relations: Case B

\[ P(\nu) = \Lambda \left(\frac{\nu}{\nu_{\nu}}\right)^{\alpha} \]

\[ \nu_{br} \propto \dot{m}_{edd} / M_{BH} \]

\[ \nu_{br,2} \]

\( \alpha = 0 \)

\( \alpha = -1 \)

\( \alpha = -2 \)
Model 'variability-luminosity' relations: Case B

\[ P(v) = A(v/v_{br})^\alpha \]

\[ \nu \propto \frac{\dot{m}_{edd}}{M_{BH}} \uparrow \]
ULXs could be explained using Case B model with IMBH of \( \sim 5000-10000 \) M\( \odot \) and accretion rate > 5% of the Eddington limit.
This second break has been observed in at least one AGN (Ark 564, Papadakis et al. 2002) and in GBHs in low/hard and very high states (Klein-Wolt & van der Klis 2008).

Moreover Heil et al. (2009) detected the required 0 to -1 break in some of their PSDs (e.g. M82 X-1 and NGC 5408 X-1) and in other cases is consistent with it including the error bars.
Model 'variability-luminosity' relations:

Mix group of object

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Conclusions:

♠ We have found an anti-correlation between the normalised excess variance and the luminosity for ULXs.

♠ The slope is consistent with that found for AGN although luminosities are 4 orders of magnitude lower.

♠ The variability amplitude of ULXs is significantly lower than that predicted by a simple extrapolation of AGN.

♠ It can be consistent with the hypothesis that some ULXs operate like AGN but only if: (i) they host an IMBH of ~5000-10000 M⊙, (ii) their accretion rate is > 5% of the Eddington limit, and (iii) their PSDs should have a shape showing two breaks.
End

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