Timing properties and X-ray lags of an ultraluminous X-ray source

Barbara De Marco

Max-Planck-Institut für Extraterrestrische Physik

With thanks to: G. Ponti, T. Muñoz-Darias, G. Miniutti, M. Cappi, T. Belloni, M. Dadina
Soft time lags

P. Uttley’s talk + review [Uttley et al. 2014]
“soft excess”-dominated band lagging behind primary power law dominated band

FeK reverberation: see E. Kara’s and A. Zoghbi’s talk + Dovciak’s poster K01
More on soft lags in AGN: see E. Gardners’s talk
Soft time lags in AGN

[De Marco et al. 2013a, see also Fabian et al. 2009, Zoghbi et al. 2010, Emmanouulopoulos et al. 2011]
Soft time lags in GBHs

GX 339-4

2–8 Hz

[Utley et al. 2011]
Soft time lags in neutron stars

[ Vaughan et al. 1998, Kaaret et al. 1999, deAvellar et al. 2013, Barret et al. 2013, Mendez et al. 2013, deAvellar poster B03 ]
Soft time lags vs BH mass

AGN (broad-band noise)

GX 339-4 (broad-band noise)

NS (HFQPOs)

\[ \log[\tau(s)] \]

\[ \log[M_{BH}/M_\odot] \]
Overview of the talk

• Do ULXs have soft lags as well?

• Can we link the variability properties of ULXs to those of GBHs?
Ultraluminous X-ray sources: NGC 5408 X-1

[Heil et al. 2010]

2006 XMM-Newton observation
~90 ks
(2008 observation consistent)

1-10 keV band  0.3-1 keV band
reprocessing/reverberation?
NGC 5408 X-1

1-7 keV vs 0.3-1 keV

6 XMM-Newton observations
~540 ks

≫99.9% significant soft lag!

[De Marco et al. 2013b]
NGC 5408 X-1

Energy dependence qualitatively similar to high frequency lags in other sources

[De Marco et al. 2013b]

AGN

4U 1608-522

[Barret et al. 2013]
No secure estimate of the BH mass (unknown companion star orbiting parameters)

Current estimates go from $50M_\odot$ to $10^4M_\odot$

No complete understanding of the origin of the spectral components
What we know about NGC 5408 X-1

1. X-ray luminosity $\gtrsim 10^{40}$ erg/s
   a) Isotropic emission, sub-Eddington $\rightarrow$ IMBH ($>100 \, M_\odot$)
   b) Beamed L $\rightarrow$ stellar mass ($<50 \, M_\odot$)
   c) Isotropic emission, super-Eddington $\rightarrow$ stellar mass ($<50 \, M_\odot$)
   [e.g. Roberts 2007, Feng & Soria 2011]

2. Significant high-frequency X-ray variability (unusual for ULXs)
   [Heil et al. 2009, Middleton et al. 2011]

3. mHz QPO always detected
What we don’t know about NGC 5408 X-1

1. Mass
   No detection of companion star [Kaaret & Corbel 2009]

2. Physical origin of X-ray spectral components
   Soft excess + turn over at ~4-6 keV (cool-optically thick corona?)
   [e.g. Gladstone et al. 2009]

3. Accretion state
   Canonical state or ultraluminous state?
   [e.g. Roberts 2007, Gladstone et al. 2009, Sutton et al. 2013 + T. Roberts’ talk tomorrow]

4. Identification of the mHz QPO with known QPOs from GBHs and NS
   [e.g. Strohmayer et al. 2007, Casella et al. 2008, Strohmayer & Muschotzky 2009]
BH mass estimates

1. Mass
   Indirect methods: comparison with known sources

2. Physical origin of X-ray spectral components
   e.g. Disc Temperature scaling

3. Accretion state
   Characterization through X-ray variability

4. Identification of the mHz QPO with known QPOs from GBHs and NS
   Frequency scaling (based on well established relations in GBHs)
1. Fractional rms

Same hard band fractional variability as observed in LHS and HIMS

[De Marco et al. 2013b]


Same hard band fractional variability as observed in LHS and HIMS
2. Fractional rms spectrum

Shape: typical of HIMS, SIMS, and HSS

Normalization: HIMS

[De Marco et al. 2013b, see also Middleton et al. 2011]

[Belloni et al. 2011]
3. Total rms vs flux

No sharp linear relation, LHS excluded

[De Marco et al. 2013b]

1-7 keV

4. QPOs

Type-C QPOs observed in LHS and HIMS
## Variability and accretion state

<table>
<thead>
<tr>
<th></th>
<th>LHS</th>
<th>HIMS</th>
<th>SIMS</th>
<th>HSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc fraction$^a$</td>
<td>≤ 20 percent</td>
<td>≤ 80 percent</td>
<td>≥ 75 percent</td>
<td></td>
</tr>
<tr>
<td>$rms$ vs count rate$^b$</td>
<td>linear (low scatter)</td>
<td>chaotic (overall $rms$ decreases as the flux increases)</td>
<td>linear (high scatter)</td>
<td></td>
</tr>
<tr>
<td>Fractional $rms$$^b$</td>
<td>~30-50 percent</td>
<td>≤ 30 percent</td>
<td>≥ 10 percent</td>
<td>≥ 5 percent</td>
</tr>
<tr>
<td>Fractional $rms$ vs E$^c$</td>
<td>flat/decreasing</td>
<td>flat/decreasing (early stages) or increasing (late stages)</td>
<td>increasing</td>
<td>increasing</td>
</tr>
<tr>
<td>QPO$^{d,e}$</td>
<td>type C</td>
<td>type C</td>
<td>type A/type B</td>
<td>no</td>
</tr>
</tbody>
</table>
Hard Intermediate state

![Diagram showing the relationship between Hardness and Intensity with HIMS annotations and Maccarone 2003 references.](image)

- Hardness
- Intensity

Approximately $1-2\% L_{Edd}$

Less than $10^4 M_\odot$
**IMBH:** the lag fits in the correlation (may require truncated disc)

**Stellar mass:** the lag is too long to be due to reverberation

[e.g. Gladstone et al. 2009, Middleton et al. 2011]

winds? [see C. Silva’s poster (F-32) on the response of outflowing gas in AGN]
Conclusions

• Does some ULX have soft lags?

Yes! If the soft lag in NGC 5408 X-1 is due to reverberation, it requires an IMBH

• Can we link the variability properties of ULXs to those of GBHs?

Analogies between NGC 5548 X-1 and hard intermediate state GBHs