X-ray time lags and reverberation from accreting black holes

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1. Background
Reverberation mapping

Optical time lags in AGN can be used to map scales of light-days. X-rays can map <light-mins in AGN, and <light-ms in XRBs!
Discovery in 1H0707-495

Fabian et al. 2009
Discovery in 1H0707-495

Positive ‘hard’ lags on long time-scales

Negative ‘soft’ lags on short time-scales

Hard lags were already known in AGN & BHXRBs, soft lags new

Fabian et al. 2009
1H0707-495: Time-scale dependent lags

(Zogbi et al. 2010)

Short time-scales: soft lags hard

Long time-scales: hard lags soft
BH X-ray binary GX 339-4 hard state

Intrinsic accretion fluctuations drive the variability and lags on long time-scales (> 1 s), disc (thermal) reverberation explains switch in lags on shorter time-scales

Uttley et al. 2011
2. Phenomenology
High-frequency soft lags are common in AGN (De Marco et al. 2013)

\[1.7 \times 10^6 \, M_{\text{Sol}}\]

\[2.3 \times 10^7 \, M_{\text{Sol}}\]
Lag vs. luminosity and black hole mass

De Marco et al. 2013

Lag correlates with mass, not with luminosity

Contrasts with strong L vs. lag correlation found in optical reverberation (Kaspi et al. 2005)

There is a common, small size-scale in AGN: set by inner edge of disc?
Discovery of Fe K reverberation in NGC 4151 (Zoghbi et al. 2012)

Longer time-scales: line core
shorter time-scales: red wing

Signature of disk reflection reverberation

More importantly: first independent confirmation of inner-disk origin of broad Fe K feature seen in energy spectrum since its discovery!
Low frequencies:
- smooth continuum lags

High frequencies:
- looks like reflection

(Inconsistent with large-scale reflection (e.g. Miller et al. 2010))

(Kara et al. 2013)
Complex soft lags, but ‘clean’ Fe K

Fe K ‘bump’ in lags is common (Kara et al. 2013)

Shape of soft lags changes from source to source!

Different origins for soft excess?
  • Photoionised reflection
  • Disc bb
  • Comptonisation (e.g. see Gardner & Done 2014)
Flux-dependent lags: complex picture

NGC 4051: Alston et al. 2013
IRAS 13224-3809: Kara et al. 2013
3. Basic interpretation

(see next talk for the full treatment!)
How to model the lags

Emission

lag = t_2 - t_1 = (d_2 - d_1)/c

“Impulse response”

The light curve from the reflected/reprocessed component is a delayed and smeared out version of the continuum light curve.

The lags and amplitudes are given by the Fourier cross-spectra of the impulse response in each band.
Effect of impulse response width

Top hats with same centroid but different widths

'Zero-crossing' depends only on centroid

Oscillations due to 'phase-wrapping' from $\pi$ to $-\pi$

$\delta$–function

TH, $\Delta \tau = 500 \text{s}$

TH, $\Delta \tau = 1000 \text{s}$

TH, $\Delta \tau = 2000 \text{s}$
Effect of impulse response shape + ‘dilution’

Dilution is the inclusion of some primary continuum in the same band as the reflector.

R=1 means equal contributions.

Dilution reduces lag, but does not change zero-crossing.

Shape only affects high-frequencies.

TH: undiluted
Gauss: undiluted
TH: $R = 1$
Gauss: $R = 1$
Are we seeing phase-wrapping?
(e.g. Miller et al. 2010, Legg et al. 2013)

Unlikely: 
-ve lags seen over > factor 2 range!

Suggests hard-soft lag switch is due to change in lag mechanism: continuum -> reverberation (consistent with lag-energy spectra)
4. Future of lag observations
XRBs - the next breakthroughs?

Hard State

- Disc blackbody
- Power-law
- Reflection

What produces the jet?

Soft State

Energy (keV)

Flux (10^9 erg/s/cm²)

- Why does the jet switch off?

- What produces the variability?

- Where does the power-law come from? Corona above the disc? Inner hot flow? Jet?

- Does the disc extend all the way down to the ISCO?
Sensitivity of lag measurements

\[ \Delta \phi(v_j) = \sqrt{\left( \frac{P_{X,\text{noise}}}{P_{X,\text{signal}}} + \frac{P_{Y,\text{noise}}}{P_{Y,\text{signal}}} \right) \left( \frac{P_{X,\text{noise}}}{P_{X,\text{signal}}} \cdot \frac{P_{Y,\text{noise}}}{P_{Y,\text{signal}}} \right)} / 2M \]

1-\(\sigma\) error on phase lag (time-lag = \(\Phi/2\pi\nu\))

AGN case: this term dominates

XRB case: this term dominates

Low rate, many cycles

Number of cycles
Lag sensitivity curves: AGN
Lag sensitivity curves: XRBs
Conclusions

✧ Wealth of evidence that the high-frequency lags are associated with light-travel delays on small scales: soft lags due to reverberation + possibly continuum lags

✧ Fe K reverberation has been found - confirmation of basic diskline interpretation and that reflection plays a role in generating lags

✧ Reverberation measurements of XRBs will overtake quality of AGN measurements: should finally resolve controversies about disc inner radius changes, coronal geometry etc.