X-ray reverberation mapping

Phil Uttley (University of Amsterdam)
on behalf of the eXTP strong field gravity working group
Reverberation mapping close to the event horizon

Radii+redshifts ➔ test dynamics of matter in strong field gravity
X-RAY REVERBERATION IN AGN
AGN: time scale-dependent delays

Fabian et al. 2009, Zoghbi et al. 2010, 11

Low-frequencies: propagating accretion fluctuations?
High-frequencies: switch to X-ray reverberation?

-> we need to ensure good measurements of the lag at high frequencies
Fe K reverberation lags: measuring light-travel times to the inner disc

**Lag vs energy spectrum**: measure lag of small energy bins relative to a broad reference band. Note the different shapes in the soft band!

![Graph showing lag vs energy spectrum for NGC 4151](image)

Zoghbi et al. 2012

![Graph showing relative lag vs energy for various sources](image)

Uttley et al. 2014

(adapted from Kara et al. 2013)
AGN X-ray reverberation with NuSTAR

Swift J2127.4+5654 (Kara et al. 2015)
Impulse response relates intensity of line response at a given time-delay to energy.
GR-raytracing modelling of Fe K lags

NGC 4151: Cackett et al., 2014

Good fit obtained for $7 \, R_g$ source height, reflection fraction $\sim 1$, assuming $4.6 \times 10^7 \, M_{\odot}$. Spin unconstrained due to low S/N in red wing.
Tidal disruption events: reverberation in Swift J1644+57

- **Kara et al. 2016**: first evidence for reverberation signature from a tidal disruption event.

- Blueshifted iron line implies signal is reverberating from the wall of a super-Eddington, mildly relativistic outflow.
X-RAY REVERBERATION IN X-RAY BINARIES
Lag sensitivity: why XRBs are currently worse than AGN for reverberation lag measurements

AGN: variations already well-sampled with many counts per variability time-scale ➔ limited improvements from increasing count rate (S/N scales with \( \sqrt{\text{rate}} \))

XRBs: significant improvements from increasing count rate so individual rapid variability events are better sampled: S/N scales linearly with rate
The need for large collecting areas

Effective area (m^2)

Fe K time lag signal-to-noise

Assumes 100 ks exposure (see Uttley & Casella 2014 for details)

S/N for 1 R_g/c time lag from 6.2–6.38 keV

XMM-Newton (with count rate limits)

NICER

XRBS (0.3–3 Crab)

eXTP

AGN (0.4–4 mCrab)
Disc reverberation components

- In addition to the iron line and reflection continuum, the absorbed flux is reradiated by the disc as thermal blackbody radiation.
- Uniquely, eXTP can study all three components simultaneously!

![Graph showing energy distribution with percentages of incident flux.]
The disk drives broadband noise variability in the hard state

Power-law photons lag disk photons on variability time-scales of seconds

Uttley et al. 2011
Uttley et al. 2011

Energy (keV)

Relative phase lag (radians)
X-RAY REVERBERATION WITH eXTP
Modelling the lags

Impulse response relates intensity of line response at a given time-delay to energy

(Cackett et al., 2014)
Building the impulse response

In practice we can make the impulse response for a given detector (e.g. LAD, 40 modules) by making a fake spectrum (xspec fakeit command) for each time delay bin of the impulse response:

Direct power-law continuum
BH XRB: eXTP reverberation lag simulations

100 ks on bright hard (1 Crab) state/hard-intermediate state, lag vs energy measured in 50-150 Hz range, combination of measurements from SFA+LAD.
AGN: eXTP reverberation lag simulations

100 ks on bright (2 mCrab) AGN (4e6 Msolar), lag vs energy measured in 0.3-3 mHz range, combination of measurements from SFA+LAD.
Self-consistency of lag and disk continuum measurements

Independent measurement of radius vs temperature (and test of accretion disk theory!).

By giving a radius, lags also give an area: consistency check on continuum fitting method.
Returning radiation of disk photons bent back on to disk has significant impact on observed polarization signal: strongly dependent on black hole spin

(Schnittman & Krolik 2009)
Reverberation mapping polarimetry

(Schnittman & Krolik 2009)
Light-travel times of order $\sim 10 \, R_g/c$ but the changes in polarisation are tiny so observed delay between different ‘bands’ of detected angle is only $\sim 0.1 \, R_g/c$. 
eXTP sensitivity to polarisation lags from the inner disk (100 ks)

1 Crab = 127000 cps in LAD, 660 cps in GPD (2 units)

Expected < 10 $R_g$ inner disk signal
Summary and Outlook

- Inner disk reverberation signatures have been detected and are an active field of study in AGN (also TDEs!) and XRBs.

- Sensitivity to reverberation signal increases linearly with count rate for XRBs: going to few $m^2$ area enables detailed study of the reverberation signal and hence accurate mapping of inner radius and strong gravity effects.

- Soft eXTP response from SFA also enables reverberation mapping of disk thermal emission to large radii.

- eXTP opens up new field of timing-polarimetry, allowing new independent tests of the disk reverberation signal.