X-ray reverberation in NLS 1

Lance Miller (Oxford)

Jane Turner (UMBC)
James Reeves (Keele)
Valentina Braito (Leicester)
Andrew Lobban (Keele)
Stuart Sim (MPA)
Knox Long (STScI)
Daniel Proga (Nevada)
Steve Kraemer (Catholic)
Mike Crenshaw (Georgia)
The reverberation between optical/UV continuum and optical emission lines is the principal method of BH mass measurement in AGN (Peterson, Bentz, Denney et al. tomorrow).

In our analysis, we consider how individual Fourier modes behave.

NGC 4051 optical: Denney et al. 2009
gappy, noisy time-series

NGC 4051 optical: Denney et al 2009
optical continuum

NGC 4051 X-ray: Miller et al 2010
Suzaku X-ray

optical Hβ

- time series are both “gappy” and noisy
- developed maximum-likelihood analysis based on CMB methods
- immune to gaps, accounts for shot noise, rigorous error estimation
- only method that accounts for covariance in Fourier domain
reverberation Fourier analysis

\[ T = 1905. \text{ s} \]

thin scattering shell
partial covering
optical ($\text{H}\beta$) reverberation in NGC 4051 (Denney et al 2009)
X-ray reverberation

- at X-ray energies not enough counts to separate lines and continuum on short timescales.
- measure reverberation between continua in different broad X-ray bands: hard X-rays are Compton-scattered; soft X-rays are absorbed.
- key difference with optical reverberation: we measure signals where the reflected and direct components are mixed together. Both bands can contain scattered light.
X-ray reverberation in NLS1

- Lags known for 10 years but not previously recognized as reverberation
- Primarily detected in highly-variable NLS1
- Dependence on frequency as expected from reverberation

NGC 4051
Miller et al. (2010a)

IH0707-495
Miller et al. (2010b)

Mrk 766
X-ray reverberation: energy dependence

**Dependence on photon energy** as expected from scattering by X-ray opaque material

- lag times increase with the difference in photon energy of the bands being cross-correlated.
- compare the required reflection fractions with the “scattered-light” component seen in the spectral analysis (top right).

![Graph of reverberation scattered fraction as a function of photon energy](image)

*NGC 4051: Miller et al. (2010a)*

![Graph of PCA decomposition - scattered light component](image)

![Graph of PCA decomposition - variable component](image)

*NGC 4051*
Time lags in 1H0707-495

Fabian et al. (2009); Zoghbi et al. (2010, 2011)

- Negative lags at high $\nu$ - ie SOFT band lags Medium band
- Claimed to indicate that soft band contains significant reflection, supposed to arise from strong Fe L-shell line emission at $\sim 0.9$ keV from reflector few 10s light-s away
- “Relativistic blurring” spectral model fit requires strong GR blurring $r_{in}=1.23$ $r_g$ emissivity $\sim r^{-7}$
- Positive lags at low frequency attributed to different mechanism (see later)

lags: “medium” 1-4 keV v. “soft” 0.3-1 keV
reflection fractions: $f_{\text{soft}} = 1.60$, $f_{\text{med}} = 0.57$, $f_{\text{hard}} = 2.03$

In this blurred reflection model, hard (FeK) band has most reflection, then soft band, then medium band.
From the Z10 spectral model, the hard 4-7.5 keV band should contain a larger fraction of reflection than the softer bands and hence should be the most lagged.

High ν lags should be positive if Zoghbi et al are correct.

They are not!

Miller, Turner, Reeves & Braito, 2010
Confidence Regions for the Lags

Z10, Z11 model predictions (lines show estimate of spectral model uncertainty)

68%, 90%, 99%, 99.9% confidence contours

- Lag constraints from the full high-state data set
- Z10 spectral model lies outside the 99.9% confidence region.
- Revised Z11 spectral model outside 99% confidence region.

Miller, Turner, Reeves & Braito, 2010
problems with light bending

• light-bending model was invented to fix the problems of the relativistic-blurred models ($R \gg 1$, $\varepsilon \sim r^{-7}$, lack of response of line to continuum).
• requires a small source close to the black hole (~1 rg) moving vertically up and down (mechanism?).
• no a priori expectation of this.

Where is the continuum source and its variations produced? It can’t be both in the accretion disk and in the “lamp-post” source.

Positive lags from fluctuations propagating inwards over the surface of the accretion disk from soft to hard regions?
X-ray reverberation: 1H0707-495

Miller, Turner, Reeves & Brait 2010

- (over-)simple top-hat reverberation transfer functions easily fit lag spectra
- Size of the reverberating region ~2000 light-seconds
  - 20-100r_g if M_{BH} = 10^7 M_\odot (Leighly 2004) or 2\times10^6 M_\odot (Zoghbi et al 2010)
- The soft band also needs time lag ~150s coupled with 2000s hard-band lags
  - no requirement for reflection physically close to the BH
  - difference between hard & soft caused by energy-dependent opacity
  - the hard-band FeK region cannot be dominated by short timescale lags
  - short lags may also arise in transfer function of primary source

\[
\begin{align*}
1-4 \text{ keV} & \text{ v. } 0.3-1 \text{ keV} \\
4-7.5 \text{ keV} & \text{ v. } 0.3-1 \text{ keV}
\end{align*}
\]
Reverberation predicts clear signatures in Fourier lag spectra which are observed in both optical and X-ray AGN/NLS1 time series.

We see both the expected frequency behaviour and energy behaviour in X-ray data.

X-ray reverberation places gas 10s - 100s $r_g$ from central source.

Simple X-ray reverberation explains BOTH small negative lags and large positive lags with a single, simple physical model.

Next aim to measure time lags in Sim et al radiative transfer code.

We are not seeing a naked accretion disk. Both timing and spectroscopic results independently show that X-rays are reprocessed by large amounts of circumnuclear gas with high global covering, >40 percent, often seen in absorption, likely outflowing (see Jane Turner’s talk).