The origin of UV / Optical Variability of AGN: Relationship to X-ray Variability

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Main Questions

• What drives UV/optical variability in AGN?

• How is the X-ray band related to UV/optical?

• What do X-ray/UV/optical variations tell us about AGN inner structure?
Possible drivers of UV/optical Variability

- Reprocessing of higher energy photons
  - which “high” energy? X-ray? Far-UV?
  - reprocessing off what? Disc? BLR?

- Intrinsic disc variations
Observational Diagnostics

- **Reprocessing** - High energies lead uv/optical by short (hour-days) light travel time.
  
  Allows ‘reverberation’ mapping of reprocessing structures.
  
  Measure lag from different temperature regions (different $\lambda$).

- **Intrinsic disc variability** – High energies lag: two possibilities
  
  - **Long lag** (months), viscous propagation timescale for perturbations to reach X-ray region from optical in disc
  
  - **Short lag** (hour-day), light travel time of UV seed photons to corona
REPROCESSING
Wavelength dependence of lags

For standard Shakura-Sunyaev DISC, dissipating gravitational potential energy

\[ L(R) = \sigma T^4 \propto M_{BH}^{-1} \dot{m}_E R^{-3} \]

i.e.

\[ T \propto M_{BH}^{-1/4} \dot{m}_E^{1/4} R^{-3/4} \]

Disc illumination from point source, height \( H \) above disc, also falls off as \( H R^{-3} \)

So for reprocessing from disc, we expect

\[ \text{Lag} \propto \text{Wavelength}^{4/3} \]  

(eg Cackett et al 2007)

and

\[ \text{Lag} \propto M^{2/3} \dot{m}_E^{1/3} \]

For illumination of a shell-type structure, eg the BLR or torus, illumination falls off as \( R^{-2} \) giving

\[ \text{Lag} \propto \text{Wavelength}^2 \]
Optical interband lags

Consistent with reprocessing from a disc but no link to high energies

(Cackett et al, 2007; Sergeev et al 2005,6)
Many RXTE + ground based optical programmes; eg Breedt et al 2010
NGC 4051

RXTE

V band

MJD-50000

Flux
Optical lags by 1.5 +/- 0.5 d

(Possible secondary longer (40d) lag – torus?)
Long timescales (years)  
– poorly correlated behaviour. Intrinsic disc variations in optical?

Short timescales (days-weeks)  
- well correlated. Usually a hint of optical lagging by ~day, but large uncertainty
Problems with reprocessing from a disc

MR2251-178
Arevalo et al 2008

Observed B-band lc (black dots) is smoother than model lc (purple)

Kasanas+Nayakshin 2001
Arevalo et al 2008, 2009
Gardner+Done 2016

Need illuminating source scale height ~100 Rg
for adequate DISC illumination
– much larger than measured for X-ray corona

(eg Emmanoulopoulos et al 2014; Cackett et al 2014)
Caveats interpreting CCFs

From Arevalo et al 2008: a small contribution to optical light from reprocessing of X-rays pulls the peak of the DCF close to zero lag, but DCF is asymmetric due to 2nd component.

See also Gardner and Done 2016.
Better Short Timescale Sampling:
NGC4051 XMM and RXTE X-rays vs. XMM OM UVW1

UV lightcurve reasonably (85% confidence) described by reflection from broad ring at 0.2 light days.

Mason et al 2002

OM in imaging mode.
~1200 s resolution
Large UVW1 variations on short timescales.

Tentative conclusion: UVW1 lags X-rays by 3 ks
NGC4395  Swift  (Cameron et al 2012)

Strong X-ray/UV/optical correlation (2d sampling)  \((M=3.6\times10^5, \text{ low } \dot{m}_E \approx 0.1\%)\)
Swift: NGC4395

Blue B-band
Black 2-10 keV
Swift X-ray/B-band CCF

No measurable lag of peak
(but asymmetry towards B-band lead)
Better sampled data: Swift NGC4395

Cameron et al 2012, MN, 422, 902
NGC4395: Short timescale CCF

Swift orbital sampling (96min) still not good enough to measure very short lag accurately.

suggesting reprocessing, but not confirming
NGC4395: Very Short timescale CCF

Looking within individual Swift visits (~1ks observations)
Hint that uvw2 lags X-rays by ~400s but large uncertainty

Will return to this lag with XMM-Newton observations later.
Multiwaveband Lags
For $\text{lag} \sim \text{wavelength} \beta$

Dashed line goes through X-ray point but $\beta = 0.37$, inconsistent with reprocessing

Solid line has $\beta = 1.18$ but is offset from X-ray point by 2.4d

Is this offset real?

Shappee et al, 2014

M$\sim 4 \times 10^7$

$\sim 60$ observations per band

Longer wavelengths smoothed as well as lagged
Swift Monitoring of NGC5548: First Campaign: (> 500 observations)

Good correlation, but not perfect, eg large W2 rise after day 6480

(McHardy et al, 2014, MN)
All of the data

LAG close to 0 day, but hard to be certain. Possibly W2 lags slightly.
Complex long timescale variations, which are different in different bands, can distort short timescale lags (eg Welsh1999) so are removed.
NGC5548: In period when X-ray is not identical to UVW2 on long timescales, all UV and optical bands are similar – McH et al 2014
Lags as function of wavelength

\[ \text{Lag} \propto \text{Wavelength}^{1.23} \]

- Expect 4/3 power for Shakura-Sunyaev disc. So good agreement.
- Fit goes through X-ray point
- BUT ... observed lags are longer than expected for the Mass and \( \dot{m}_E \)
- Red line is time for HALF of reprocessed light to arrive.

Microlensing obs (eg Morgan et al 2010) also require larger disc than SS model
Hotter than expected disc (eg higher \( \dot{m}_E \), higher Lx)?
Inhomogeneous disc (Dexter and Agol 2011)?

Similar long term trends in UV/optical not seen in X-rays
Using all data, HX may lead SX
For disc model, disc either too big or too hot.

Excess in u and i from Balmer and Paschen continua (Korista+Goad 2001)
NGC5548: X-ray / UV link

Raw HST (1367A) and Swift X-rays above 0.8 keV
NGC5548: Detrended HX-ray and UV

Consistent with lags in McH et al 2014

Removal of boxcar mean of full width 10d
NGC5548: lag vs wavelength

Fit does go through the X-ray point with $\beta=4/3$. 
Question:
Do the short timescale X-ray variations correlate similarly with the UV/optical in all AGN and, if so, what is the lag?

Swift can study one, or maybe 2 AGN per year.

Fastest (orbital) sampling is ~ 96 minutes.

Hard to measure lags less than a few hours, ie restricted to AGN with $M \geq \text{few } x 10^6 - 10^7$

For shorter lags (lower $M$, $m_E$) we need XMM-Newton
OM used in very fast (sub-second) readout mode using UVW1

Ground based g-band monitoring around globe.

(McHardy et al 2016 and Connolly et al in prep)
XMM and ground based monitoring of NGC4395

30-31 December 2014
NGC4395 - DCFs

X-rays vs UVW1

X-rays vs g-band

(Using Emmanoulopoulos et al 2013 improved lightcurve simulation method for simulations)
NGC4395 – Javelin lags

UVW1 lags X-rays by \(473\) \((+47, -98)\) s

g-band lags X-rays by \(788\) \((+44, -54)\) s
Simple linear fit (red) is best fit (forced through zero). However powerlaw of index 4/3 (blue) is also acceptable.
NGC4395 - Models

Solid lines – total disc energy release in band, including X-ray contribution
Dashed lines – gravitational energy release

Observed lags correspond to peak emission radii (models from P. Lira)
Less ‘disc size discrepancy’ than in NGC5548
Observational conclusions

• The X-rays and uv/optical are reasonably well correlated, particularly on short timescales, but there are long term trends in the UV/optical which are not seen in the X-rays.

• (Almost everywhere) the UV/optical lags behind the X-rays

• For the UV/optical bands, $\text{lag} \sim \lambda^\beta$, with $\beta \sim 4/3$ in most cases. Implies a flat reprocessor.

• For disc model, lags imply a larger disc than expected from SS model.

• Need a source of large scale height ($\sim 100 \, \text{R}_g$) to power reprocessing from a disc.

• Reverberation from BLR clearly seen (in u and i bands).
I would add:

Variable heating of inner edge of disc by accretion rate fluctuations on viscous timescales naturally provides the long timescale UV/optical variations, uncorrelated with X-rays.

Some part of the hard X-rays has to hit the reprocessor to provide short timescale X-ray/UV lag.

- high scale height emission from base of a jet?

Reprocessor has to have flattish geometry to give lag $\sim \lambda^{4/3}$. Hard to do with clouds.
Why don’t UV/optical disc variations drive X-ray variations?

Solid angle:

Optical/UV variations from larger radii are seen by distant observer but few are seen by central X-ray source

Larger fraction of the X-ray photons should hit the disc

Photon Conservation:

Compton scattering within X-ray emitting corona conserves photons. However an X-ray photon heating the reprocessor could lead to emission of many more optical/uv photons, dominating variations in intrinsic thermally produced photons.
Programmes for XMM-Newton

- Establish how well the X-rays in different energy bands correlate with the UV in AGN with low M, low $\dot{m}_E$, ie short lags and measure the lags. **Use OM in continuous fast readout mode.**

- Does the X-ray/UVW1 lag agree with extrapolation of the inter-UV/optical lags? If not, does offset depend on M, $\dot{m}_E$, disc temp?

- Is $\beta$=4/3 for all M, $\dot{m}_E$? Is ‘disc size discrepancy’ same in all AGN?

- Sample of ~5 AGN with ~3 orbits per AGN; would also contribute to study of inter-X-ray reverberation lags (see Fabian talk)

- **XMM is the only observatory able to observe continuously in X-rays and UV for >100ks and so able to measure correlations and lags in low M and low $\dot{m}_E$ AGN**
More XMM feasibility: eg NGC4593

\[ M = 7 \times 10^6 \quad \dot{m}_E \approx 0.1, \text{ expected lag } \sim 15\text{ks} \]

Ursini et al 2015

Pipeline MOS lc from Reynolds et al 2004 obs
NGC4593

Simulated OM UVW1 1c
(PSD parameters from Breedt 2010)

Simulated (zero lag) PN vs OM DCF
with 90% and 10% confidence contours

Correlation easily detected.
CONCLUSIONS

Measurements of correlation and lag between X-ray and UV provides a vital diagnostic of the inner geometry of AGN

- Accretion disc structure
- Hard X-ray source geometry
- Geometry of Broad Line Region

Swift can typically observe 1 AGN per year.

Swift, in low earth orbit, with shortest sampling ~96min, is best suited to AGN with X-ray/UV lags > few hours, ie mass > 5 \times 10^6

XMM is the only observatory able to observe continuously in X-rays and UV for >100ks and so able to measure correlations and lags in lower M and lower $\dot{m}_E$. 