An introduction to X-ray variability from black holes

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What do I hope to achieve?

Introduce some basic ideas that will be used a lot in the talks that follow

But the scope of this talk is rather limited...

**Will focus on:**
- XRBs and radio-quiet AGN (not ULXs)
- One-band only (no spectral-timing, interband correlations)
- detailed studies of individuals, small samples – not massive time domain surveys
- No time for “exceptions” like GRS 1915+105
- Timescales $\ll$ typical postdoc contract
Fiducial timescales, frequencies

\[ f_{lc} \sim 2 \times 10^5 \left( \frac{r}{r_g} \right)^{-1} \left( \frac{M}{M_\odot} \right)^{-1} \text{Hz} \quad \left[ \left( \frac{GM_\odot}{c^3} \right)^{-1} = 2 \times 10^5 \right] \]

\[ f_{dyn} \sim 2 \times 10^5 \left( \frac{r}{r_g} \right)^{-3/2} \left( \frac{M}{M_\odot} \right)^{-1} \text{Hz} \sim 2 \pi f_{\text{orb}} \]

\[ f_{\text{therm}} \sim f_{\text{orb}} \alpha \]

\[ f_{\text{visc}} \sim f_{\text{orb}} \alpha \left( \frac{h}{r} \right)^2 \]

<table>
<thead>
<tr>
<th>Timescale</th>
<th>10 (M_\odot)</th>
<th>10(^6) (M_\odot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light crossing</td>
<td>3( \times )10(^3) Hz (0.3 ms)</td>
<td>30 mHz (30 s)</td>
</tr>
<tr>
<td>Orbital</td>
<td>200 Hz (5 ms)</td>
<td>2 mHz (500 s)</td>
</tr>
<tr>
<td>Thermal</td>
<td>20 Hz (50 ms)</td>
<td>0.2 mHz (5 ks)</td>
</tr>
<tr>
<td>Viscous</td>
<td>0.2 Hz (5 s)</td>
<td>2\times10(^{-6}) Hz (500 ks)</td>
</tr>
</tbody>
</table>

[assuming \(\alpha \sim 0.1, h/r \sim 0.1, r/r_g \sim 6\)]

could be much longer
Time series (aka light curves)

“Aperiodic”, “random”, “stochastic”

As we can fully describe a random variable in terms of its distribution, or moments (mean, variance, skew, ...)

So we can describe a random time series in terms of its “distribution”: mean, auto-correlation function (ACF), higher-order moments

ACF and power spectrum are Fourier pairs

Power spectrum: distribution of variance, as function of frequency (~1/timescale)
Modern X-ray light curves

AGN (NGC 4051)
with XMM (0.2-10 keV)
0.5 day of data, with 50s resolution

XRB (GX 339-4)
with XMM (0.2-10 keV)
0.5 s of data, with ~0.2s resolution
The most popular spectral estimate (in astronomy, at least) is the averaged periodogram: raw periodograms from each of $M$ non-overlapping intervals are averaged. ‘Barlett’s method’ after M. S. Bartlett (1948, *Nature*, 161, 686-687)
Standard recipe:
Power spectrum analysis

observed = signal + noise
(not quite right!)

\[ x = s + n \]
\[ X = S + N \]
\[ |X|^2 = |S|^2 + |N|^2 + \text{cross-terms} \]

\[ P(f) = \langle |S|^2 \rangle = \langle |X|^2 \rangle - \langle |N|^2 \rangle \]
Standard recipe:
Power spectrum analysis

\[ |X|^2 \]

\[ |N|^2 \]

\[ |S|^2 \]
A message from Captain Data:

“More lives have been lost looking at the raw periodogram than by any other action involving time series!”

(J. Tukey 1980; quoted by D. Brillinger, 2002)

\[ I_j \sim P(f_j) \chi^2_2 / 2 \]

what we get (periodogram)
what we want
chi-sq variable
large scatter (~100%) and asymmetric distribution to each periodogram point. And this is only true in the large \( N \) limit...
A message from Captain Data:

“More lives have been lost looking at the raw periodogram than by any other action involving time series!”

(J. Tukey 1980; quoted by D. Brillinger, 2002)

Even when we can “beat down” the intrinsic fluctuations in the periodogram, biases – in the form of *leakage* and *aliasing* – can be difficult to overcome.

Especially true when \( N \) not really large, and variability is still “red”
Example power spectrum
power spectral features (zoology)

**Broad-band noise** (the “continuum”)
Previously modelled using piece-wise power laws
“soft state” power spectra often cut-off power law
Nowak (2000) and others showed Lorentzians work (for “hard state” power spectra)
See talks by L. Heil, A. Ingram (next)

**Quasi-periodic oscillations** (QPOs) are “peaked noise” (not periods) – bewildering phenomenology (but getting simpler?)
See S. Motta’s, Rapisarda’s and Steven’s talks (next)
In AGN?
See W. Alston’s talk (next)
X-ray binary power spectra

- Usually dominated by “red noise”
- Very broad range of frequencies
- Broken power-law(s)
- Or sum of broad Lorentzians
- QPOs (width: $f / \Delta f > 2$)

Done & Gierlinski (2005)

Estimating rms

Variability dominated by broad-band noise (= aperiodic, stochastic, random)
Power spectrum contains all useful information *iff* stationary, Gaussian process
⇒ mean and variance (rms) do not change with time
We can integrate 2-20 Hz in many short data segments ($n\Delta t \geq 0.5$ s) and see...
rms-flux relation I

Average X-ray count rate (flux) over $\Delta T=256$ sec segments ($=65536\Delta t$)

Calculate 2-20 Hz rms for each segment from periodogram

Compare time series of $<\text{flux}>$ with rms
Calculate $<\text{flux}>$ and rms using $\Delta T=1$ sec segments
Average rms in flux bins to measure $<\text{rms}>$ against $<\text{flux}>$
Use $<\text{rms}>$ to reduce intrinsic scatter on rms
Strong linear relationship

Uttley, McHardy & Vaughan (2005)
Heil, Vaughan & Uttley (2012)
In *all* accretion discs...?

Optical fast variability of XRBs (Gandhi 2009)

- 2 ULXs (Heil & Vaughan 2009)
  - [Hernandez-Garcia, Vaughan et al. 2015]

- many Seyfert 1s (Vaughan et al. 2011)

- neutron star XRBs (Uttley & McHardy 2001)

- Also CVs (see Scaringi et al. 2014, 2015)
what does rms-flux mean?

“amplitude modulation”: multiplicative coupling of variations on all timescales

The multiplicative analogue of a Gaussian (normal) stationary process is a lognormal stationary process.
What causes the variability?

(Lyubarskii 1997; Churazov et al. 2001; Kotov et al. 2001; King et al. 2004; Arevalo & Uttley 2006; Cowperthwaite & Reynolds 2014)

See talk by A. Ingram (next)
Other models are available

Are the $F_x$ variations intrinsic (i.e. $\sim L_x$)?
Or is $L_x \sim$ constant and $F_x$ varies due to extrinsic factors (e.g. line of sight absorption)

An important question!
Variable absorption does sometimes cause variability in AGN (see yesterday’s talks)
X-rays are “harder when fainter” (Seyfert 1s) – makes sense if absorption
Can it all be “just absorption”? (see session VIII)
Absorption variability

Not the general solution. Needs to explain:
- broad-band noise power spectrum (in common with XRBs, CVs)
  (see also the AGN-XRB scaling results: McHardy et al. 2006 etc.)
- rms-flux relation (in common with XRBs, CVs)
- rev. mapping (yesterday’s talks) assumes point-like central source (and that works ok)
- X-ray / opt correlations

Much simpler if $L_x$ is variable, and absorption (sometimes) varies in front of that.

Mehdipour et al. (2015)
Looking ahead

- rapid, recent progress in X-ray “spectral-timing” (session VII, VIII). Likely to be more advances in methods and models
- need to cope better with uneven sampling (AGN people especially)
- better coordination of studies across wavebands (e.g. optical/IR vs. soft/hard X-rays) – for both XRBs and AGN
- surprises: e.g. the ultra-pulsar (session IX)
- ASTROSAT (2015+?)