X-ray Timing

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- Why should I be ~~interested~~?
- What are the tools?
- What should I do?

Why should I be interested?

Rotation and pulsation of stellar bodies; directly yields physics

- rotational period
- rotational stability ⇝ "braking index"

Binary orbits

- orbital period
- sizes of occulter & emission regions
- orbital evolution

Accretion phenomenology

- broad band variability
- "Quasiperiodic" oscillations (broad peaks)
- non-stationarity

Typical Sources of X-ray Variability

Isolated pulsars (ms - 10's s)

Xray binary systems

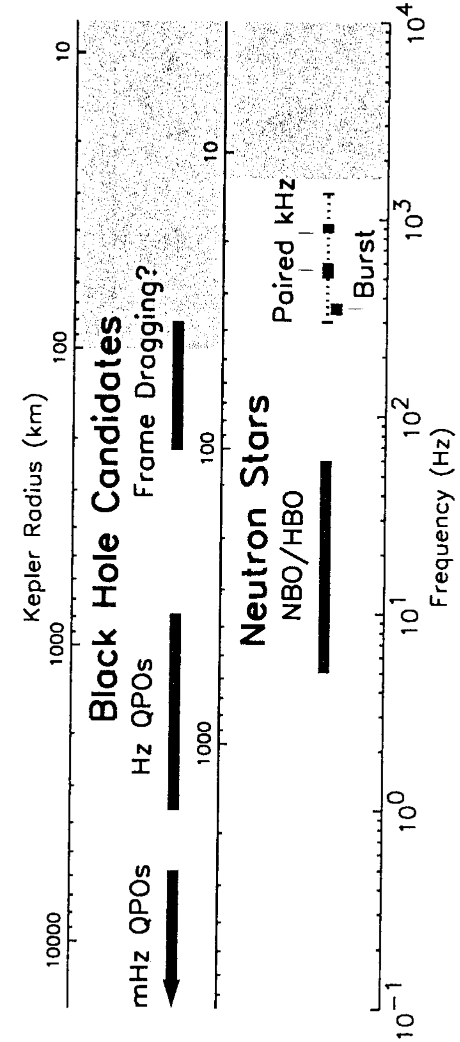
- accreting pulsars (ms - 10's s)
- eclipsing (10 min - days)
- accretion disk (~ms - years!)

Flaring stars (& Xray bursts)

⟶ in short, stellar-sized objects (& super massive BHs?)

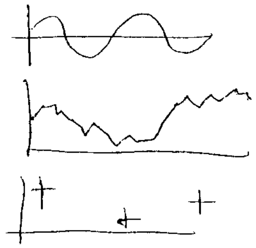
Probably <u>not</u> from supernova remnants, clusters, or ISM

ALTHOUGH, there could be serendipitous variable sources in the field, esp Chandra & XMM



Questions that Timing Analysis Should Address

Does the X-ray intensity vary with time?



On what time scales?

- Periodic / $\underline{\underline{a}}$-periodic? $f = ?$ $P = ?$
- how coherent? (Q-value)

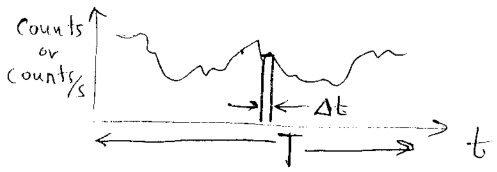
Amplitude of Variability

- rms or fractional rms

Variation with time of these parameters?

Basics

A light curve is always the first step (for each source in field of view)



Sampling period Δt and frequency $f_{samp} = 1/\Delta t$

Nyquist frequency

$$f_{Nyq} = \frac{1}{2} f_{samp}$$

is the highest signal frequency that can be accurately reconstructed

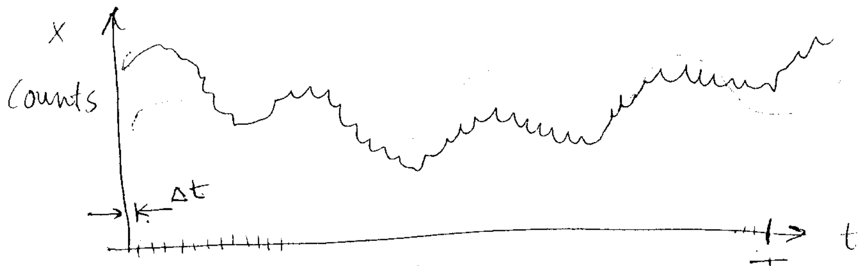
Basic variability

$\sigma^2 = \langle x^2 \rangle - \langle x \rangle^2$ variance of signal

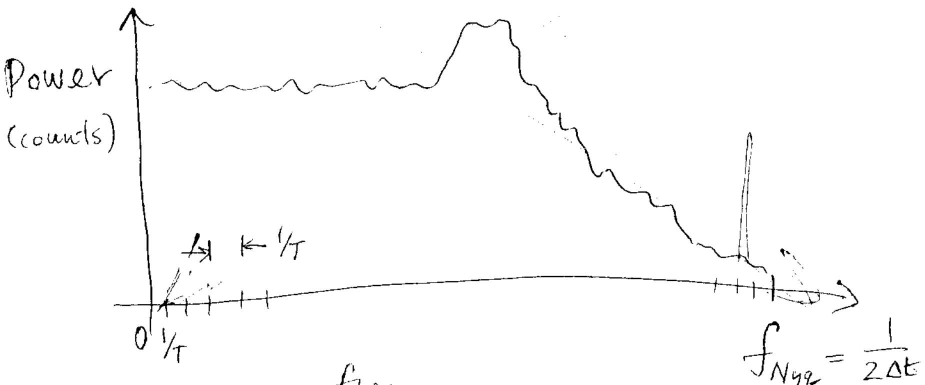
σ = Root Mean Square

Fourier Analysis

Answers the question, how is the variability of a source distributed with frequency?



time domain



frequency domain

Fourier Transform

Light curve $\{x\}$
N samples

Fourier coefficients

$$a_j = \sum_k x_k \exp(2\pi i jk/N)$$

$j = -N/2, \dots, 0, \; N/2-1$

usually FFT

Power Spectrum = (PDS)

TOOLS: powspec

Leahy Normalization $\quad P_j = \frac{2}{N_{ph}} |a_j|^2$

plotted as $\left(\frac{rms}{mean}\right)^2 Hz^{-1}$

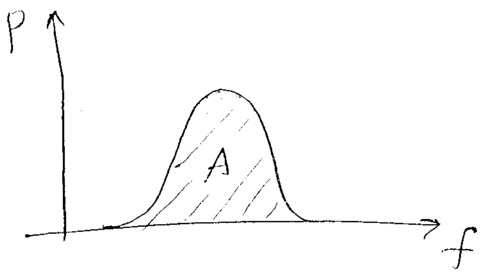
fractional rms normalization $\quad$ use $\frac{P_j}{\langle rate \rangle}$ ← mean count rate

Often plotted / rebinned log/log

Estimating Variability

from observations

Power Spectrum



Find "Area" A under curve in power spectrum

$$A = \int P \, d\nu$$

$$\approx \sum P_i \, \Delta\nu_i$$

~Nyquist spacing $= 1/T$

power spectrum values

Fractional rms

$$r = \sqrt{\frac{\text{Area}}{\langle \text{rate} \rangle}}$$

mean count rate

Coherent pulsations

$$pf = \sqrt{\frac{2(P-2)}{\langle \text{rate} \rangle}}$$

P = power

pf = pulsed fraction $= \frac{\text{peak} - \text{mean}}{\text{mean}}$

Estimating Variability

USEFUL for PROPOSALS

Broad band

$$r^2 = \frac{2 n_\sigma \sqrt{\Delta\nu}}{I \sqrt{T}}$$

r - rms fraction < amount of variability

n_σ - Number of "sigmas" of statistical significance (say, 3) demanded

$\Delta\nu$ - frequency bandwidth width of QPO or broad band freq.

I - count rate

T - exposure time

Can use to estimate variability amplitude or exposure times for a desired significance level

Ex: X-ray binary 0–10 Hz, 3σ detection
5 ct/s source, 10000 sec

$\longrightarrow$ 3.8% rms threshold

Estimating variability

Coherent pulsations

$$(pf)^2 = \frac{4\, n_\sigma}{I\,T}$$

I = count rate
T = exposure

pf is pulsed fraction

Power Spectrum Statistics

Any form of noise will also have a contribution to the PDS; even Poisson (counting) noise.

Distributed as χ^2 w/ 2 D.O.F. (Leahy norm)

	P
3σ	11.8
5σ	28.7

GOOD: All the hypothesis testing you use in spectroscopy also works for a PDS

BAD: Mean value is 2
Variance is 4 !!
Typical noise measurement is 2 ± 2

Adding more light curve points won't help $\longrightarrow$ makes more finely spaced frequencies

Statistics: Solutions

- Average adjacent frequency bins
- Divide up data into segments, make power spectra, average them

(in practice, both are the same)

In total, you average M bins together

- distributed as $\frac{\chi^2}{M}$ with 2M D.o.f.

Hypothesis testing → still Chi square, but with more d.o.f.

HOWEVER, in detecting a source, you examine many Fourier bins, perhaps all of them. Thus, the significance must be reduced by the number of trials.

$$\text{Confidence} = 1 - N_{bins} \cdot P(M \cdot P_i, 2 \cdot M)$$

N_{bins} - # bins in PDS = # trials

$P(\chi^2; \nu)$ - χ^2 hypothesis test

P_i - Fourier power being tested

Tips

Pulsar searches are most sensitive when no rebinning is done

QPO searches need to be done at multiple rebinning scales

Beware of signals introduced by

- instrument - CCD read time
- dead time
- orbit of spacecraft
- rotation period of earth (and harmonics)

What to do

Step 1. Light curves for each source in your field of view

(inspect for nifty features like eclipses)

Usually this enough to know whether to proceed.

You can't always see variability by eye.

Step 2 Power Spectrum

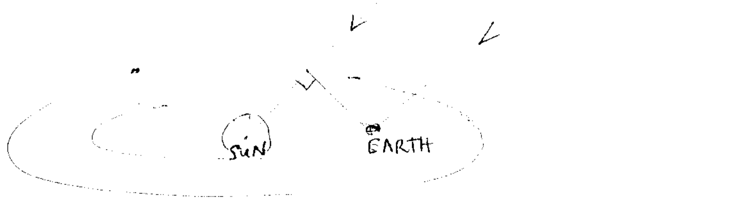
Run "powspec" or equivalent

- peak search
- length of FFT ~ 500 s

Step 3 Pulsar or Eclipses found?

Refinement of timing properties

a. Barycenter the data



Corrects to arrival time at solar system barycenter

TOOLS: fxbary
axbary

b. Refined timing

- epoch folding (efold)
- Rayleigh's statistic (Z^2)
- Arrival timing (Princeton TEMPO program?)

HINT: very unwise to do complete timing solution all at once, if data have long time base line.

Step 4 Broad band features?

Best done interactively { IDL, MATLAB, ??

a. PLOT

b. DETECT (use χ^2 threshold)

c. REBIN (factor ~8)

If broad band signal detected, fit to simple-to-integrate model(s) (gaussians & bkn power law)

Compute rms

Suggested Reading

van der Klis, M. 1989
"Fourier Techniques in X-ray Timing"
in Timing Neutron Stars, NATO ASI 262
Ögelman, H. van den Heuvel, E.P.J. eds
Kluwer

Press et al
Numerical Recipes
- power spectrum chapter
- Lomb Scargle periodogram

Leahy et al 1983 ApJ 266 160
FFT; power spectra; statistics; pulsars

Leahy et al 1983 ApJ 272 256
epoch folding vs. Z^2

Vaughan et al 1994 ApJ 435 362