LAT Light Curve Analysis: Aperture Photometry and Periodicity Searches

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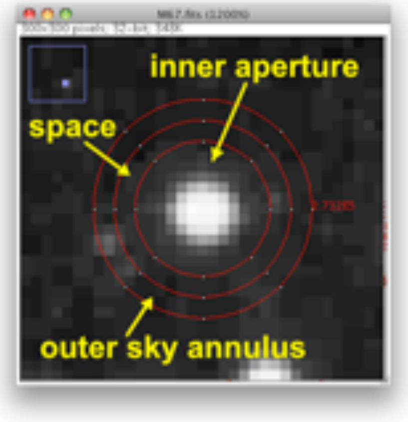
Talk Outline

- Photometry
  - Two methods
  - LAT specific considerations
  - Recipe for LAT aperture photometry
  - Error bars for low count rates
- Periodicity Searches
  - Binary gamma-ray sources
  - Searching for periods, power spectra
  - Weighting power spectra, exposure weighting

What is Photometry?

- Photometry is the measurement of the flux from an astronomical source of photons.
- It can either be an absolute measurement of the flux (e.g. ergs cm^{-2} s^{-1}) or a relative measurement (e.g. counts s^{-1}).
- Relative measurements may be either relative to other objects, or to the same object at different times.
- A light curve is a series of photometric measurements as a function of time.

Aperture Photometry



- The simplest form of photometry is aperture photometry.
  - You just measure the flux collected inside a particular region of the sky.
- This is originally done with optical telescopes by using a physical aperture (e.g. a hole in a piece of metal).
- Now, with imaging instruments, it is possible to use a software defined aperture.

LAT Photometry

- LAT light curves can be obtained in two basic ways:
  - Likelihood analysis (B. Lott presentation)
  - Aperture photometry
- Likelihood analysis has the potential for greater sensitivity and absolute flux measurements.
- Aperture photometry is easier, faster, and has the benefit of model independence.
- This presentation only deals with aperture photometry.

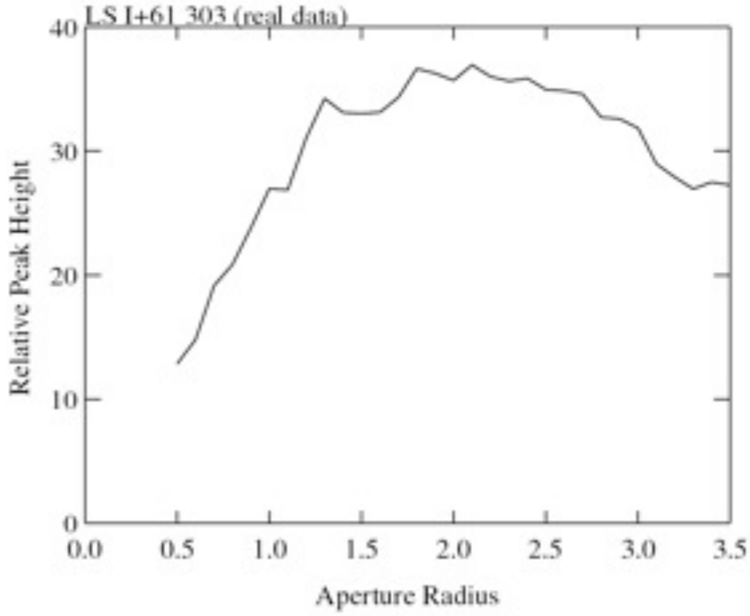
Things to be Aware of with Aperture Photometry

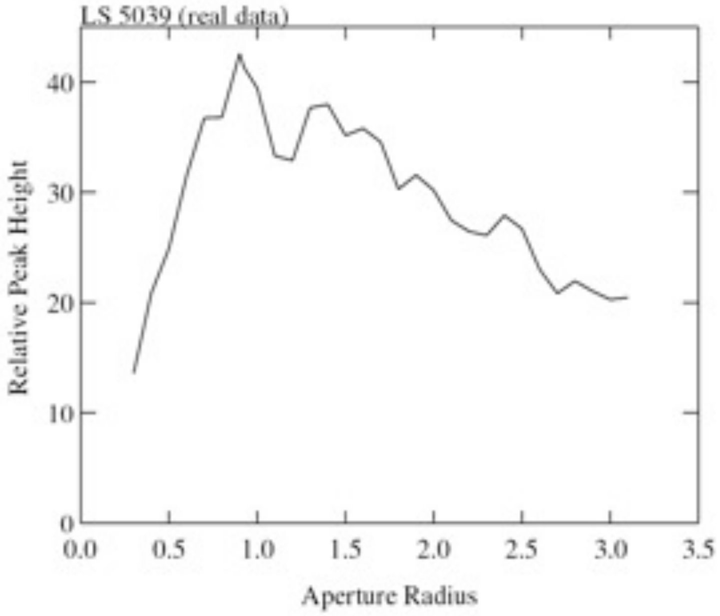
- The aperture contains photons from not just the source you're interested in.
  - It also contains photons from nearby sources and the background. The background is particularly strong in the Galactic plane.
- The aperture can be made smaller to reduce the background. But this also reduces the number of photons from the source.
- The aperture can be made larger to increase the photons from the source. But this increases the background.

LAT Aperture Optimization

- In optical/X-ray, aperture photometry relatively straightforward. e.g. point spread function not energy dependent.
- Want to choose aperture to maximize signal to noise ratio:
  - $S/N = S/(S + B)^{1/2}$ (S = source photons, B = background)
- LAT aperture photometry complicated by:
  - PSF energy dependence
  - Background from other sources and Galactic plane is complex and energy dependent.
- Optimum aperture size and energy range to maximize S/N varies from source to source...

LAT S/N aperture dependence





For two different sources the optimum signal-to-noise ratio is obtained for different radii.

Tools Used for Aperture Photometry

- Data server
- fkeypar/pget
- gtselect
- gtmktime
- gtbin
- gtexposure
- fv or fdump + external data manipulation scripts

Steps

- It is recommended to use a script to chain together the tools.
  - fkeypar – determine file start and stop times
  - gtselect – filter data based on time, zenith limit, energy, position, and event class
  - gtmktime – create good time intervals
  - gtbin – make quasi-light curve (counts rather than rate)
  - fdump – export data
  - other tools – convert counts to rates, calculate errors

Get Photon File Start/Stop Times

$ fkeypar "L090923112502E0D2F37E71_PH00.fits[1]" TSTART

(photon start time = 266976000.)

$ fkeypar "L090923112502E0D2F37E71_PH00.fits[1]" TSTOP

(photon stop time = 275369897.)

The values obtained with “fkeypar” will then be accessible using “pget”

Filter the Photon File

```
$ gtselect zmax=105 emin=100 emax=200000 infile="L090923112502E0D2F37E71_PH00.fits"
outfile=temp2_1DAY_3C454.3.fits ra=343.490616 dec=16.148211 rad=1 tmin=26697
6000. tmax=275369897. evclsmin=3 evclsmax=10
```

Parameters specify:
- Energy range (100 to 200,000 MeV)
- Source coordinates
- 1 degree radius aperture
- start and stop times previously determined

(N.B. If you're going to barycenter then the min and max times should instead be slightly greater/less than the times in the spacecraft file.)
- evclsmin = 3 for DIFFUSE class (for <u>simulated</u> data use 0)

Writes to file: temp2_1DAY_3C454.3

Calculate GTIs (Good Time Intervals)

```
$ gtmktime scfile="L090923112502E0D2F37E71_SC00.fits" filter="(DATA_QUAL==1) &&
(angsep(RA_ZENITH,DEC_ZENITH,343.490616,16.148211)+1<105) &&
(angsep(343.490616,16.148211,RA_SCZ,DEC_SCZ)<180)" roicut=n
evfile=”temp2_1DAY_3C454.3" outfile="temp3_1DAY_3C454.3"
```

Parameters specify:
- Good data quality
- photons less than 105 degrees from zenith (+ 1 is because using a 1 degree aperture)
- photon locations less than 180 degrees from center of field of view
- input file is output from gtselect

Writes to file: temp3_1DAY_3C454.3

Extract a Light Curve

$ gtbin algorithm=LC evfile=temp3_1DAY_3C454.3.fits outfile=lc_1DAY_3C454.3.fits scfile=L090923112502E0D2F37E71_SC00.fits tbinalg=LIN tstart=266976000. tstop=275369897. dtime=86400

Parameters specify:
- Make a light curve (LC)
- Input file is output file from gtselect
- Spacecraft file
- Linear time bins
- Start and stop times again
- dtime = 86400: 1 day bins

Writes to file: lc_1DAY_3C454.3.fits

Calculate Exposures of Time Bins

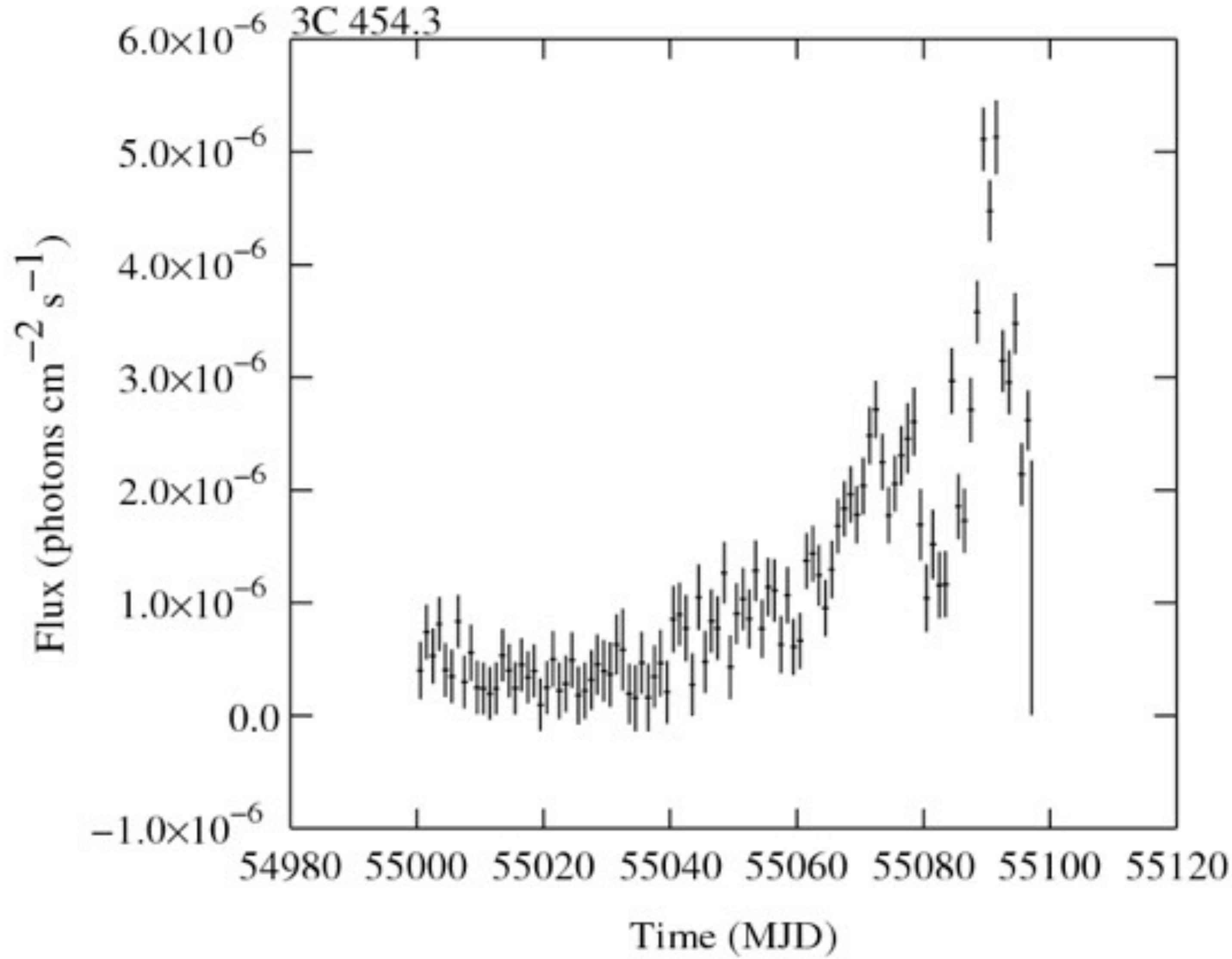
```
$ gtexposure infile="lc_1DAY_3C454.3.fits" scfile="L090923112502E0D2F37E71_SC00.fits" irfs="P6_V3_DIFFUSE" srcmdl="none" specin=-2.1
```

Parameters specify:
- Spacecraft file
- Instrument response functions ("irfs"). If, for example, SOURCE class rather than DIFFUSE was used in gtselect then use irfs="P6_V3_SOURCE"
- srcmdl – enables a more complex model than the default simple power law to be used in the exposure calculation.
- specin – photon spectral index for power-law spectrum. Note that the minus sign must be used.

An EXPOSURE column is added to the input file: lc_1DAY_3C454.3.fits

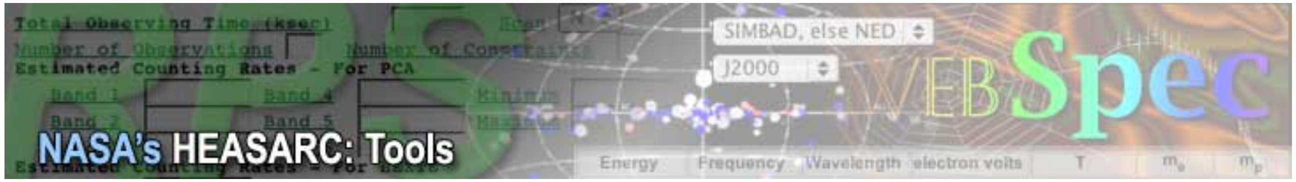
The Output File

- The “final” file will contain Time (in MET), Bin width (s) number of counts in the bin, Error Exposure.
- To convert to rates use e.g. fv or other software to divide counts by exposure. (Also convert from MET to MJD.)
- Error bars in output file are sqrt(counts)
  - For (e.g.) few counts this may be incorrect.
  - To do things correctly is more complicated (see supplemental material).


3C 454.3
6.0×10^−6
5.0×10^−6
4.0×10^−6
3.0×10^−6
2.0×10^−6
1.0×10^−6
0.0
−1.0×10^−6
Flux (photons cm^−2 s^−1)
54980 55000 55020 55040 55060 55080 55100 55120
Time (MJD)

http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xTime/xTime.pl

HEASARC HOME | OBSERVATORIES | ARCHIVE | CALIBRATION | SOFTWARE | TOOLS | STUDENTS / TEACHERS / PUBLIC



GENERAL TOOLS | MULTI-MISSION TOOLS | MISSION TOOLS

HELP

xTime - A Date/Time Conversion Utility

Calendar Time Formats	Input Time [UTC]	Output Time
ISO 8601 date (yyyy-MM-dd hh:mm:ss)		
Calendar date (yyyyMondd at hh:mm:ss)		
Year and day number (yyyy:ddd:hh:mm:ss)		
Julian Day (ddddddd.ddd...)		
Modified Julian Day (ddddd.ddd...)		
Mission-Specific Time Formats	**Input Time [MET]**	**Output Time [MET]**
RXTE seconds since 1994.0 UTC (decimal)		
RXTE seconds since 1994.0 UTC (hexadecimal)		
RXTE mission day number (dddd:hh:mm:ss)		
RXTE decimal mission day (dddd.ddd...)		
Swift seconds since 2001.0 UTC (decimal)		
Swift mission day number (dddd:hh:mm:ss)		
Fermi seconds since 2001.0 UTC (decimal)		
Fermi mission week (integer)		
Swift decimal mission day (dddd.ddd...)		
Suzaku seconds since 2000.0 UTC (decimal)		

barycentering

- barycentering - correction of times to center of mass of the solar system
- `gtbary` can also be used to barycenter light curves.
- `gtbary` must be done as the last step.
  - If you barycenter the photon file the exposure time calculations will be wrong!
- Spacecraft file must cover longer (not same) time range than photon file.
  - If needed, use gtselect to trim down time range by tiny amount (e.g. 60 seconds)

More Advanced Error Bar Treatment

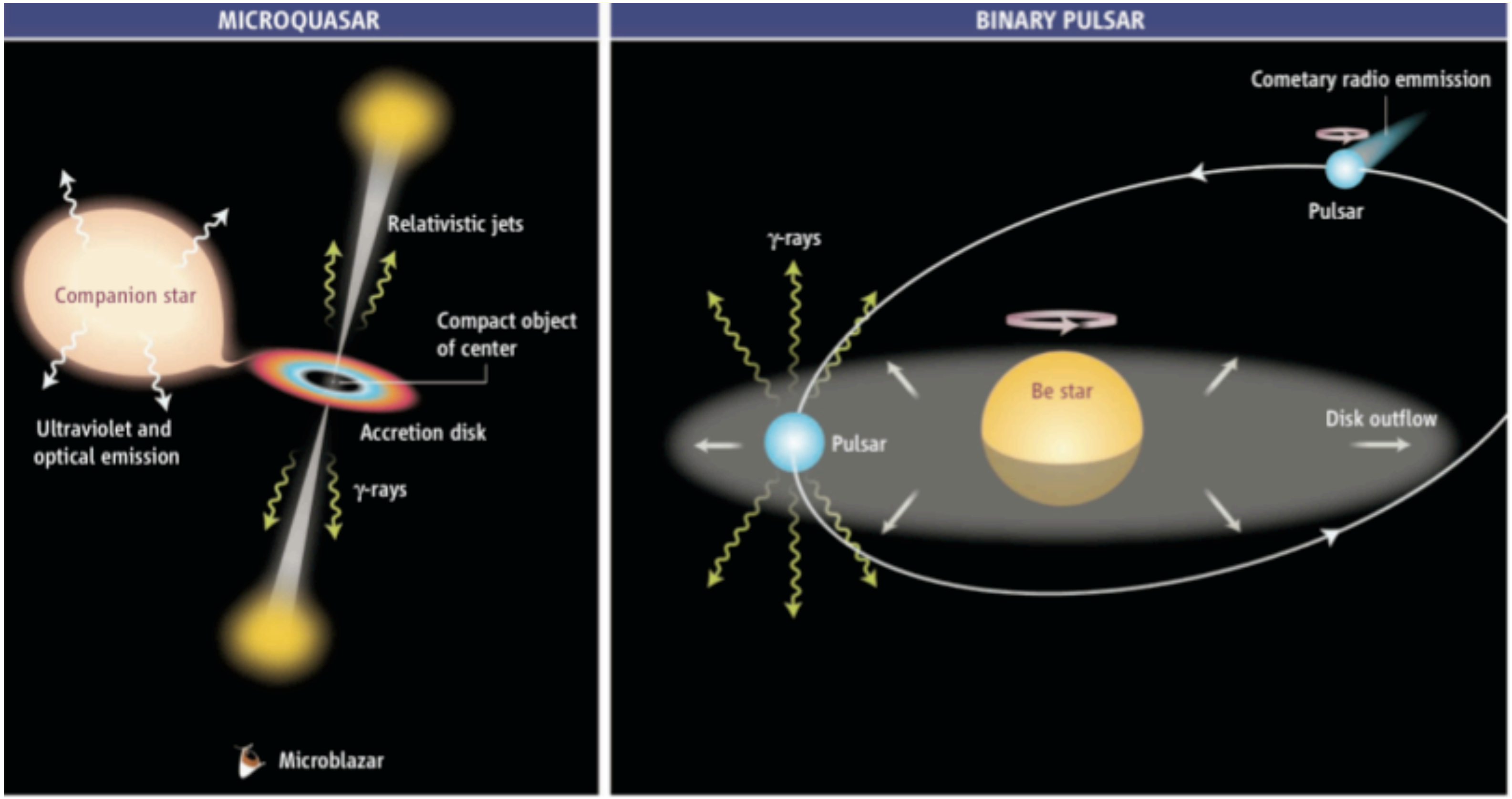
- Dealing with error bars for small numbers of counts has been discussed in the astronomical literature by e.g.
  - Gehrels, 1986, ApJ, 303, 336
  - Kraft, Burrows, & Nousek, 1991, ApJ, 374, 344
- Useful review of concept of "coverage" by Heinrich in:
  - *www-cdf.fnal.gov/publications/cdf6438_**coverage**.pdf*

Crude Approach to Low-Count Errors

- Instead of taking errors as $N^{1/2}$, where N is the observed number of counts, look at the ends of the error bars.
  - i.e. what underlying "population" count rate would be consistent with the "sample" count rate?
  - $\sigma = \pm 0.5 + \mathrm{sqrt}(N + 0.25)$
    - e.g. $0 \rightarrow 0, +1, -0$
    - $1 \rightarrow 1, +1.62, -0.62$
    - $2 \rightarrow 2, +2, -1$
- If needed, these errors can be "symmetrized".

Binary Gamma-Ray Sources

- Some types of binary star systems are expected to be gamma-ray sources.



from: Mirabel (Science 309, 714, 2006)

Looking for Binary Orbital Periods

- Detection of a (non-pulse) period in an unidentified γ-ray source would be a strong indicator that the source is a binary.
- Modulation of the γ-ray light curve would give key information on the γ-ray production mechanism.
- Periods are expected to be mainly between ~hours to ~years long.
- A powerful way to search for a period in a light curve is to calculate the power spectrum…

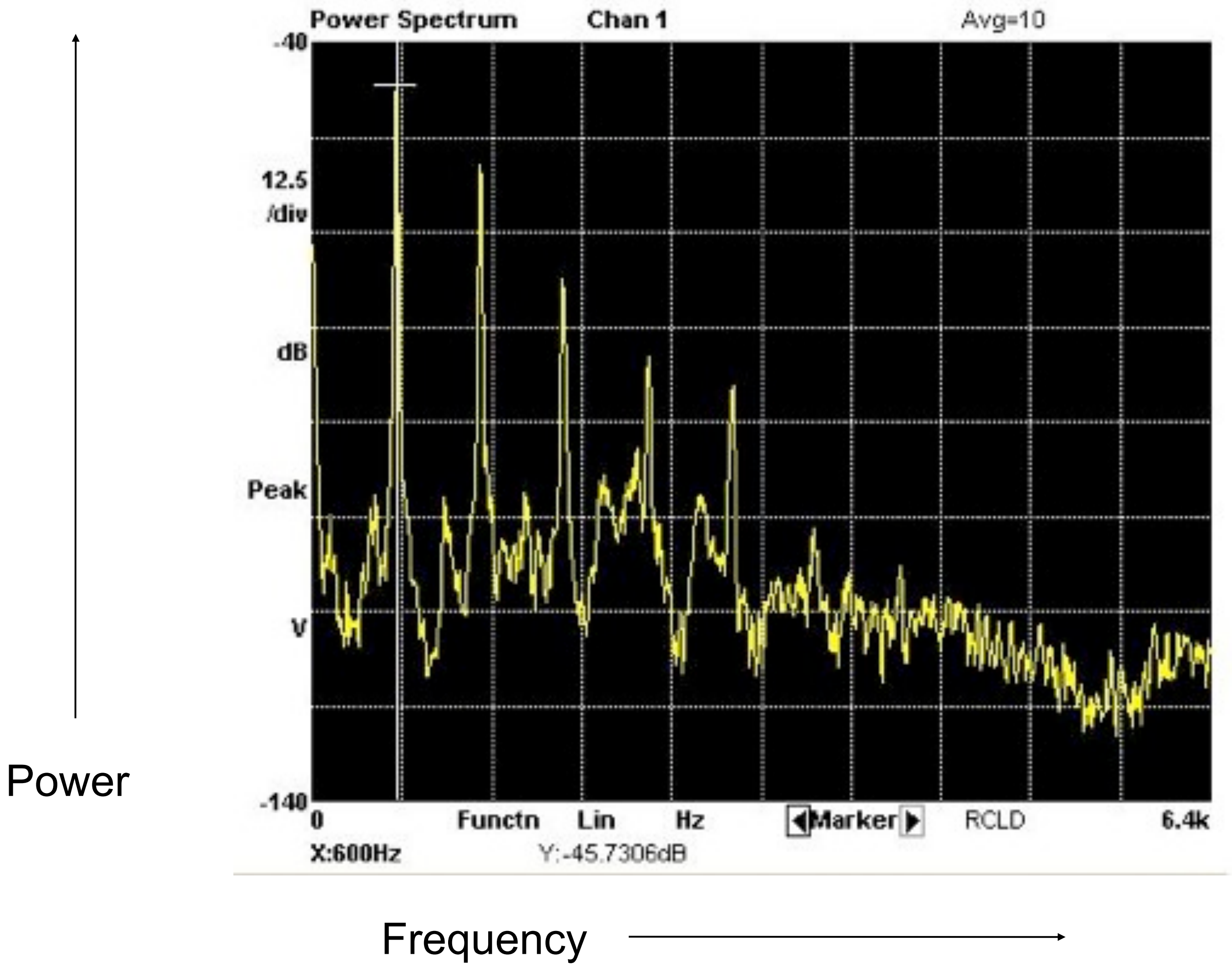
Power Spectra

A power spectrum is obtained by calculating the Fourier transform of a time series (e.g. a light curve), and then summing the sine and cosine amplitudes at each frequency.

$$P(\omega) = \frac{1}{N}\left[\left(\sum_i y_i \cos\omega t_i\right)^2 + \left(\sum_i y_i \sin\omega t_i\right)^2\right]$$

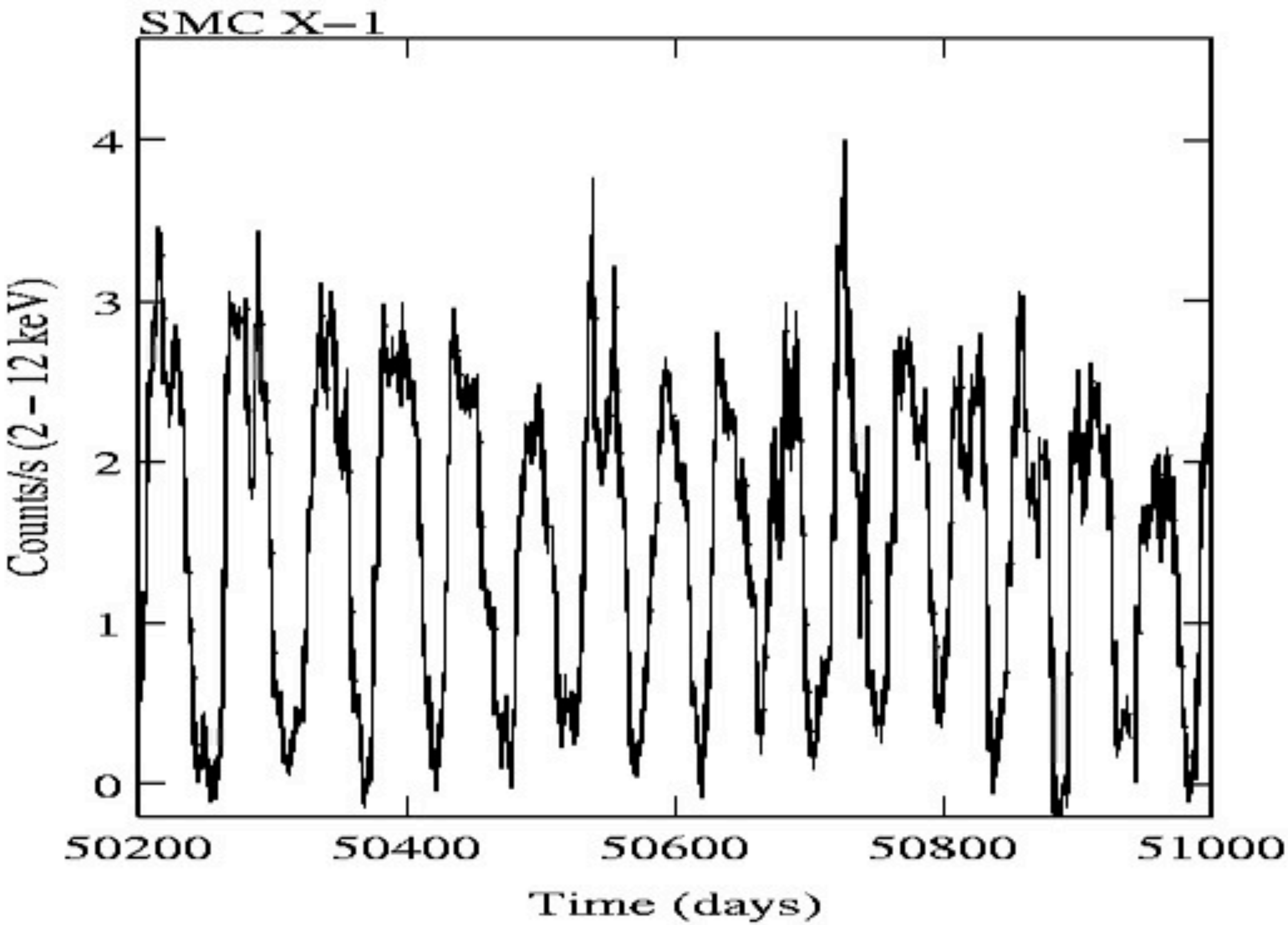
- A periodic signal will give a peak in the power spectrum.

Power Spectrum of a Note Played on a Flute

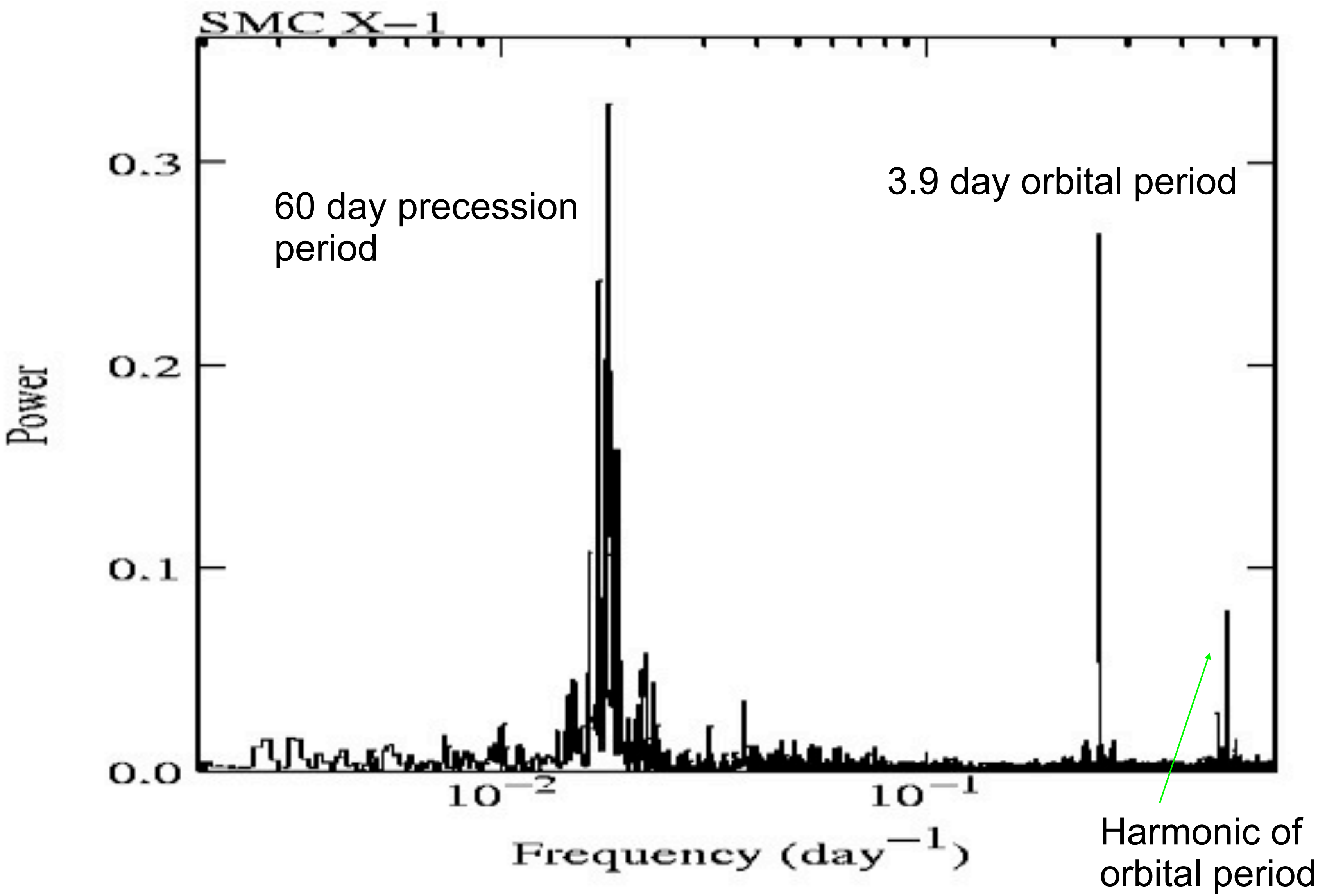


(Figure from Tasha Vanesian)

The X-ray Light Curve of the X-ray Binary SMC X-1…



…and its Power Spectrum



Calculating Power Spectra

- A variety of software is available to calculate power spectra.
  - e.g. “powspec” in HEASARC Xronos package.
- If data are evenly spaced, then it is possible to calculate a Fast Fourier Transform (FFT) which uses less computer time.
- For unevenly spaced data, a power spectrum based on the Fourier Transform can still be calculated.
  - An important refinement of this is the Lomb-Scargle periodogram which has better statistical properties (Scargle 1982, ApJ, 263, 835).

Other Period Search Techniques

- Although the power spectrum is very powerful, there are other ways to look for periodicities in the power spectrum.
- The power spectrum is well-suited for the detection of <u>sinusoidal</u> modulation. Other techniques may work better if the modulation consists of, e.g., brief flares.
- Many other techniques are related to “folding” data. i.e. taking a trial period and replacing data times with phase values for that period.

Beyond the Basics: Weighted Power Spectra

- What should be done if data points have different errors?
- Scargle (1989) proposed that the effect of unequally weighted data points can be found by considering two points that coincide, and treating them as a single point of double weight.
- A "natural" approach to combining data points of different error bar size is to use the same weights as when calculating a weighted mean.

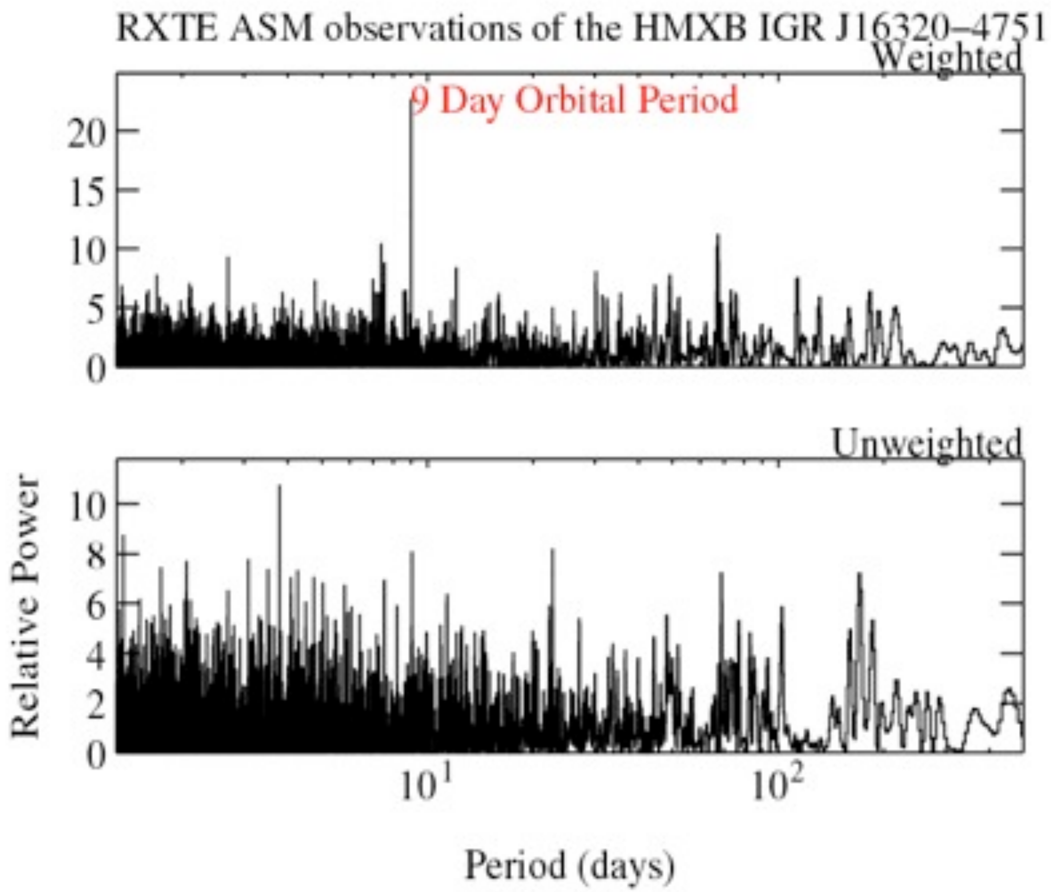
The Weighted Power Spectrum

The weighted mean of a series of values: y_1, y_2, ... y_n, is defined as:

$$\overline{y} = \frac{\sum_{i=1}^{n} y_i / \sigma_i^2}{\sum_{i=1}^{n} 1/\sigma_i^2}$$

- Based on the weighted mean, calculate the power spectrum of $(y_i - y_{mean})/\sigma_i^2$
  - y_i is the measured flux at time t_i and σ_i is its error.

Weighting Can Reveal Orbital Periods in Faint Sources (X-ray example)



Should LAT data be weighted?

- Fermi operates almost exclusively in sky survey mode:
  - For half day time bins and longer (and also time bins that are multiples of the survey period) there is little variation in exposure.
    - Weighting not needed.
  - But, if time resolutions less than survey period are required then there are huge variations in exposure.
    - Appropriate weighting expected to be crucial.

How should LAT data be weighted?

- Weighting RXTE ASM and oher light curves by their errors works very well? Can/should LAT data be weighted by their errors?
    - LAT rates are counts/exposure.
    - Errors are ~$(\text{counts})^{1/2}$/exposure.
    - But, there are very few counts in each time bin. There are therefore shot-noise variations in count rate & error.
  - Alternative is to use Exposure weighting.

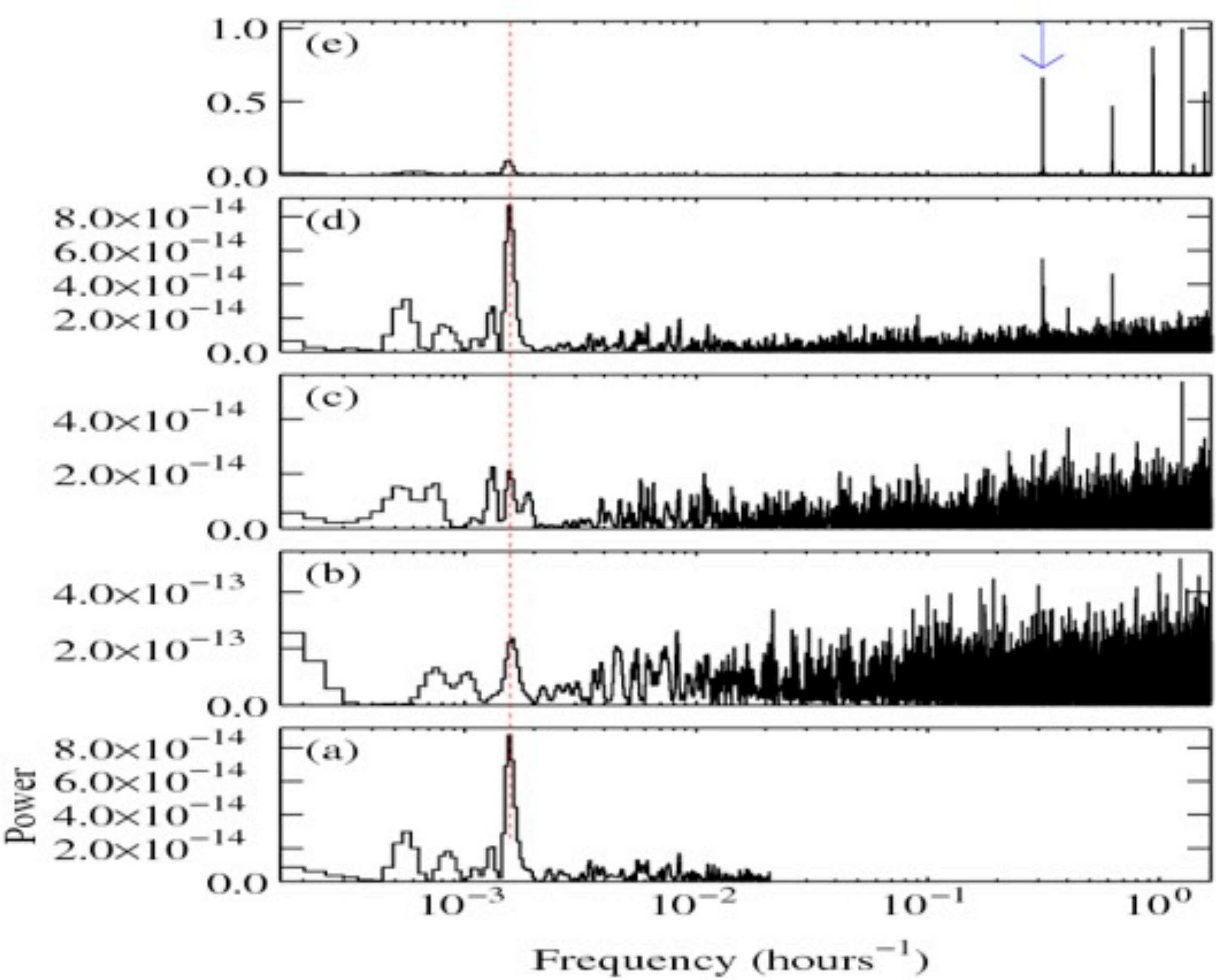
Exposure-Based Errors

- Calculate mean count rate.
- For each time bin, calculate the predicted number of counts for the exposure of that time bin.
- Take the square root of predicted number of counts.
- Divide by exposure to get rate error.
- This gives an error based only on the "quality" of each time bin.

Exposure Weighted Rates vs. Unweighted Raw Counts

- Exposure weighting of rates:
  - Divide counts in bin by exposure time to get rates.
  - Use a weight based on time - the weight is essentially multiplying by exposure time.
  - i.e. both divide and multiply by exposure.
- Do effects of exposure just cancel out?
- No! - Crucial difference is subtraction of mean before calculating power spectrum.

Comparing weighting methods:



1ks
"Counts"

1ks
Exposure weighted

1ks
Error weighted

1ks time bins.
No weighting

1 day time bins.
No weighting.

Red line = known binary period. Blue arrow = Fermi orbital period.

Results of Looking for Binary Orbital Periods in LAT Light Curves...

... will be reported on Monday!