Hunting for New Gamma-ray Binaries - Technique Development

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We are investigating techniques for searching for new gamma-ray binaries. These include determining optimal parameters for aperture photometry and power spectrum weighting techniques.

Abstract

There are only a few sources that are definitely known to be gamma-ray binaries. Two of these are listed as associations in the Fermi LAT Bright Source List. We are developing novel techniques to extract high signal-to-noise light curves of all cataloged Fermi sources and to search for periodic variability using appropriately weighted power spectra. The detection of periodic variability would be strong evidence for the detection of a new gamma-ray binary. The LAT's sensitivity provides the opportunity to open up completely new discovery space for additional binary systems, potentially involving novel astrophysics. We present here demonstrations of the sensitivity gains obtained through the use of these techniques.

Introduction

At X-ray energies, the extra-solar sky is dominated by the emission from accreting binary systems. However, at higher energies (GeV to TeV) very few binary systems are known to be sources. The emission mechanisms of gamma-ray binaries are still unclear. The principal models proposed are that either the gamma-ray emission could originate from relativistic jets generated by accretion onto a neutron star or black hole ("microquasars") or be due to the interaction between the relativistic wind coming from a pulsar and the stellar wind of its companion.

We are investigating techniques to obtain LAT light curves with increased signal-to-noise levels and search for periodic modulation of the gamma-ray flux. The usual way to search for periodic variability is to use a periodogram (e.g. Scargle 1982). The sensitivity of the periodogram for the detection of a periodic signal strongly depends on the signal strength compared to the noise level: the probability of a peak in the periodogram reaching or exceeding a value "Z" scales as exp(-Z) when the periodogram is normalized by the variance of the data set. Small changes in signal-to-noise can thus result in large significance changes in a power spectrum.

The Challenge

In the optical and X-ray wavebands aperture photometry is relatively straightforward. Although the ideal aperture to use may depend on source brightness, the PSF typically has little energy dependence and minor dependence on the source location in the field of view. The signal-to-noise ratio (SNR) of a single observation will be given by:

$SNR = S/(S + B)^{1/2}$,

where S is the number of source photons and B is the number of background photons. In the optical it is generally relatively easy to determine the aperture at which the SNR is greatest (e.g. Howell 1989). For the Fermi LAT the situation is more difficult: the PSF depends strongly on energy, in addition, the background, both from other sources and the Galactic plane, is complex.

The usual alternative to aperture photometry for LAT data is to use maximum likelihood fitting (the equivalent of profile fitting in the optical). However, this procedure is both very compute intensive and can also be problematic when few or zero photons are detected in a time bin.

Approaches to the Problem

1) Optimal aperture and energy range selection.
We are developing tools to determine the ideal aperture size and energy range to use for any source. This takes into account the cataloged spectrum of the source of interest, potentially contaminating nearby sources, and emission from the Galactic plane.

Once apertures and energy ranges have been determined, aperture photometry will then be generated for all sources. We choose to analyze all sources, not just those thought most likely to be gamma-ray binaries. This ensures that a misclassified gamma-ray binary will not be missed.

A large fraction of the light curves will be of AGNs and we will provide our light curves to the community as a general service. We will use discrete Fourier Transforms and Lomb-Scargle analyses to search for the periodic modulation that is expected to be a signature of a gamma-ray binary.

2) Photon Weighting
Evaluating the probability that each individual photon came from a specific source should give the maximum possible SNR. This is being investigated for pulsars by Kerr (see separate presentation).

3) Multiple Apertures
As an intermediate step between optimal apertures and photon weighting we also will investigate the SNR gain provided by obtaining light curves in several energy bands with different aperture sizes at each energy band. i.e. smaller apertures at higher energies where the PSF is smaller. These light curves can then be combined together with appropriate weighting into an overall light curve. This technique has some similarities to Naylor's (1989) "optimal photometry" method.

Examples of Aperture Dependence Results

The graphs in the next column show the dependence of a peak in the power spectrum at the orbital period of modulation in actual sources (LSI +61° 303 and LS 5039) and for simulations using `gtobssim`. These illustrate some of the dependencies of optimal aperture size on source spectrum and the level of background.
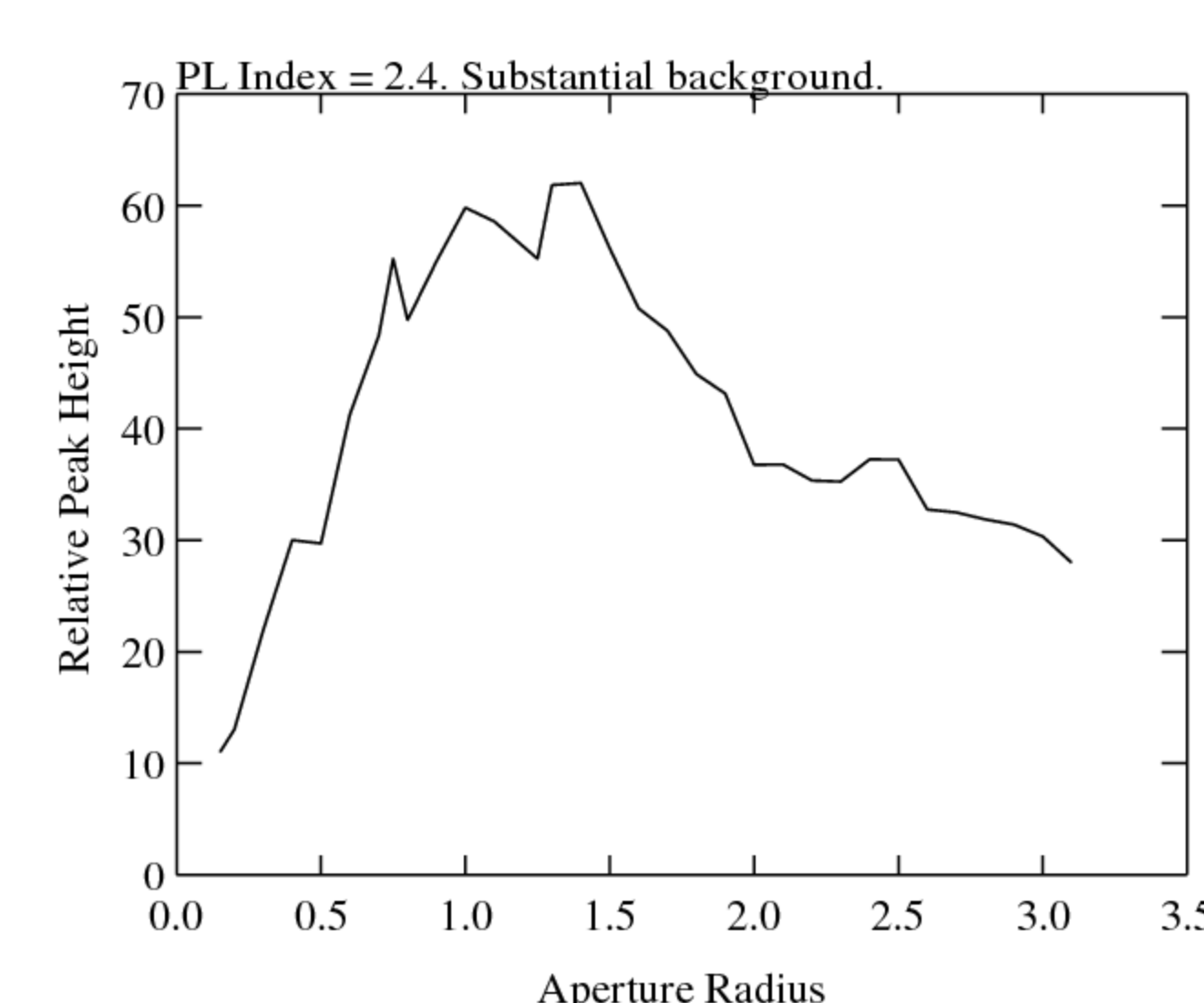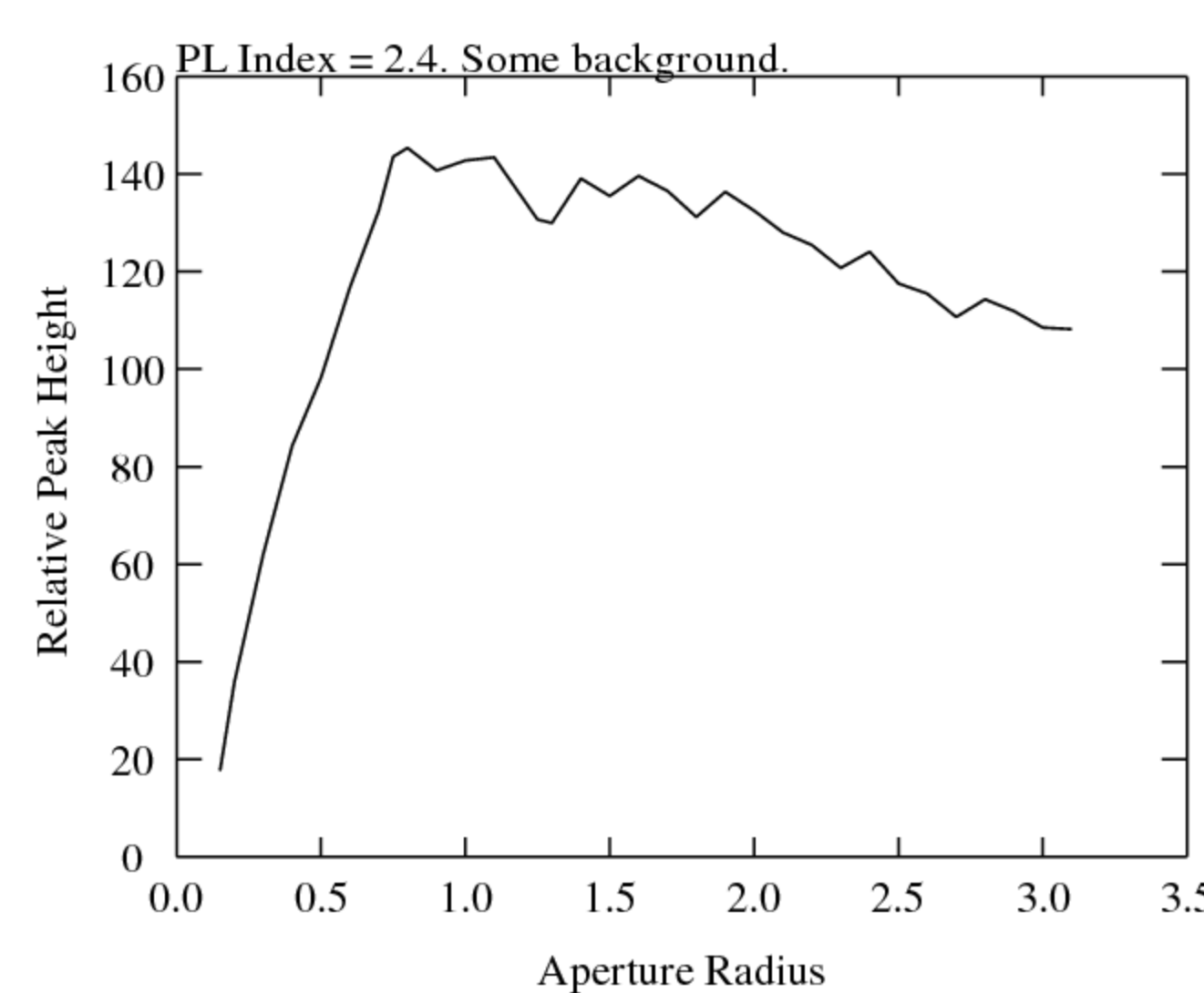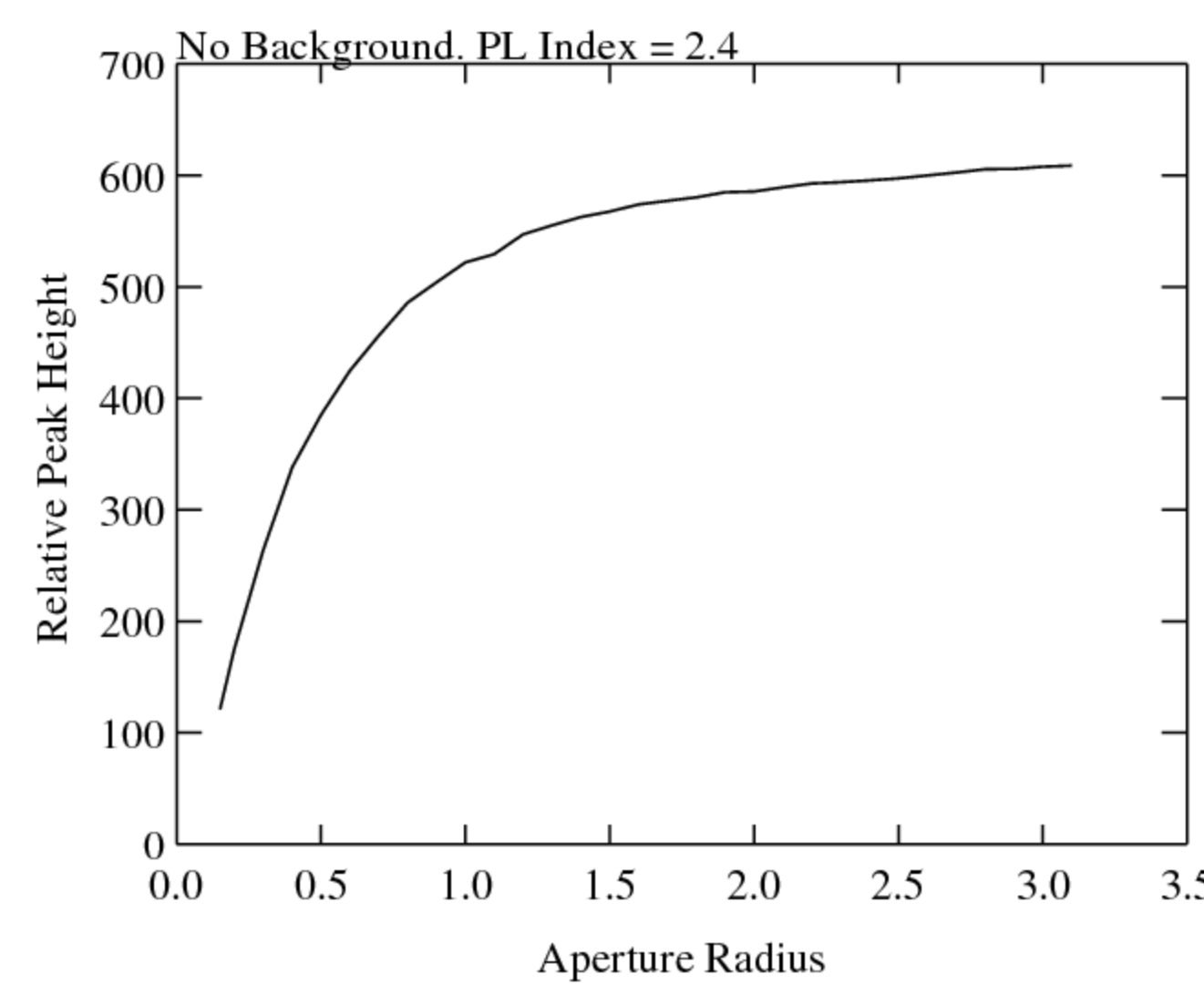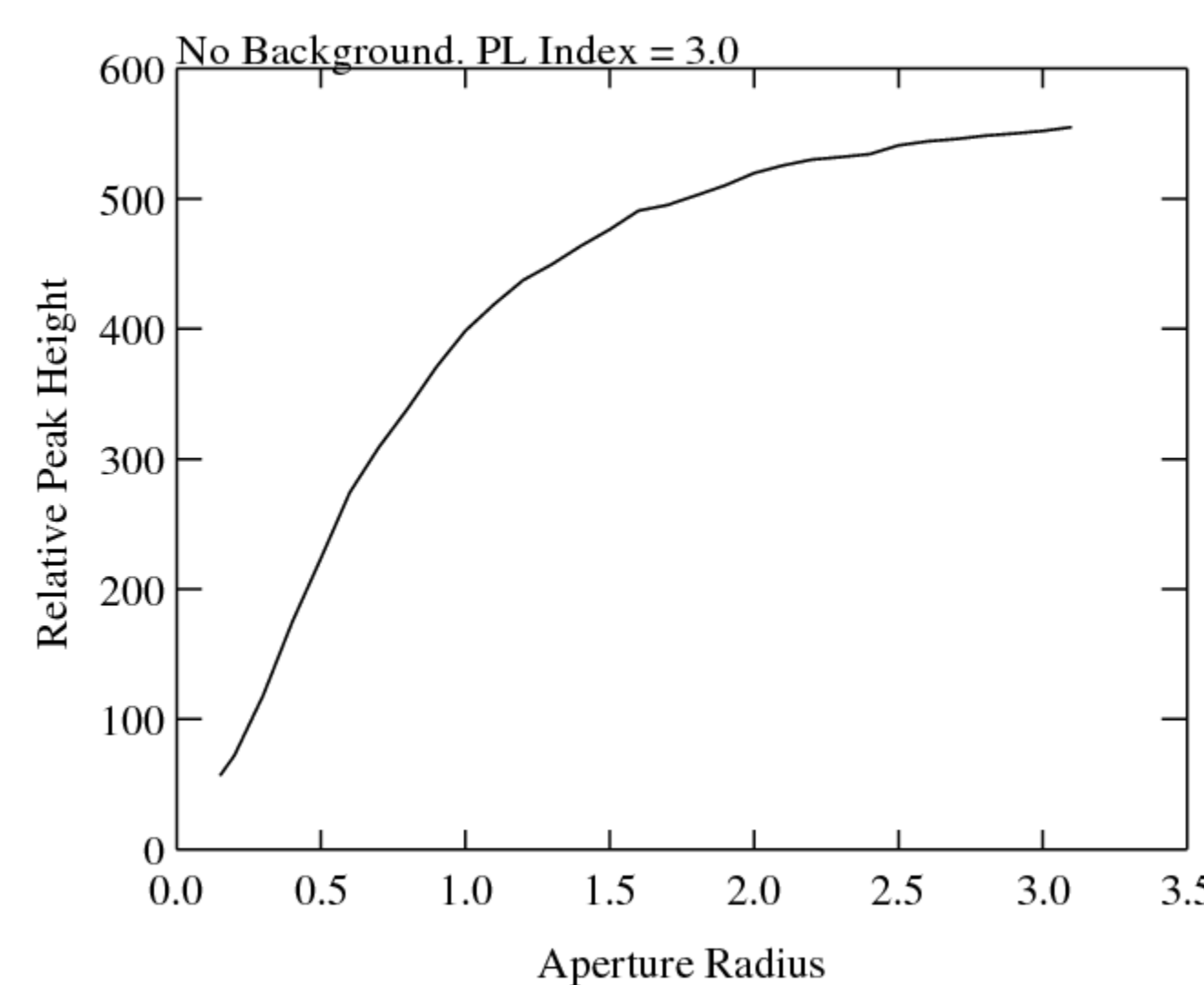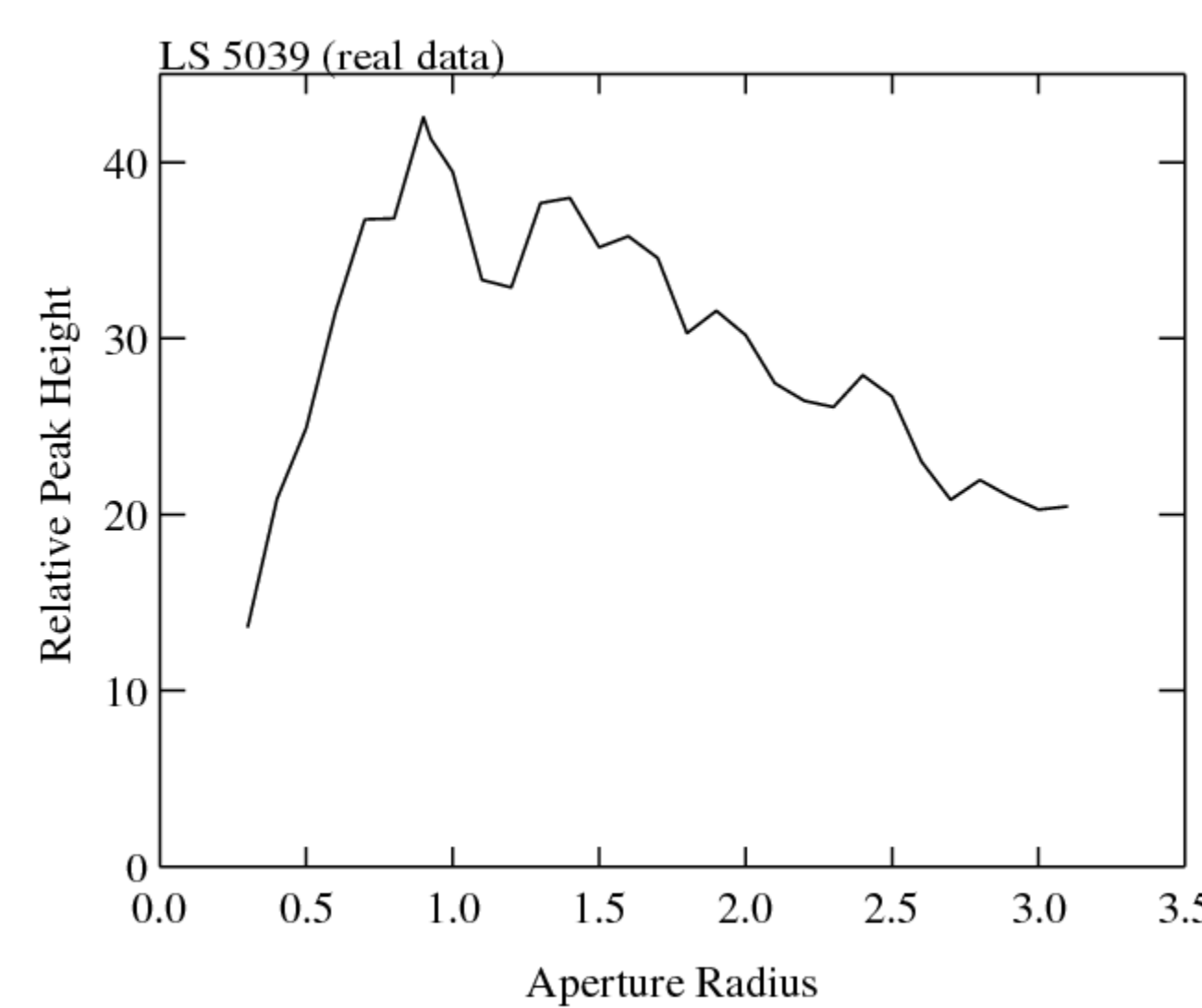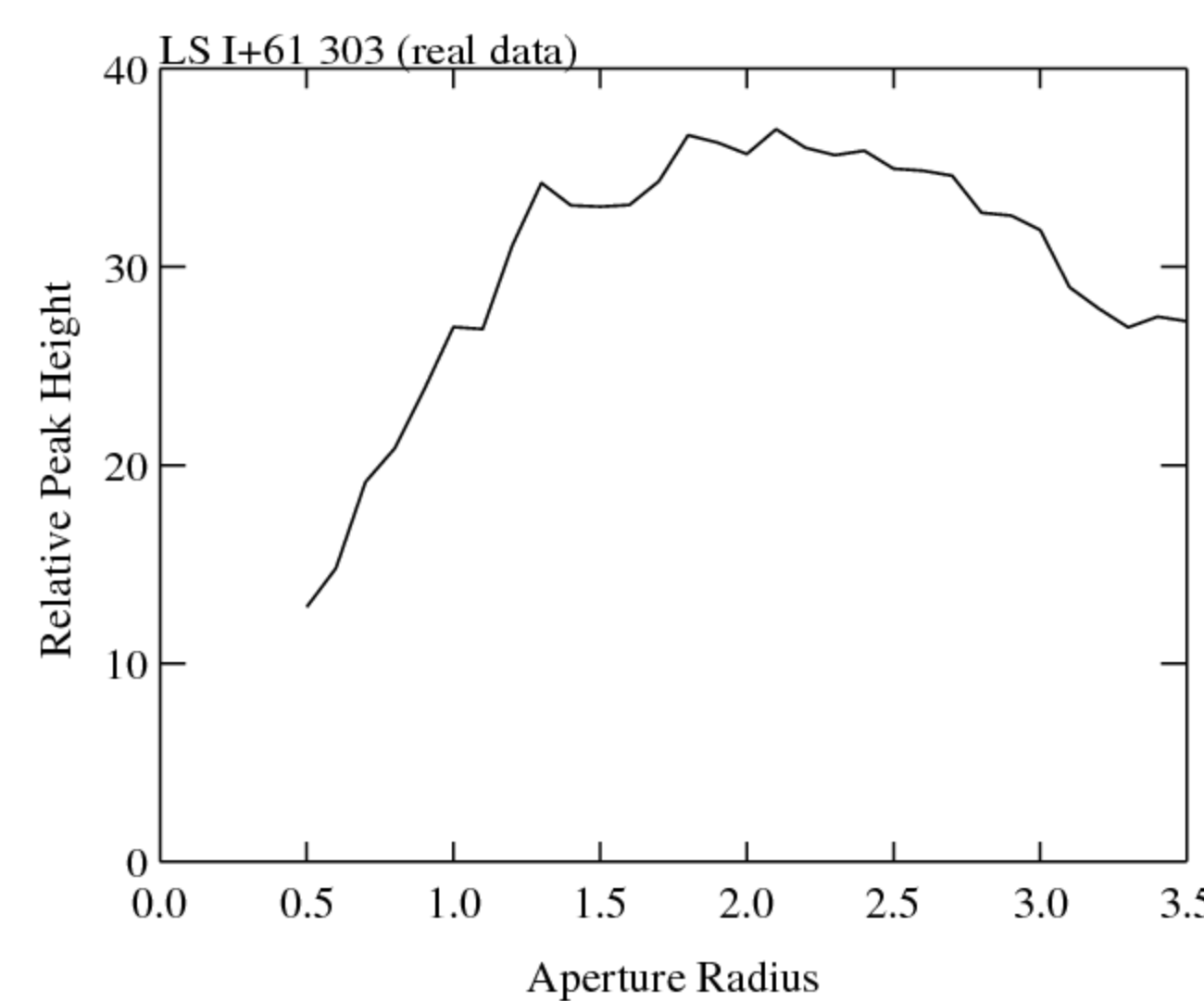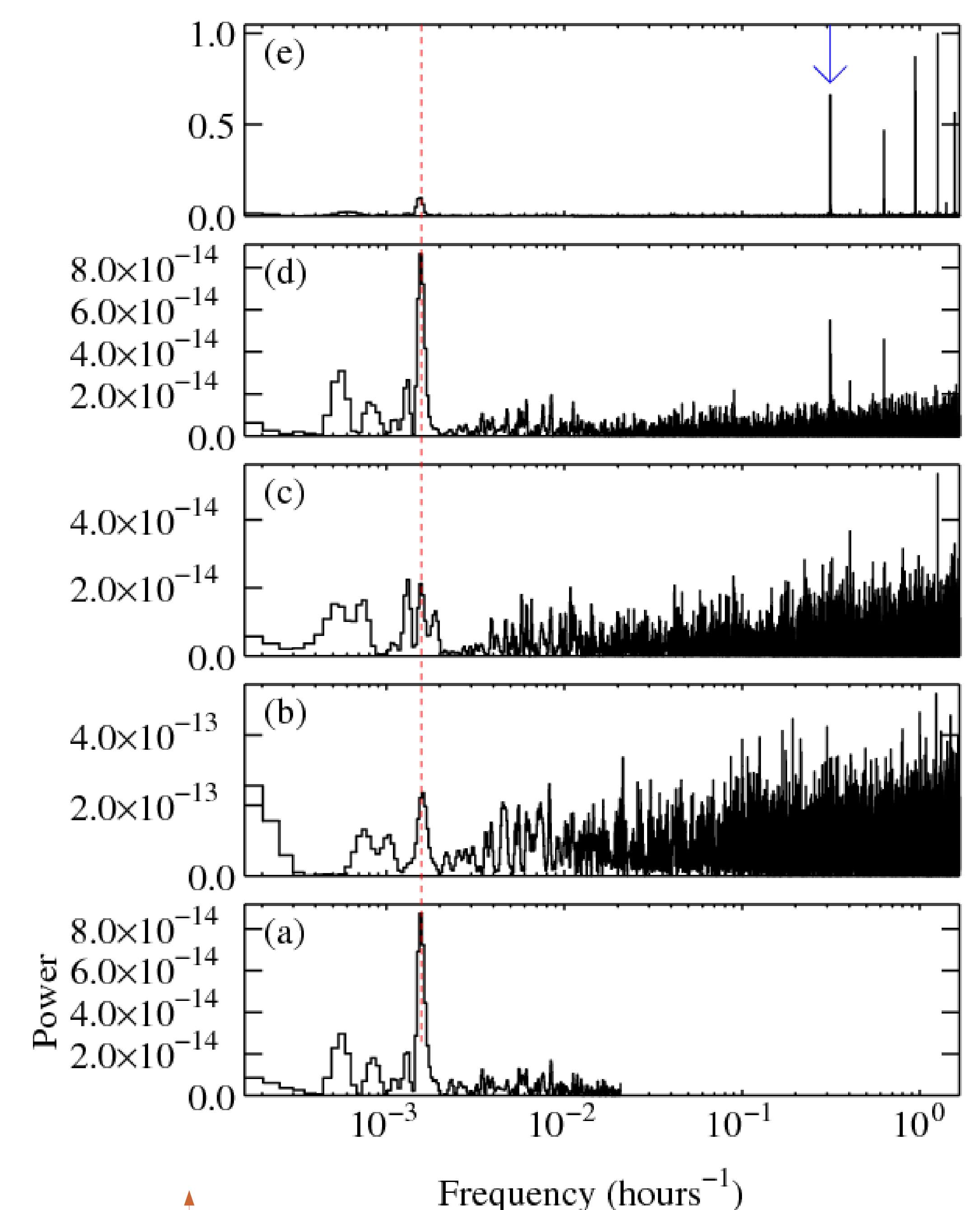

Power Spectrum Weighting

For Fermi light curves the exposure of time bins is not necessarily uniform. For example, if the time bin size is a lot shorter than the survey repeat time, then there can be extreme differences in the exposure of the time bins. Scargle (1989) noted that the effect of unequally weighted data points in the calculation of a periodogram could be understood by considering the combination of points that coincide in time. This leads to an analogy between a weighted power spectrum and the weighted mean. However, although the procedure to calculate a weighted periodogram is straightforward, it is important to that the correct weights are chosen. For example, if source variability is significant compared to the typical errors on data points then a procedure based on the semi-weighted mean is more generally applicable (Corbet 2007a, b).

For LAT light curves the number of photons in a time bin is typically extremely small. If a weight is chosen based on the number of counts in a bin, then bins with the same exposure could receive different weighting. The number of photons for the same underlying count rate will exhibit variations due to Poisson fluctuations and a weighting based on this would also have noise due to this shot noise. For LAT light curves we therefore use weighting factors based on the relative exposure of the time bins. We calculate the mean count rate of all bins and then calculate the number of counts expected in each bin based on its exposure. We adopt an effective error for each bin which is the square root of the number of *predicted* photons divided by the exposure.

The gain in sensitivity using weighting is illustrated in the Figure below where we show the power spectrum of the light curve of LS I +61° 303 (Abdo et al. 2009) calculated in several different ways. The bottom panel shows the power spectrum of a one day time resolution light curve without using weighting. In this case the exposure of the time bins is fairly uniform and the orbital period of the system is readily detected. In the other panels are shown power spectra of LS I +61 303 using 1,000 s time bins. It can be seen that without weighting the periodicity is not detectable. Even if weighting based on the number of photons in a time bin ("error weighting") is used negligible gain in signal at the orbital period is obtained. **For weighting based on the exposure ("exposure weighting") the signal strength is comparable to that obtained with one day binning, but provides higher time resolution.** We note that although the exposure weighted power spectrum of the count rate has some mathematical similarity with just taking the power spectrum of the number of counts in a time bin, that procedure produces large artifacts at Fermi's rocking period and its harmonics.

Power spectra of LS I +61° 303 obtained in five different ways. (a): power spectrum of a 1 day time resolution light curve without weighting. (b): power spectrum of a 1ks time resolution light curve without weighting. (c): power spectrum of a 1ks light curve with "error weighting". **(d): power spectrum of 1ks light curve with "exposure weighting".** (e): power spectrum of the raw number of counts in each time bin, not corrected or weighted by exposure. The dashed red line shows the frequency corresponding to the orbital period of LS I +61° 303 and the blue arrow in the top panel indicates Fermi's sky survey repeat frequency.

References

Abdo et al., 2009, ApJ, 701, L123
Corbet, R.H.D., Markwardt, C.B., & Tueller, J. 2007a, ApJ, 655, 458
Corbet, R.H.D. et al., 2007b, Progress of Theoretical Physics Supplement, 169, 200
Howell, S.B., 1989, PASP, 101, 616
Naylor, T., 1998, MNRAS, 296, 339
Scargle, J.D. 1989, ApJ, 343, 874