LAT Light Curve Analysis: Aperture Photometry and Likelihood-based Light Curves

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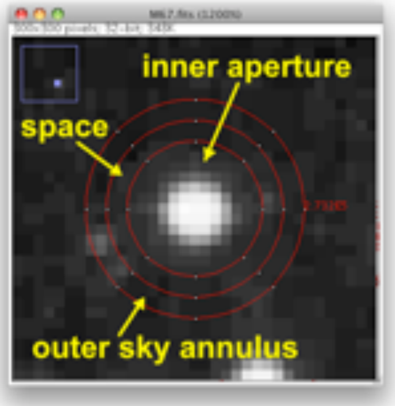
Presentation Outline

- Photometry
  - Two methods (aperture photometry & likelihood)
  - LAT specific considerations
- Recipe for LAT aperture photometry
  - Light curve of 3C 454.3
  - Error bars for low count rates
- Recipe for LAT likelihood photometry
  - Example likelihood script (like_lc.pl)
  - Light curve of binary LS I +61 303 - comparison of likelihood and aperture photometry.

LAT Photometry

- LAT light curves can be obtained in two basic ways:
  - Likelihood analysis
  - 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.

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.

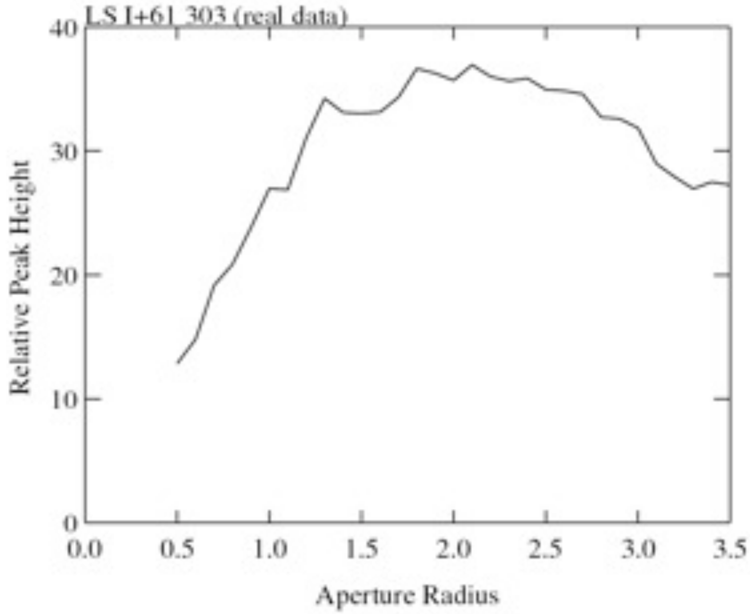
Things to be Aware of with Aperture Photometry

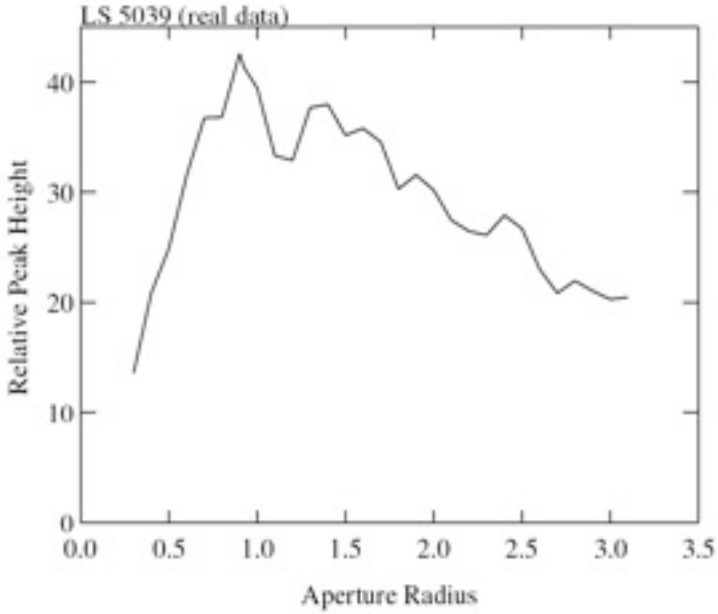
- The aperture contains photons from not just the source you're interested in.
  - It also contains photons from nearby sources and the background. The background is particularly strong in the Galactic plane.
- The aperture can be made smaller to reduce the background. But this also reduces the number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

But, for many sources 1 degree radius seems to work fairly well!

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.
  - (gtselect - combine together all photon files)
  - (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)
  - (gtbary - barycenter correction)
  - fv/fdump/other tools – convert counts to rates, calculate errors, convert MET -> MJD

Get Photon and Spacecraft File Start/Stop Times

Before doing this, if you have multiple photon files, you may want to combine them together using gtselect.

If you are not going to do barycenter correction, then you generally don't need to bother determining the start and stop times! (Use "0" as start and stop time.)

$ fkeypar "L090923112502E0D2F37E71_PH00.fits[1]" TSTART
(photon start time = 266976000.)

$ fkeypar "L090923112502E0D2F37E71_PH00.fits[1]" TSTOP
(photon stop time = 275369897.)

$ fkeypar "L090923112502E0D2F37E71_SC00.fits[1]" TSTART
(spacecraft start time = 266976000.)

$ fkeypar "L090923112502E0D2F37E71_SC00.fits[1]" TSTOP
(spacecraft stop time = 275369896.360675)

The values obtained with "fkeypar" are accessible using "pget"

Filter the Photon File

```
$ gtselect zmax=105 emin=100 emax=200000 infile="L090923112502E0D2F37E71_PH00.fits" outfile=temp2_1DAY_3C454.3 ra=343.490616 dec=16.148211 rad=1 tmin=266976000. 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) &&
(LAT_CONFIG==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.fits"
```

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.fits

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
- Output file is lc_1DAY_3C454.3.fits
- 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 (the slowest step)

$ 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 <u>must</u> be used.

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

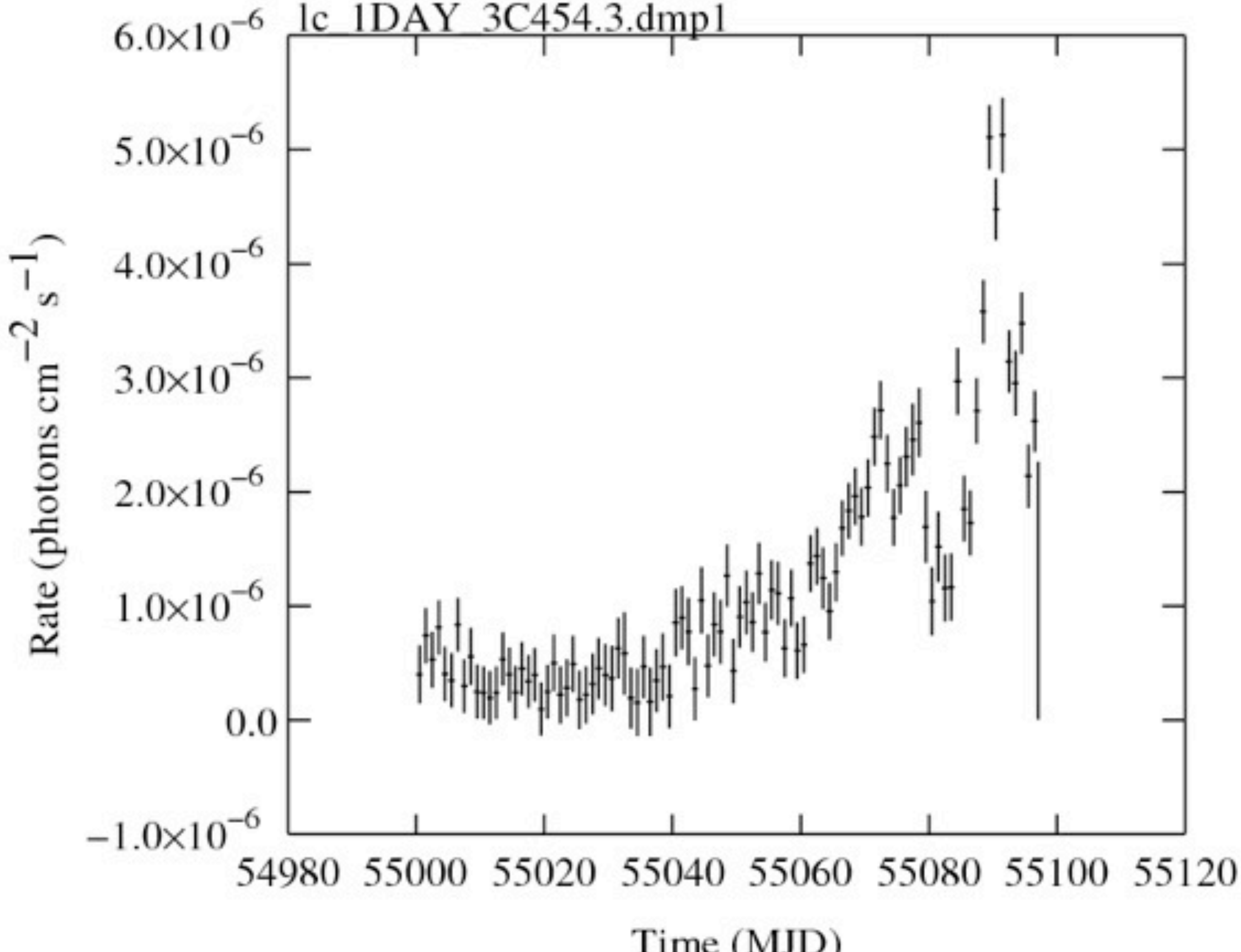
The Output File

- 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 useful to 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).

barycentering

- gtbary is advertised as doing barycenter corrections to photon files. However, it can also be used to barycenter light curves.
- gtbary must be done as the last step.
  - If you barycenter the input photon file, the exposure calculations will be wrong. (Don’t do this!)
- Spacecraft file must cover longer (not same) time range than photon file.
  - Use gtselect to trim down time range of the photon file by a tiny amount (e.g. 60 seconds)

Resulting Light Curve of 3C 454.3



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".

Alternative: 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.

Scripting

- It is fairly easy to construct a script to do aperture photometry.
- On request, I can provide an example perl script (“bex”) that does
  - aperture photometry
  - rate based errors
  - exposure based errors
  - barycenter corrections
- But, “bex” also requires a small Fortran program to work.

Part 2: Likelihood Photometry

- More details on likelihood analysis, and other useful presentations by LAT team members at a 2 week COSPAR workshop, (2010 Bangalore).
  - http://www.rri.res.in/fermi_cospar_2010/fermi-cospar-2010_files/lecture_files.html
- The presentations by B. Lott in particular are useful for an introduction to likelihood analysis of Fermi data.

Likelihood Analysis Steps

- Create a source model
- Select a spatial and temporal region:
  - gtselect, gtmktime
- Calculate exposure
  - gtlcube, gtexpmap
- Diffuse response
  - gtdiffrsp
- Perform the fit
  - gtlike
- Extract results (flux etc.) from gtlike output

Creating a Source Model

- This topic was covered in an earlier presentation.
- Depending on your objectives, the model files created with the user contributed script make1FGLxml.py can be very useful.
- For the generation of a light curve, the number of photons will typically be rather small.
  - The number of free parameters in the model cannot be too large. e.g. leave only flux and spectral index of source of interest free.
  - Time bins must be long enough to contain sufficient photons - restricts time resolution possible.

Region/Temporal Selection

- Use `gtselect` to specify spatial and temporal data selection.
- For photometry this has two purposes.
  - Selecting the appropriate spatial region.
  - Repeated selection of time intervals so as to create a light curve.
- Repeated time selections cannot be done inside `gtlike` itself. Need to “wrap” `gtlike` inside a script and repeatedly call `gtselect`.

like_lc.pl

- This perl script is in the user contributed area.
- It is intended as an example, and might not meet your scientific needs...
- "like_lc.pl -help" gives some information.
- You can either specify a model file, or else the script can generate one automatically using make1FGLxml.py
  - To use make1FGLxml, the environment variable $MY_FERMI_DIR must be set to a directory where both make1FGLxml.py and gll_psc_v02.fit (1FGL catalog) must be present.

Inputs to like_lc.pl

- A file containing a list of photon files ("plist.dat")
  - e.g. from the workshop download area
    - LSI_61_303_PH00.fits
- A file containing a list of source names and coordinates to analyze ("slist.dat").
  - If the model file is to be auto-generated the source name must match the 1FGL name, without spaces.
  - e.g. for the binary "LSI +61 303"
    - 1FGLJ0240.5+6113, 40.1317, 61.2281
- Other parameters are prompted for on the command line...

Running like_lc.pl

```
$ like_lc.pl
like_lc.pl: V1.02
Auto-generate model files from 1FGL catalog? [y/n; default = y]:
(Using default: "Y")
auto model
Give minimum TS value for including fluxes in output [default = 2]: 3
Give source parameter file [default = slist.dat]:
(Using default: "slist.dat")
Give photon file name list [default = plist.dat]:
(Using default: "plist.dat")
Give spacecraft (FT2) file name [default = LSI_61_303__SC00.fits]:
(Using default: "LSI_61_303__SC00.fits")
Give aperture radius (degrees) [default = 10]: 9
Give Emin (MeV) [default = 100]:
(Using default: "100")
Give Emax (MeV) [default = 200000]:
(Using default: "200000")
Give Zenith limit (degrees) [default = 105]:
(Using default: "105")
Give EVENT_CLASS minimum (use 0 for simulated data) [default = 3]:
(Using default: "3")
Give Bore limit (degrees) [default = 180]:
(Using default: "180")
Give bin size (days) [default = 5]: 3
Getting sources
line = 1FGLJ0240.5+6113 40.1317, 61.2281
```

Use < 10 degrees for workshop data

Summary of like_lc Steps

gtselect chatter=0 zmax=180 emin=100 emax=200000 infile="@plist.dat" outfile='tmp_12426eventfile0.fits' ra=40.1317 dec=61.2281 rad=9 evclsmin=3 evclsmax=10 tmin=0 tmax=0

python tmp_12426pyfile.py (This is make1FGLxml version 03_rc. [...])

fkeypar "tmp_12426eventfile0.fits" TSTART (photon start time = 240000000.)
fkeypar "tmp_12426eventfile0.fits" TSTOP (photon stop time = 260000000.)

Stuff in the box is in a loop!

gtselect chatter=0 zmax=180 emin=100 emax=200000 infile="tmp_12426eventfile0.fits" outfile='tmp_12426eventfile1.fits' ra=40.1317 dec=61.2281 rad=9 evclsmin=3 evclsmax=10 tmin=240000000. tmax=240259200

gtmktime chatter=0 scfile="LSI_61_303_SC00.fits" filter="(DATA_QUAL==1) && (angsep(RA_ZENITH,DEC_ZENITH,40.1317,61.2281)+9<105) && (angsep(40.1317,61.2281,RA_SCZ,DEC_SCZ)<180)" roicut=n evfile="tmp_12426eventfile1.fits" outfile="tmp_12426eventfile2.fits"

gtltcube chatter=0 evfile=tmp_12426eventfile2.fits scfile=LSI_61_303_SC00.fits outfile=tmp_12426expcube.fits dcostheta=0.025 binsz=1
Working on file LSI_61_303_SC00.fits

gtexpmap chatter=0 evfile=tmp_12426eventfile2.fits scfile=LSI_61_303_SC00.fits expcube=tmp_12426expcube.fits outfile=tmp_12426expmap.fits irfs=P6_V3_DIFFUSE srcrad=19 nlong=120 nlat=120 nenergies=20

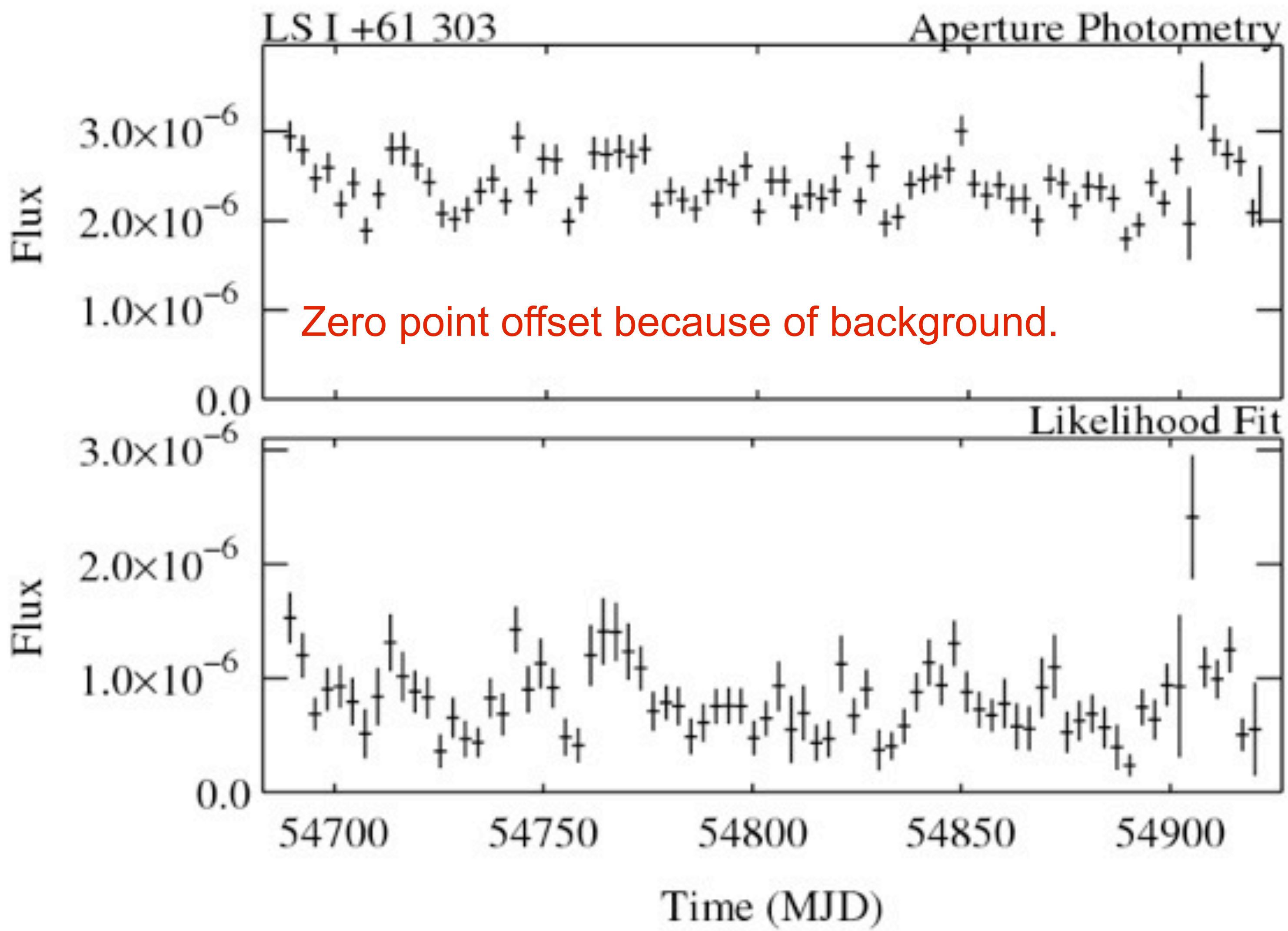
gtdiffrsp chatter=0 evfile='tmp_12426eventfile2.fits' scfile=LSI_61_303_SC00.fits srcmdl=edit_myLATxmlmodel.xml irfs=P6_V3_DIFFUSE

gtlike results=tmp_12426results.dat specfile=tmp_12426counts_spectra.fits chatter=0 irfs=P6_V3_DIFFUSE expcube=tmp_12426expcube.fits srcmdl=edit_myLATxmlmodel.xml statistic=UNBINNED optimizer=MINUIT evfile=tmp_12426eventfile2.fits scfile=LSI_61_303_SC00.fits expmap=tmp_12426expmap.fits cmap=none bexpmap=none

Output of like_lc.pl

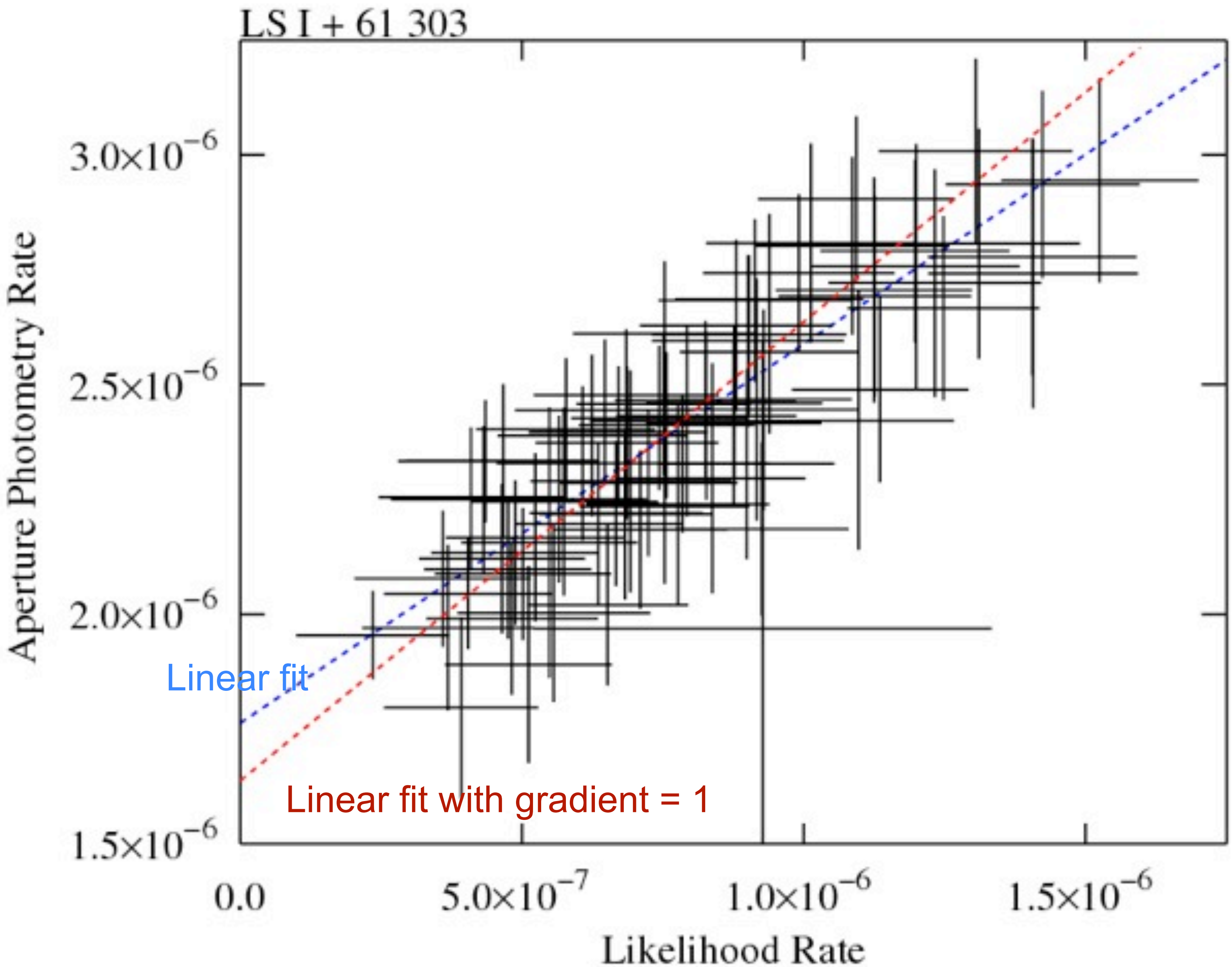
- While it's running, the script produces a lot of screen output.
- A number of temporary files are created in the directory where it is run, and then deleted.
- The output ASCII files have names of the form
  - XXX_like_lc.dat (XXX is the source name in)
- Columns are:
  - Time (MJD), flux (cts/cm2/s), flux error, bin half width (days), TS value, spectral index, index error
- Look out for bad points with low flux/small errors!
  - (Generally have low TS values.)

Comparison of Two Methods (i)

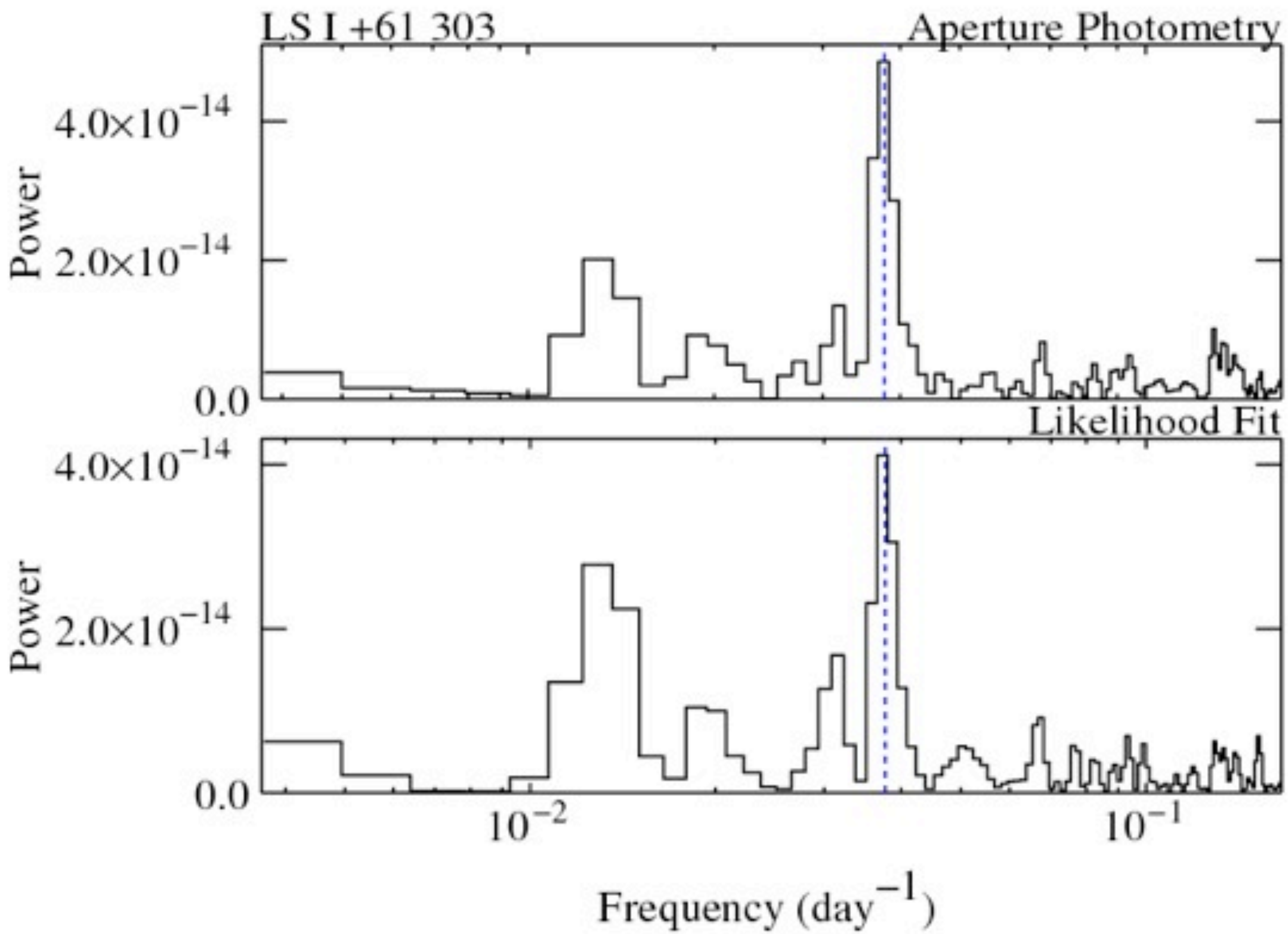


Binary system LS I +61 303 (1FGL J0240.5+6113) - varies on known 26.5 day period

Photomery Comparison (ii)



Photometry Comparison (iii)



Both light curves show known 26 day orbital period at similar significance.

Summary

- LAT light curves can be obtained using either aperture photometry or likelihood analysis.
- Aperture photometry advantages:
  - Fast (~30 minutes for 2 yr lc., likelihood ~50x slower)
  - Model independent
  - Short time bins can be used (including bins with no photons)
- Likelihood analysis advantages:
  - Gives background-subtracted flux
  - No aperture size choice to maximize S/N needed
  - Potentially higher S/N (all photons used)