Fermi Science Tools
Pulsar Timing Analysis

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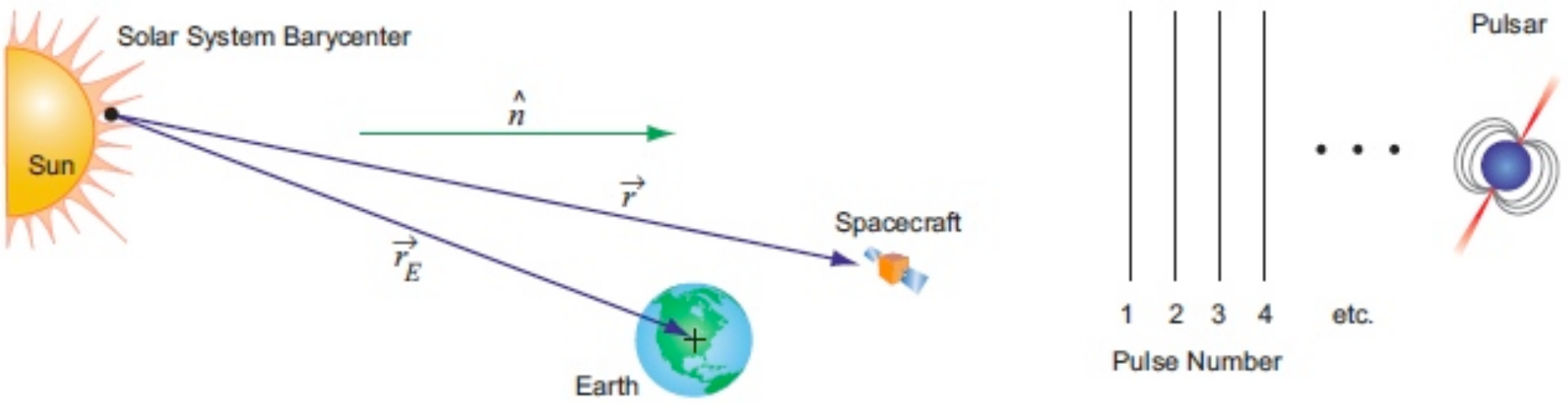
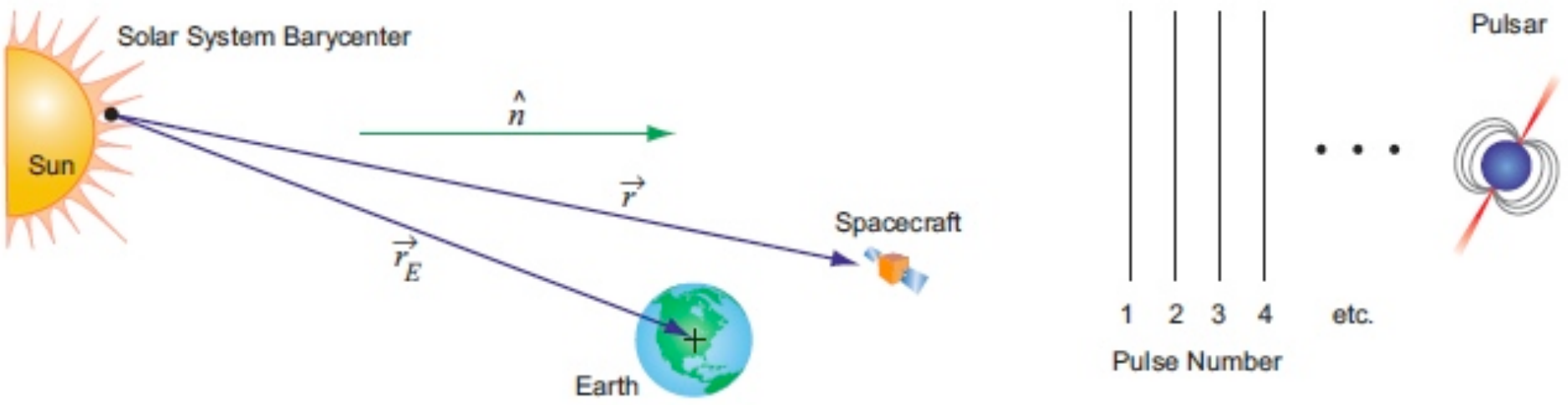
Pulsar Timing - Basic Situation



- As the neutron star rotates, the pulses we see can be thought of as plane waves, one per pulse.
- Gamma-ray data are sparse. Thousands of rotations may occur between detected gamma rays.
- The motions of the spacecraft and the Earth are significant compared to the time between pulses (msec to sec).

Pulsar Timing - Basic Situation



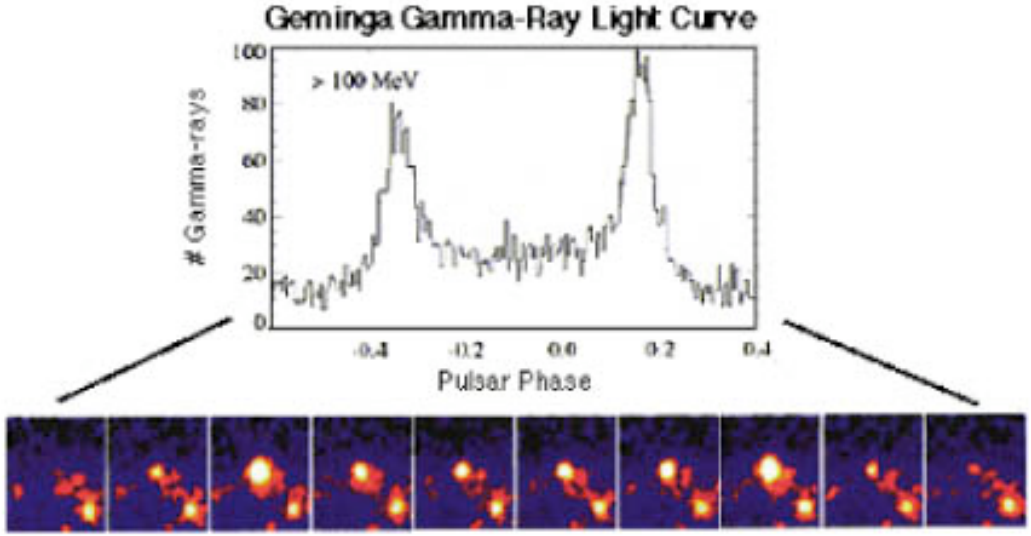
- Solution: do the timing analysis in an intertial reference system, not moving with respect to the pulsar.
- The solar system barycenter (SSBC) is a good approximation to an intertial system.
- Need to calculate when the gamma rays seen by the LAT would have arrived at the SSBC.

Pulsar Timing - Basic Situation

- What we are interested in is the phase ϕ of each gamma ray, the fraction of one rotation relative to a reference.

$$\phi(t) = \phi_0 + f(t - t_0) + \frac{1}{2}\dot{f}(t - t_0)^2 + \ldots,$$

- The phase is calculated using the pulsar rotation frequency f (or Period P = 1/f), its time derivative $\dot{f}$, and higher order terms.
- The timing parameters can be obtained from radio, X-ray, or gamma-ray data.



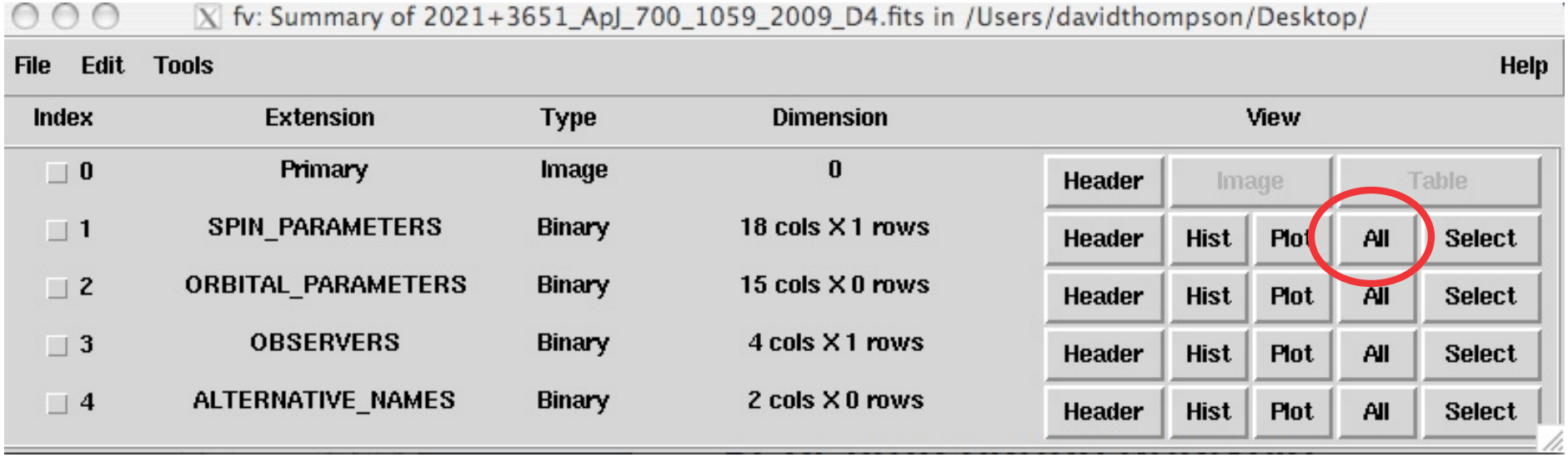
Typical Pulsar Analysis

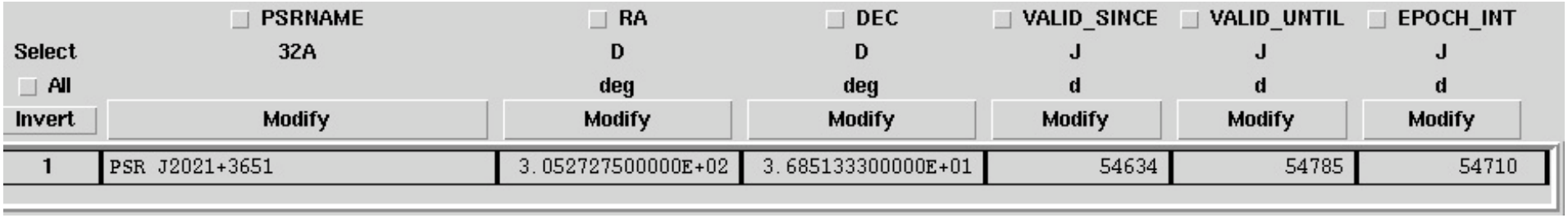
- *Download data and screen events*
  - ***Event file***
  - ***Spacecraft file***
  - ***Pulsar database file (Fermi_PulsarDB_v001.fits, or other)***
- *Analyze time series data*
  - *Search for pulsations*
  - *Determine or refine pulsar ephemeris*
  - *Confirm periodicity published in the literature*
- *Assign pulse phase or orbital phase to each photon*
  - *Folded light curve (pulse shape or pulse profile)*
  - *Phase-resolved spectrum*
  - *Phase-resolved image*

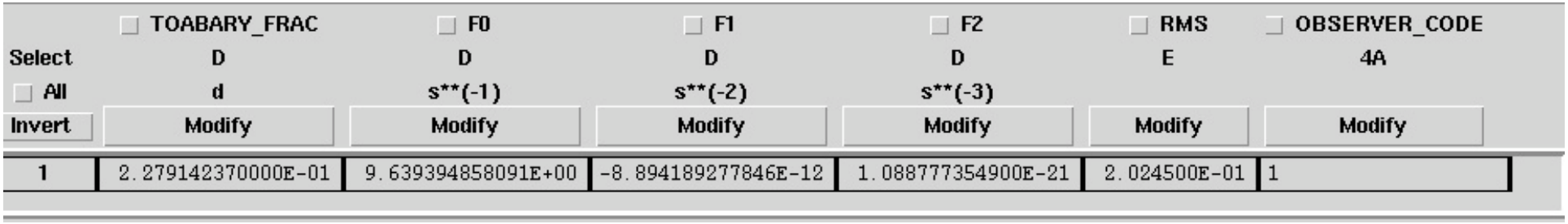
Tips for Data Screening

- *For time series analysis*
  - *For maximum sensitivity on pulse detection and frequency determination, screen data to maximize pulsed component and minimize constant ("background") component.*
    - *Tight spatial selection (typically size of a couple of PSFs)*
    - *Wider energy range*
    - *Broader choice of event types*
- *For analysis using pulse/orbital phase*
  - *Use standard event selection for spectral or image analysis.*
- *When using existing timing solution, watch for range of validity*
  - ***http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/***

Example - PSR J2021+3651 - D4 Timing





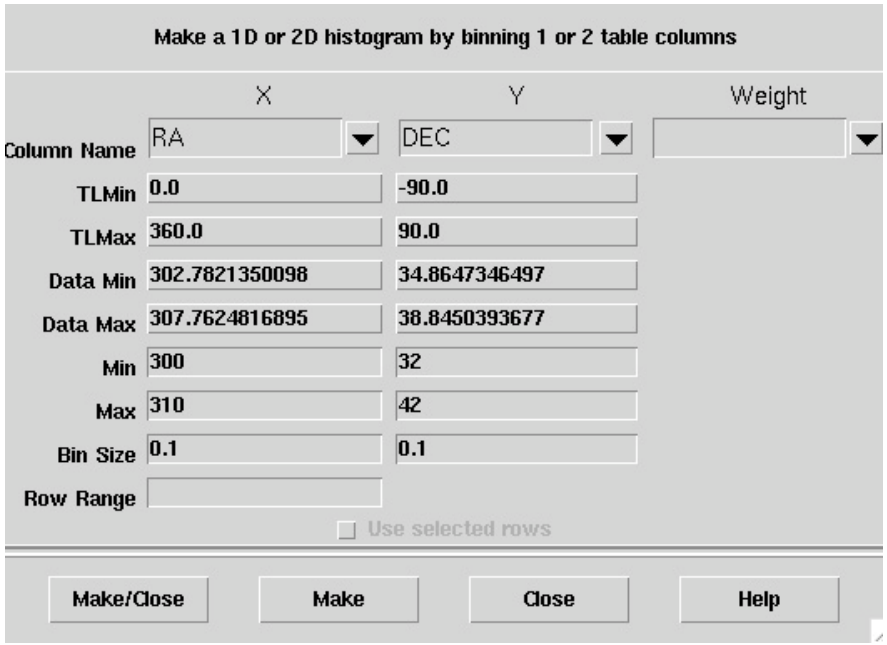


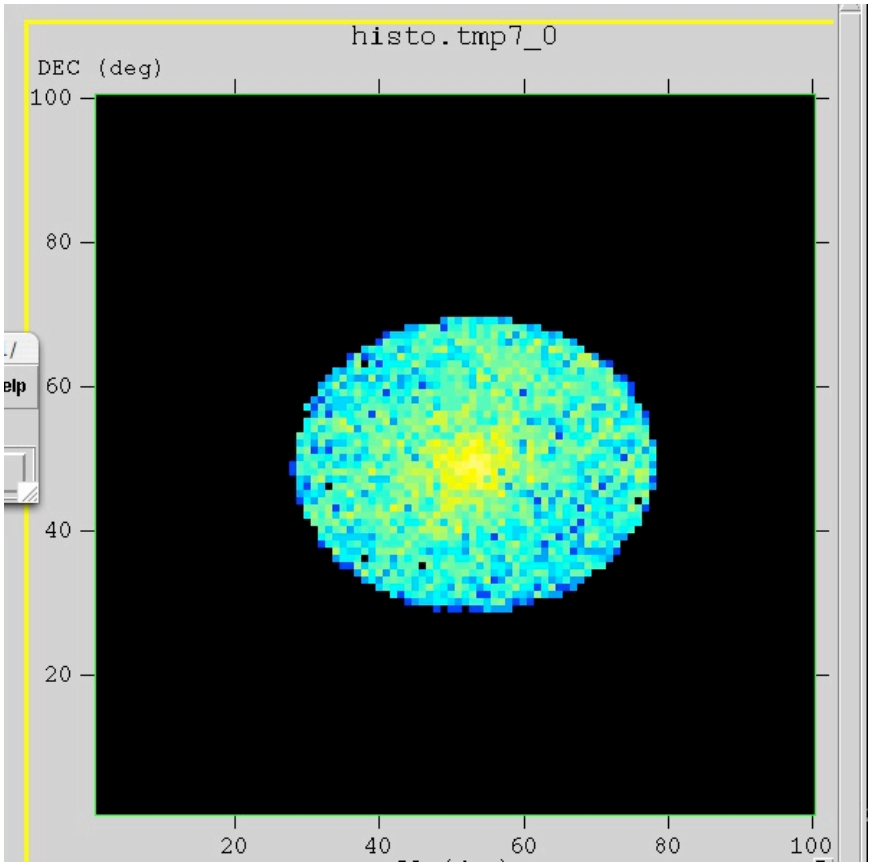
Example - PSR J2021+3651 - TEMPO2 Timing

```
PSRJ           J2021+3651
RAJ            20:21:05.46000036              82505.92249883854528036409
DECJ           36:51:04.8000000               1237588.837482578179219672l7
F0             9.6393948580913804             0.00000400000000000000
F1             -8.894189277846E-12
PEPOCH         54710                          1.00000000000000000000
POSEPOCH       54710                          1.00000000000000000000
DM             367.5                          0.10000000000000000000
START          54634.183
FINISH         54785.919
TZRMJD         54715.22401076969653
TZRFRQ         1949.805
TZRSITE        1
EPHVER         2
CLK            TT(TAI)
UNITS          TDB
TIMEEPH        FB90
DILATEFREQ     N
PLANET_SHAPIRO N
T2CMETHOD      TEMPO
CORRECT_TROPOSPHERE  N
EPHEM          DE405
NITS           1
NTOA           21
TRES           202.45
```

Example - PSR J2021+3651 - Data

Data Selection - Choose time range for valid solution, 2 degree circle about the source position.





Remember to use gtselect and gtmktime as for other data.

Pulse / Orbital Phase Assignment

- *Pulse Phase*
  - *Computes a pulse phase for each photon.*
  - *Appends the phase value to the event entry for later use.*
    - *Science Tools:* ***gtpphase*** ***Uses D4 timing solution***

davidthompson% gtpphase
This is gtpphase version ScienceTools-v9r15p2-fssc-20090808
Event data file name[P2010_events_diffuse_gti.fits] P2010_events_diffuse_gti.fits
Spacecraft data file name[L091130144149E0D2F37E47_SC00.fits] L091130144149E0D2F37E47_SC00.fits
Pulsar ephemerides database file name[2021+3651_ApJ_700_1059_2009_D4.fits] 2021+3651_ApJ_700_1059_2009_D4.fits
Pulsar name[PSR J2021+3651] J2021+3651
How will spin ephemeris be specified? (DB|FREQ|PER) [DB] DB

    - *Other tools: TEMPO2 with Fermi plugin or manual entry of timing parameters.*

- *Orbital Phase*
  - *Computes an orbital phase for each photon.*
  - *Appends the phase value to the event entry for later use.*
    - *Science Tools: gtophase*

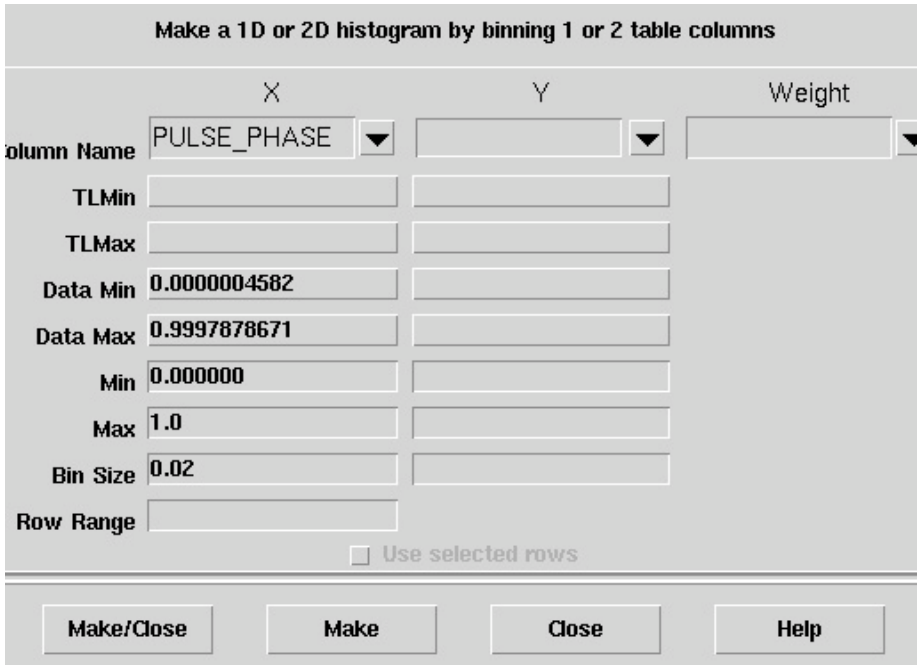
Pulse Phase Assignment

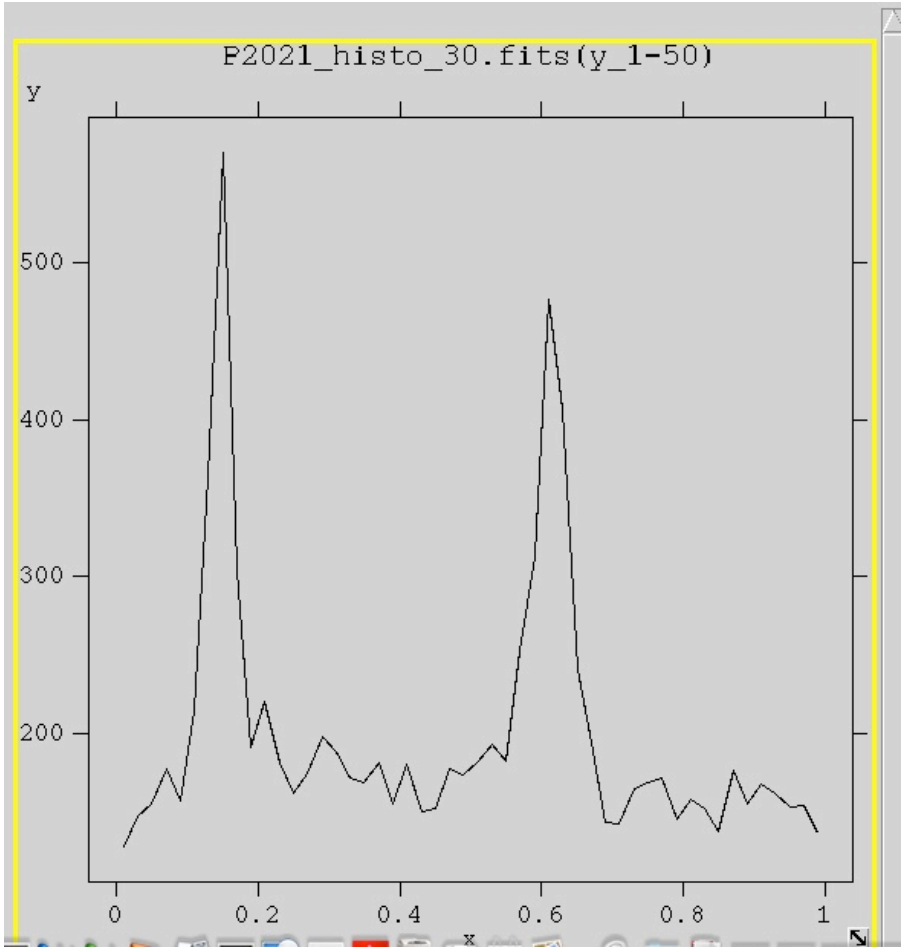
- *Output checks - histograms*
  - ***Look in the Phase column of the file P2010_events_diffuse_gti.fits***
  - ***Use histogram function in FV to construct a plot***
  - ***Use fhisto to generate a histogram, then view it with FV or use fplot***

davidthompson% fhisto lowval=0.0 highval=1.0
Name of FITS file and [ext#][P2010_events_diffuse_gti.fits] P2021_events_diffuse_gti.fits
Name of output FITS file[P2021_histo_.01.fits] P2021_histo_30.fits
Name of column to generate histogram[PULSE_PHASE]
Size of bins[.01] .02
input file (no binspec): file://P2021_events_diffuse_gti.fits[1]
input file: file://P2021_events_diffuse_gti.fits[1][bin PULSE_PHASE=0:1:0.02]
The histogram extension: 1dhisto

Pulse Phase Assignment

- *Output checks - using FV histogram*





Pulse Phase Assignment - TEMPO2

- *TEMPO2 is a timing program developed by radio astronomers. Information at* http://www.atnf.csiro.au/research/pulsar/tempo2/index.php?n=Main.HomePage
- *There is a Fermi plugin for TEMPO2 that allows it to be used to analyze LAT data, included with the distribution.*
- *The .par timing solutions for TEMPO2 have more flexibility and can cover broader time ranges than the D4 timing solutions.*
- *As longer intervals of observations are accumulated, more and more of the LAT pulsar results are using TEMPO2 analysis.*
- *Unfortunately, the installation of TEMPO2 with the Fermi plugin is not fully documented yet. Coming soon.*

Pulse Phase Assignment - TEMPO2

- *Running TEMPO2*

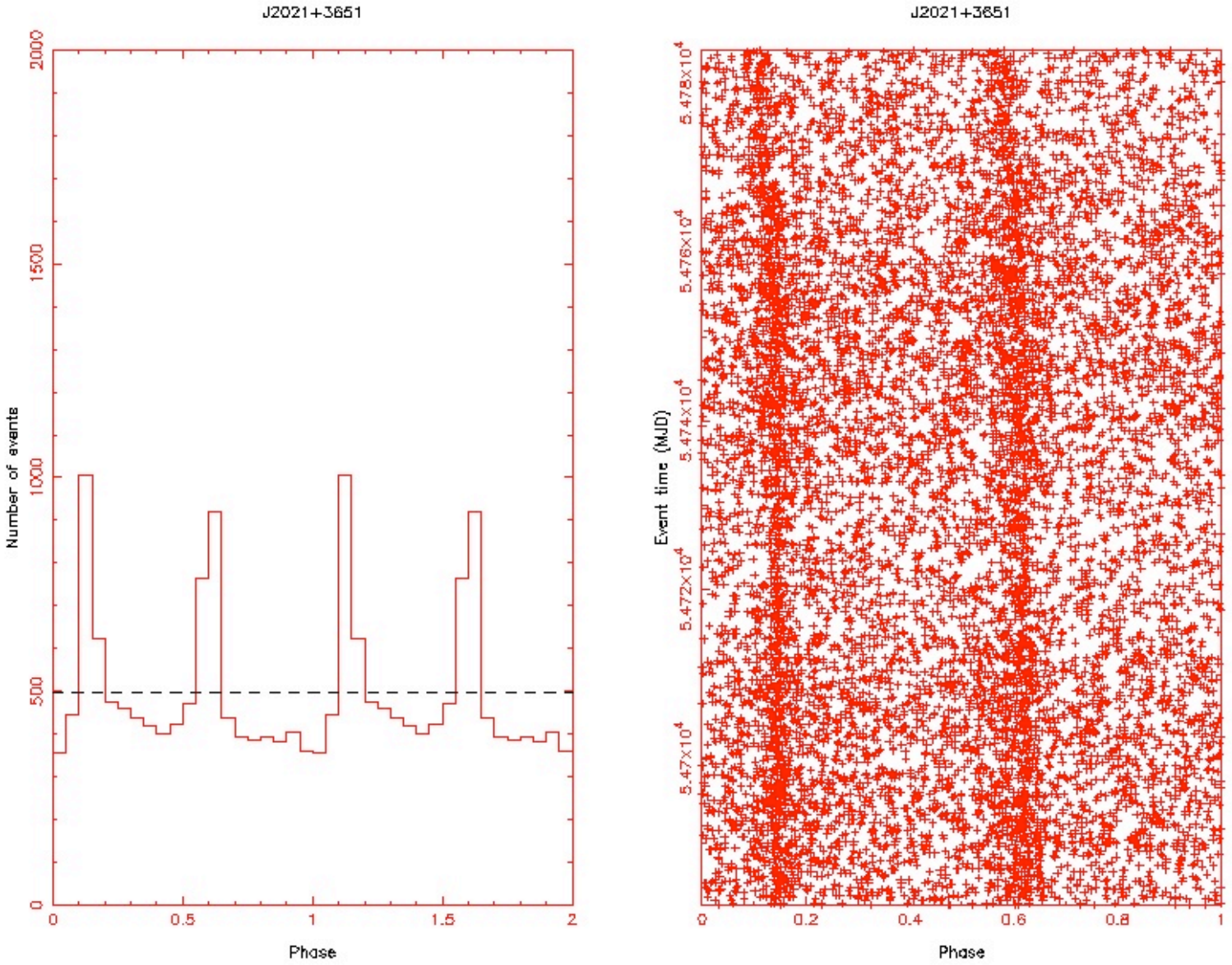
tempo2 -gr fermi -ft1 P2021_events_diffuse.fits -ft2 L091130144149E0D2F37E47_SC00.fits -f 2021+3651_mod.par -phase

This program comes with ABSOLUTELY NO WARRANTY.
This is free software, and you are welcome to redistribute it
under conditions of GPL license.

Looking for
/Users/davidthompson/tempo2_build/tempo2/T2runtime/plugins/fermi_darwin_plug.so

----
Output interface: fermi
Author: Lucas Guillemot
Updated: 7 September 2009
Version: 4.2

Pulse Phase Assignment - TEMPO2



Testing Pulsation Significance

- *Periodicity tests*
  - *Chi-squared test (Leahy et al. 1983, ApJ 266, 160; Vaughan et al. 1994, ApJ 435, 362)*
  - *Z_n^2 test (Buccheri et al. 1983, A&A 128, 245)*
  - *Rayleigh test (equivalent to Z_n^2 test for n = 1)*
  - *H test (De Jager et al. 1989, A&A 221, 180)*
    - *Science Tools: gtpsearch, gtptest*
    - *Other tools: efsearch (XRONOS)*

davidthompson% gtptest
This is gtptest version ScienceTools-v9r15p2-fssc-20090808
Event data file name[P2021_events_diffuse.fits]
Output FITS file name (NONE for no FITS output)[gtptest.P2021.fits] NONE
Number of phase bins for Chi2 test[10]
Number of harmonics for Z2n test[10]
Maximum number of harmonics for H test[10]

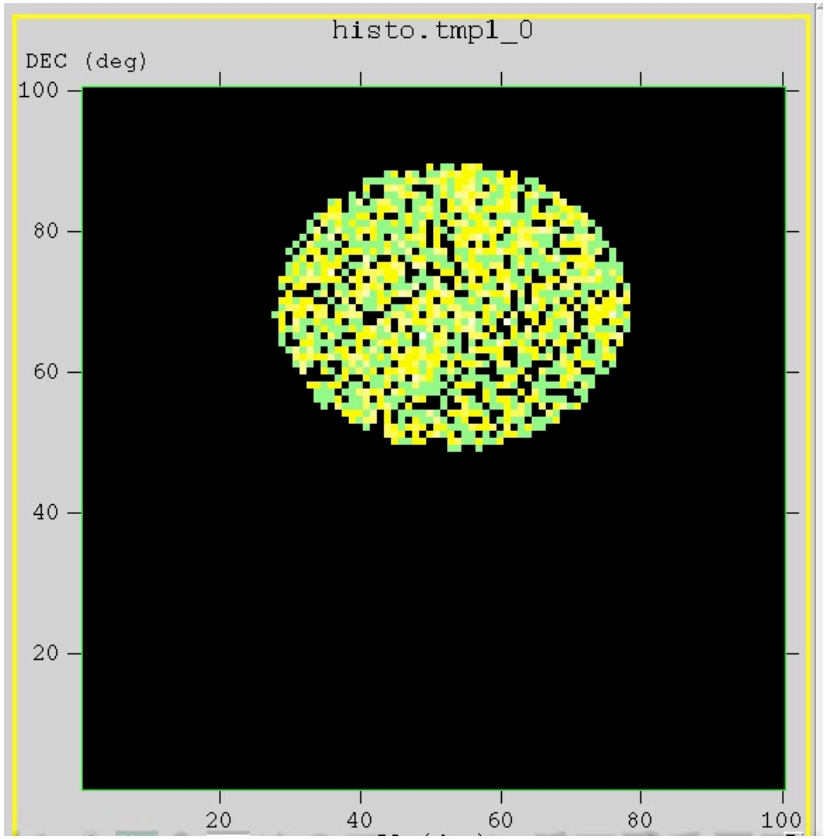
Testing Pulsation Significance - Output

Type of test: Chi-squared Test, 10 phase bins
Probability distribution: Chi-squared, 9 degrees of freedom
Test Statistic: 824.028880866426
Chance Probability Range: (0, 2.037570469030 54e-99)
Type of test: Rayleigh Test
Probability distribution: Chi-squared, 2 degrees of freedom
Test Statistic: 46.2571601550502
Chance Probability Range: (9.02305042259081e-11, 9.02395272685048e-11)
Type of test: Z2n Test, 10 harmonics
Probability distribution: Chi-squared, 20 degrees of freedom
Test Statistic: 1511.03487971911
Chance Probability Range: (0, 2.078533864426 7e-99)
Type of test: H Test, 10 maximum harmonics
Probability distribution: H Test-specific
Test Statistic: 1475.03487971911
Chance Probability Range: (0, 4e-08)

Also produces a light curve plot

Looking for Offpulse Emission

Use gtselect with
phasemin=0.7
phasemax=1.0

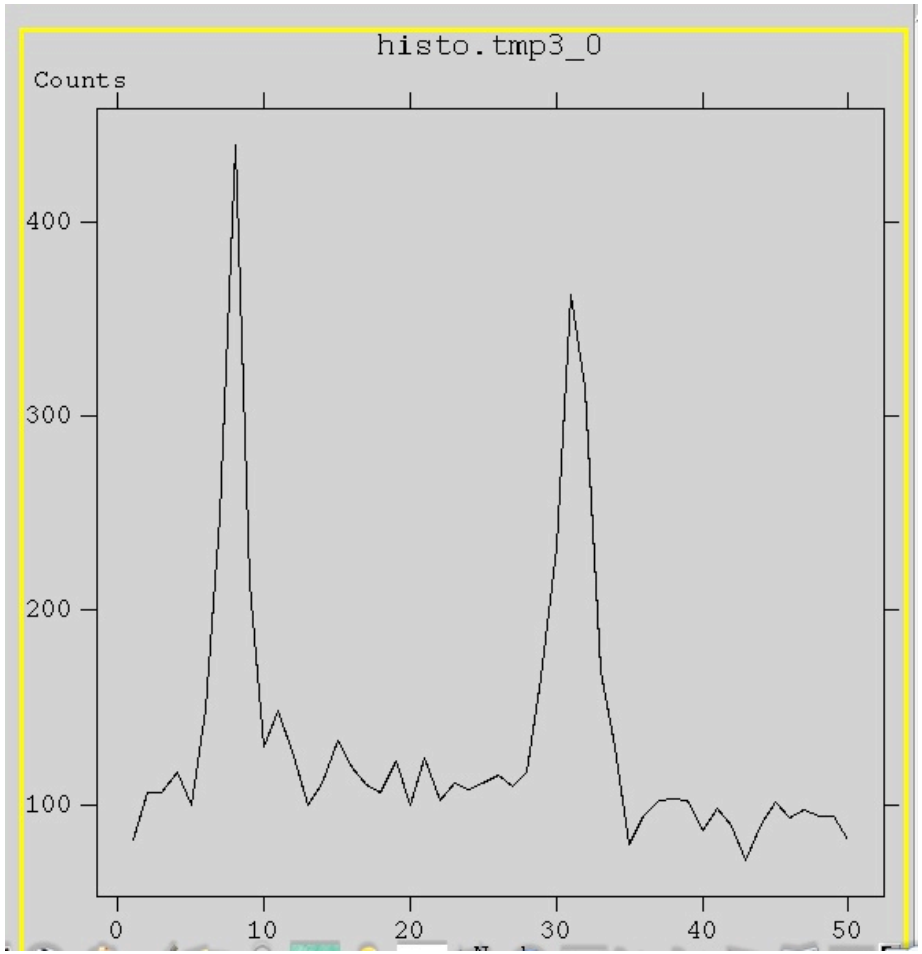


Offpulse map can be used to search for SNR or PWN emission, or to look for fainter sources hidden by the pulsar.

Energy-Dependent Event Selection

```
fselect "P2021_events_diffuse_gti.fits[EVENTS]"
P2021_energydep.fits  "angsep(305.273, 36.851, RA, DEC)<=
min(2.5, max(0.35,(0.8*(ENERGY*1.0e-3)^(-0.80))))"
```

Note that fselect does not handle the exposure information, so it should only be used for pulse shape analysis (light curves).



Utility Tools

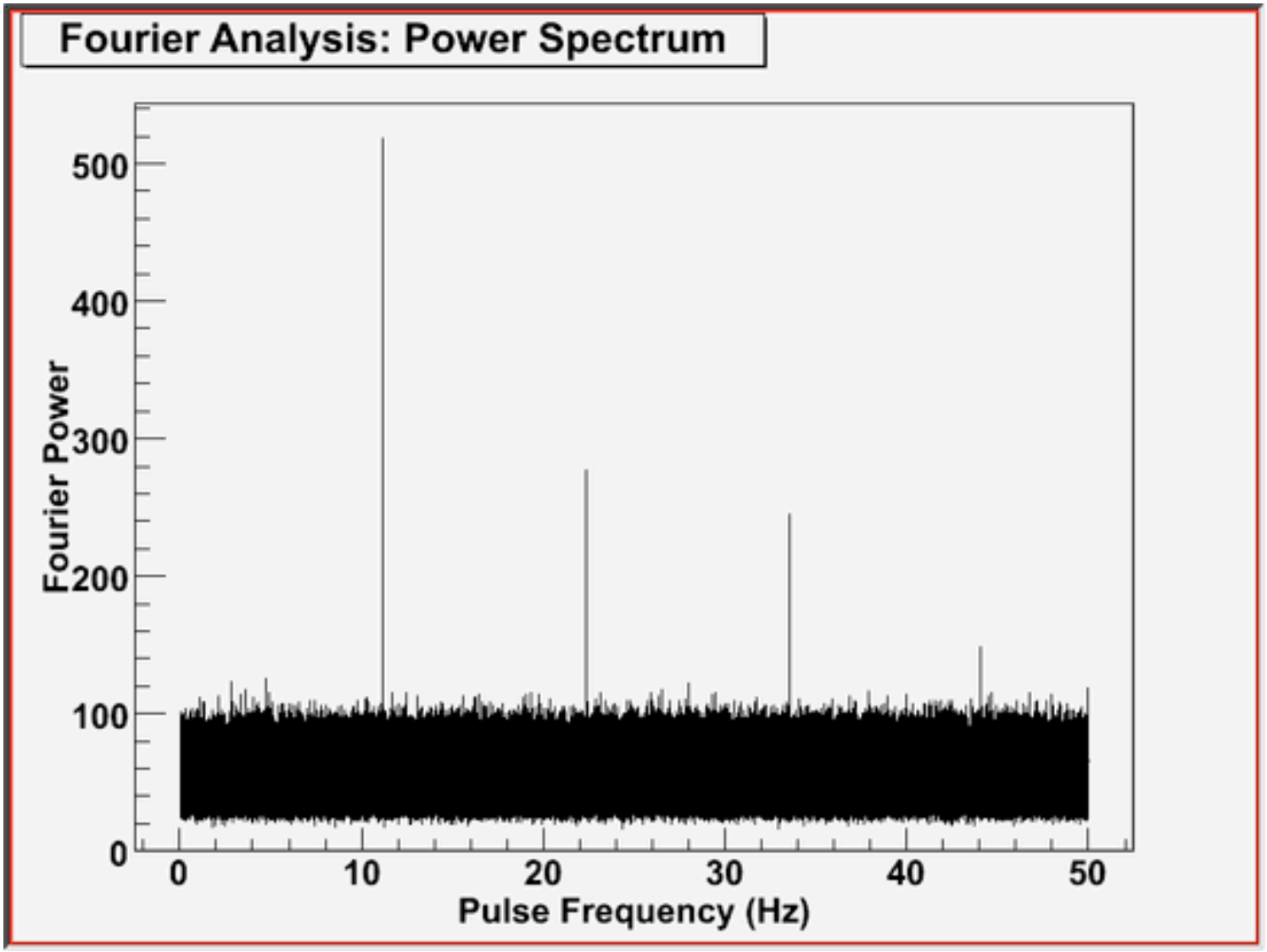
- *Ephemeris computer **gtephem***
  - *Reads pulsar ephemerides database and computes pulsar's spin ephemeris (such as pulse frequency) at a given moment in time.*
  - *Also serves as a sanity checker for first-time users of our pulsar ephemerides database.*
- *Pulsar ephemerides manipulation tool **gtpulsardb***
  - *Sub-selects pulsar ephemerides from a master database.*
  - *Also used to create, modify, merge pulsar ephemerides database.*
- *Photon arrival time correction **gtbary***
  - *Computes barycentric or geocentric time for each event and modifies event time in event file, for use with non-Fermi analysis tools such as XRONOS tools.*
  - ***CAUTION:** event files processed by gtbary must not be used in any analysis with Science Tools.*

Appendix - Analyzing Vela data

```
prompt> gtpspec
This is gtpspec version ScienceTools-v9r15p2-fssc-20090701
Event data file name[] Vela_100_300000_evt02.fits
Spacecraft data file name[] L090923110451E0D2F37E17_SC00.fits
Name of input pulsar ephemerides database file (for binary demodulation only)[]  Fermi_PulsarDB_v001.fits
Pulsar name (for binary demodulation only)[ANY] PSR J0835-4510
Output FITS file name (NONE for no FITS output)[] gtpspec_out.fits
Width of time bins, in seconds (0.:) [1.e-2] 0.01
Number of time bins to be transformed at once[1000000] 10000000
How will the time origin of the periodicity test be specified? (START|STOP|MIDDLE|USER) [MIDDLE] MIDDLE
Right Ascension to be used for barycenter corrections (degrees)[0.] 128.836048
Declination to be used for barycenter corrections (degrees)[0.] -45.176425
How will spin ephemeris be specified? (FREQ|PER) [FREQ] FREQ
Ratio of frequency first time derivative to frequency at the time origin (Hz)[0.] 0.0
Ratio of frequency second time derivative to frequency at the time origin (Hz/s)[0.] 0.0
Search Type: Fourier Analysis
Fourier Resolution: 1e-05 Hz
Sampling Frequency: 1e-05 Hz
Data Binning: 27 segments with 10000000 time bins in each segment
Probability Distribution: Chi Squared with 54 degrees of freedom
Search Range (Hz): [0.01, 50]
Number of Trial Frequencies: 4999000
Number of Independent Trials: 4999000
Maximum Statistic: 518.813411319925 at 11.19001 Hz
Chance Probability Range: (1.75188080614015e-70, 1.75205599227056e-70)
Warning in <TClass::TClass>: no dictionary for class st_graph::IFrame is available
prompt>
```

Gtpspec is a period search routine, only useful for bright sources.

Analyzing Vela data (cont.)

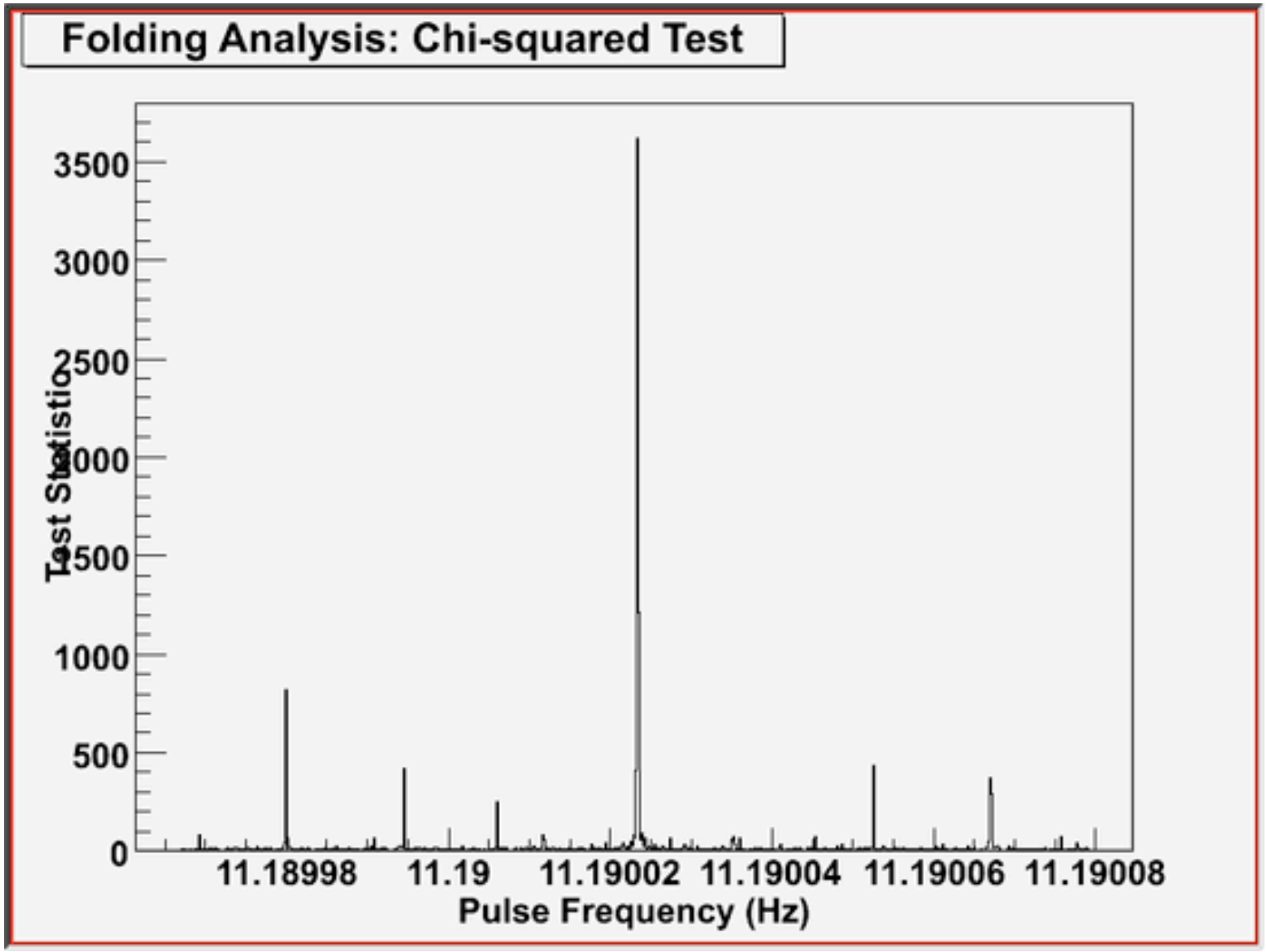


Analyzing Vela data (cont.)

```
prompt> gtpsearch
This is gtpsearch version ScienceTools-v9r15p2-fssc-20090701
Event data file name[] Vela_100_300000_evt02.fits
Spacecraft data file name[] L090923110451E0D2F37E17_SC00.fits
Pulsar ephemerides database file name[] Fermi_PulsarDB_v001.fits
Pulsar name[ANY] PSR J0835-4510
Output FITS file name (NONE for no FITS output)[] gtpsearch_out.fits
Type of statistical test to perform (CHI2 - Chi squared, RAYLEIGH - Rayleigh test, Z2N - Z2n test, H - H test) (CHI2|RAYLEIGH|Z2N|H) [CHI2] Chi2
Number of phase bins for Chi2 test[10] 10
Size of steps for trials, in units of the Fourier resolution (0.:) [0.5] 0.5
Number of trials[100] 600
How will the time origin of the periodicity test be specified? (START|STOP|MIDDLE|USER) [MIDDLE] USER
Time origin of the periodicity test[0.] 55028.5
Time format for the user-supplied time origin (FILE|MJD|ISO|FERMI|GLAST) [FILE] MJD
Time system for the user-supplied time origin (FILE|TAI|TDB|TT|UTC) [FILE] TDB
How will spin ephemeris be specified? (DB|FREQ|PER) [DB] FREQ
Epoch for the spin ephemeris[0.] 54663.0
Time format for spin ephemeris epoch (FILE|MJD|ISO|FERMI|GLAST) [FILE] MJD
Time system for spin ephemeris epoch (FILE|TAI|TDB|TT|UTC) [FILE] TDB
Right Ascension to be used for barycenter corrections (degrees)[0.] 128.836048
Declination to be used for barycenter corrections (degrees)[0.] -45.176425
Pulse frequency at the epoch of the spin ephemeris (Hz) (0.:) [1.] 11.19051540397055
First time derivative of the pulse frequency at the epoch of the spin ephemeris (Hz/s)[0.] -1.559072535133380e-11
Second time derivative of the pulse frequency at the epoch of the spin ephemeris (Hz/s/s)[0.] 0.0
Search Type: Folding Analysis
Fourier Resolution: 3.73754e-07 Hz
Sampling Frequency: 1.86877e-07 Hz
Type of test: Chi-squared Test, 10 phase bins
Probability distribution: Chi-squared, 9 degrees of freedom
Search Range (Hz): [11.1899669982264, 11.1900789375696]
Number of Trial Frequencies: 600
Number of Independent Trials: 300
Maximum Statistic: 3617.22319536 at 11.1900234350906 Hz
Chance Probability Range: (0, 6.11271140709163e-97)
Warning in <TClass::TClass>: no dictionary for class st_graph::IFrame is available
prompt>
```

Gtpsearch can be used to find a period once a range is known.

Analyzing Vela data (cont.)



Analyzing Vela data (cont.)

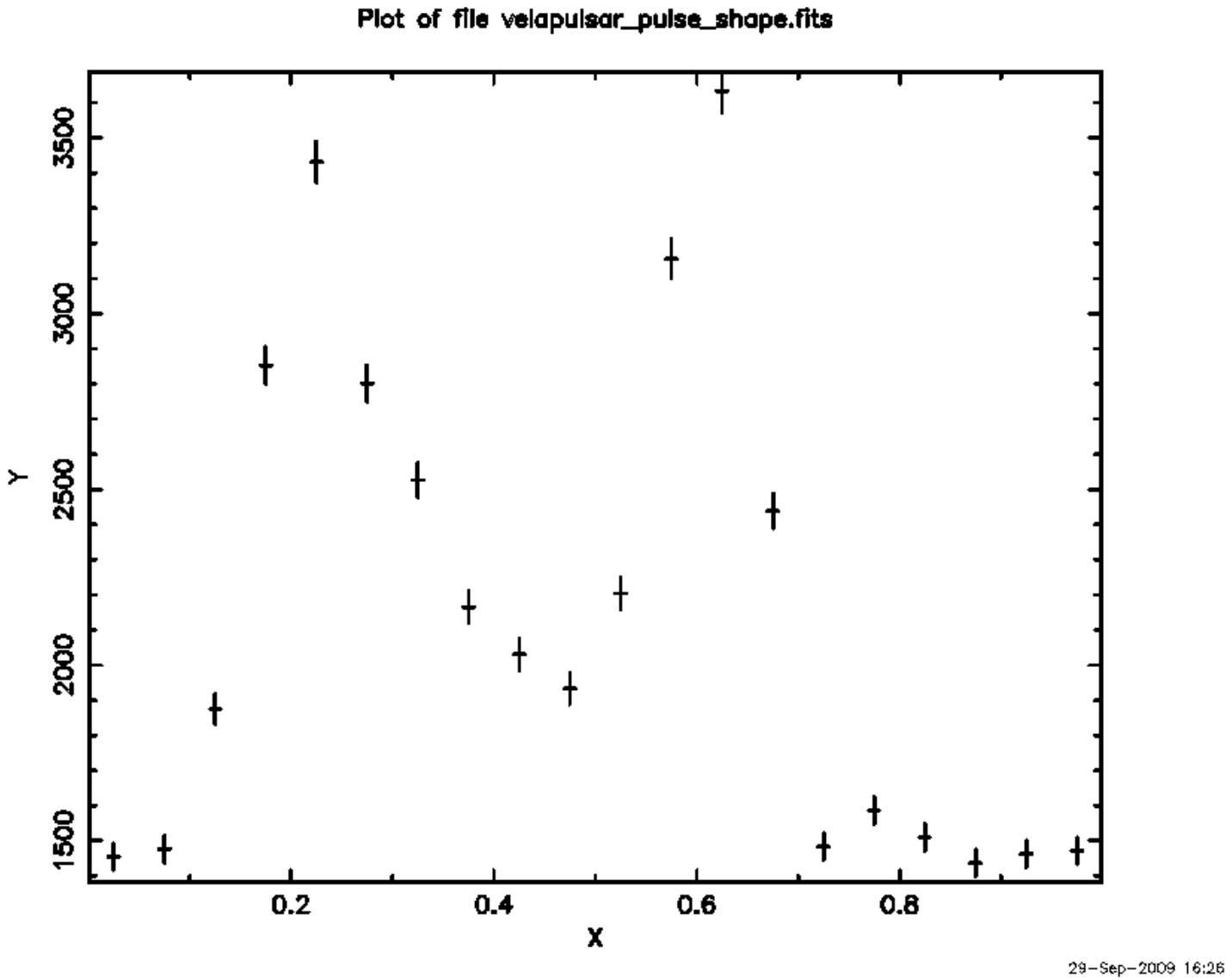
```
prompt> gtpphase
This is gtpphase version ScienceTools-v9r15p2-fssc-20090701
Event data file name[] Vela_100_300000_evt02.fits
Spacecraft data file name[] L090923110451E0D2F37E17_SC00.fits
Pulsar ephemerides database file name[] Fermi_PulsarDB_v001.fits
Pulsar name[ANY] PSR J0835-4510
How will spin ephemeris be specified? (DB|FREQ|PER) [DB] FREQ
Epoch for the spin ephemeris[0.] 55028.5
Time format for spin ephemeris epoch (FILE|MJD|ISO|FERMI|GLAST) [FILE] MJD
Time system for spin ephemeris epoch (FILE|TAI|TDB|TT|UTC) [FILE] TDB
Right Ascension to be used for barycenter corrections (degrees)[0.] 128.836048
Declination to be used for barycenter corrections (degrees)[0.] -45.176425
Base value of phase at this epoch[0.] 0.5
Pulse frequency at the epoch of the spin ephemeris (Hz) (0.:) [1.] 11.1900234350 906
First time derivative of the pulse frequency at the epoch of the spin ephemeris (Hz/s)[0.] -1.559072535133380e-11
Second time derivative of the pulse frequency at the epoch of the spin ephemeris (Hz/s/s)[0.] 0.0
prompt>
```

Analyzing Vela data (cont.)

```
prompt> fhisto lowval=0.0 highval=1.0
Name of FITS file and [ext#][] Vela_100_300000_evt02.fits
Name of output FITS file[] velapulsar_pulse_shape.fits
Name of column to generate histogram[] PULSE_PHASE
Size of bins[INDEF] 0.05
input file (no binspec): file://Vela_100_300000_evt02.fits[1]
input file: file://Vela_100_300000_evt02.fits[1][bin  PULSE_PHASE=0:1:0.05]
The histogram extension: 1dhisto
prompt>
```

```
prompt> fplot
Name of FITS file and [ext#][] velapulsar_pulse_shape.fits
Name of X Axis Parameter[error][] X
Name of Y Axis Parameter[error] up to 8 allowed[] Y[Error]
Lists of rows[-] -
Device: /XWindow, /XTerm, /TK, /PS, etc[/XW] /xserv
Any legal PLT command[] marker on
PLT> exit
prompt>
```

Analyzing Vela data (cont.)



Analyzing Vela data (cont.)

```
prompt> gtptest
This is gtptest version ScienceTools-v9r15p2-fssc-20090701
Event data file name[] Vela_100_300000_evt02.fits
Output FITS file name (NONE for no FITS output)[] gtptest_out.fits
Number of phase bins for Chi2 test[10] 10
Number of harmonics for Z2n test[10] 10
Maximum number of harmonics for H test[10] 10
Type of test: Chi-squared Test, 10 phase bins
Probability distribution: Chi-squared, 9 degrees of freedom
Test Statistic: 3617.22319536
Chance Probability Range: (0, 2.03757046903054e-99)
Type of test: Rayleigh Test
Probability distribution: Chi-squared, 2 degrees of freedom
Test Statistic: 1700.6017260263
Chance Probability Range: (0, 2.00883927982452e-99)
Type of test: Z2n Test, 10 harmonics
Probability distribution: Chi-squared, 20 degrees of freedom
Test Statistic: 4797.77337691268
Chance Probability Range: (0, 2.07853386442652e-99)
Type of test: H Test, 10 maximum harmonics
Probability distribution: H Test-specific
Test Statistic: 4762.16995611264
Chance Probability Range: (0, 4e-08)
Warning in <TClass::TClass>: no dictionary for class st_graph::IFrame is available
prompt>
```

Analyzing Vela data (cont.)