



Publication Year	2017
Acceptance in OA	2020-08-26T08:41:42Z
Title	pyLCSIM: X-ray lightcurves simulator
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Handle	http://hdl.handle.net/20.500.12386/26826
Journal	Astrophysics Source Code Library

pyLCSIM Documentation

Release 0.4.0

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Mar 20, 2017

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DOCUMENTATION FOR PYLCSIM

1.1 Introduction

pyLCSIM is a python package to simulate X-ray lightcurves from coherent signals and power spectrum models.

Coherent signals can be specified as a sum of one or more sinusoids, each with its frequency, pulsed fraction and phase shift; or as a series of harmonics of a fundamental frequency (each with its pulsed fraction and phase shift).

Power spectra can be simulated from a model of the power spectrum density (PSD), using as a template one or more of the built-in library functions. The user can also define his/her custom models. Models are additive.

A PDF version of these notes is available [here](#).

Warning: the current release (0.x.y) is HIGHLY EXPERIMENTAL! Use at your own risk...

1.2 Prerequisites

pyLCSIM requires [Numpy](#) (at least v1.8) and [Astropy](#) (at least v0.3).

[Matplotlib](#) is highly recommended if you want to plot your simulations.

1.3 Installation

The most straightforward way to install pyLCSIM is to use the [Python Package Index](#) and its pip utility (may require administrator privileges):

```
$ pip install pyLCSIM
```

To upgrade from a previous version:

```
$ pip install pyLCSIM --upgrade
```

The package source can be also downloaded [here](#).

The installation in this case follows the usual steps:

```
$ tar xzvf pyLCSIM-0.x.y.tar.gz
$ cd pyLCSIM-0.x.y
$ python setup.py install
```

The last step may require administrator privileges.

1.4 Mailing list

A dedicated mailing list is available, to host announcements of new releases, to report issues and to get support. If interested, subscribe [here](#).

1.5 License

The package is distributed under the [MIT license](#).

1.6 Example 1

Let's begin with a PSD model simulation.

We import the usual packages:

```
import matplotlib.pyplot as plt
import numpy as np
import pyLCSIM
```

We assume that our source has a rate of 30000 counts/s. Moreover, we have a 5000 counts/s background rate, and we have made a 50 s exposure. Our observation has a time resolution of 10 ms. We want to simulate a QPO at a frequency of 10 Hz, superimposed to a continuum modelled as a smoothly-varying broken power law (spectral indices 1 and 2, with a steepness change at 1 Hz). The required fractional RMS variation of the signal is 1%:

```
rate_src    = 30000.0
rate_bkg    = 5000.0
t_exp       = 50.0
dt          = 0.01
frms        = 0.1
```

The total bins of the lightcurve are therefore:

```
nbins = t_exp/dt
```

The simulation follows as:

```
# Instantiate a simulation object
sim = pyLCSIM.Simulation()

# Add two PSD models: a smooth broken power law and a Lorentzian representing a QPO.
# See the documentation for details.
sim.addModel('smoothbknp', [1., 1, 2, 1])
sim.addModel('lorentzian', [10., 1., 10, 2])

# Run the simulation
sim.run(dt, nbins, rate_src, rms=frms)

# Add Poisson noise to the light curve
sim.poissonRandomize(dt, rate_bkg)
```

```
# Get lightcurve and power spectrum as 1-D arrays
time, rate = sim.getLightCurve()
f, psd = sim.getPowerSpectrum()
```

Done! We can save the results as FITS files:

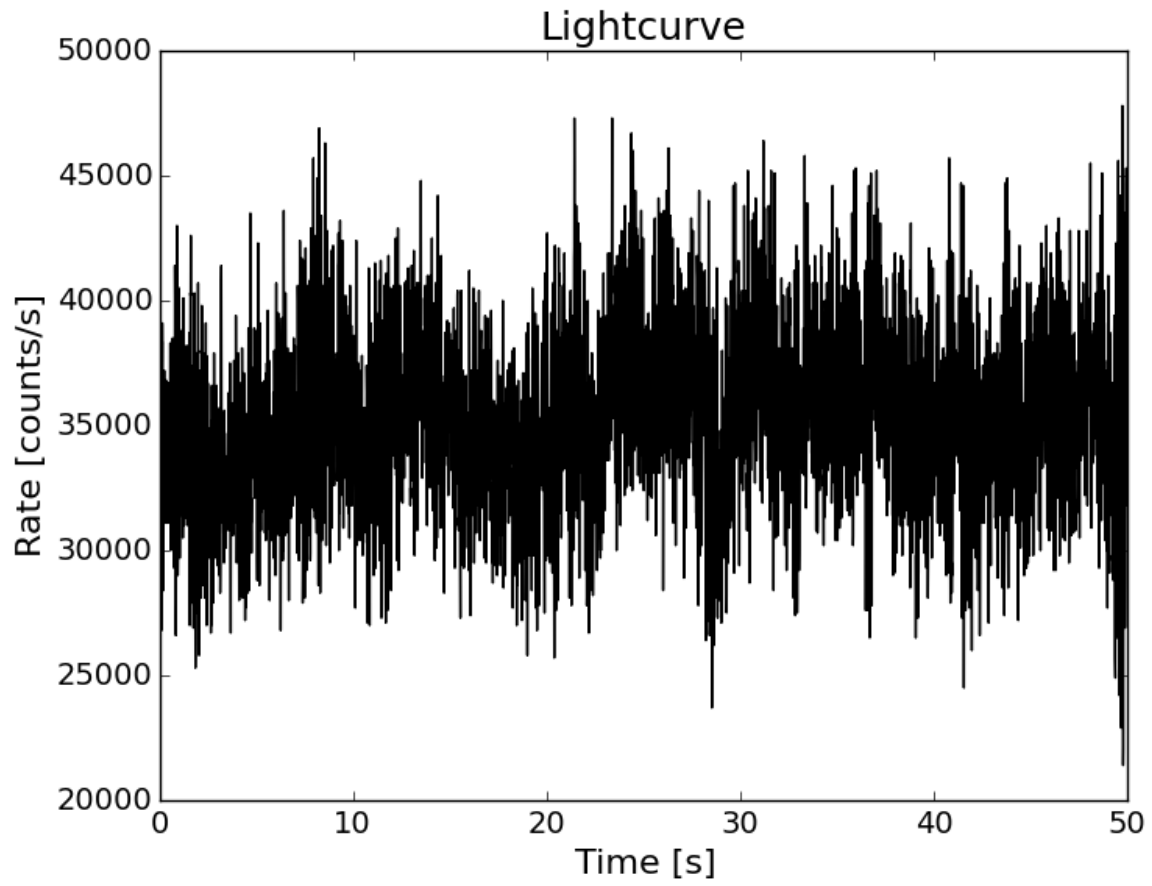
```
# Save FITS files with lightcurve and spectrum
pyLCSIM.saveFITS LC("myLC.fits", time, rate)
pyLCSIM.saveFITSPSD("myPSD.fits", f, psd)
```

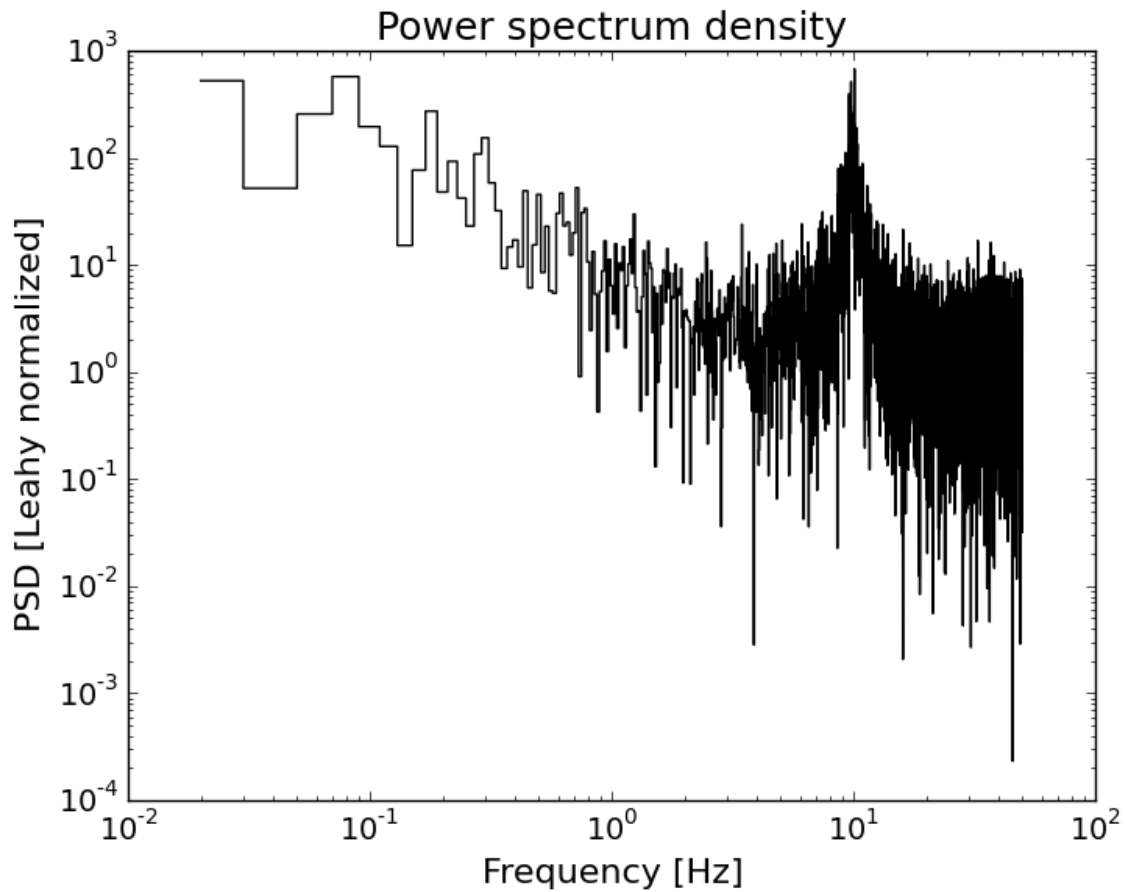
and view the results:

```
# Plot the lightcurve and power spectrum
fig0 = plt.figure()
plt.plot(time, rate)
plt.xlabel("Time [s]")
plt.ylabel("Rate [counts/s]")
plt.title("Lightcurve")

fig1 = plt.figure()
plt.loglog(f, psd, drawstyle='steps-mid', color='black')
plt.xlabel("Frequency [Hz]")
plt.ylabel("PSD [Leahy normalized]")
plt.title("Power spectrum density")

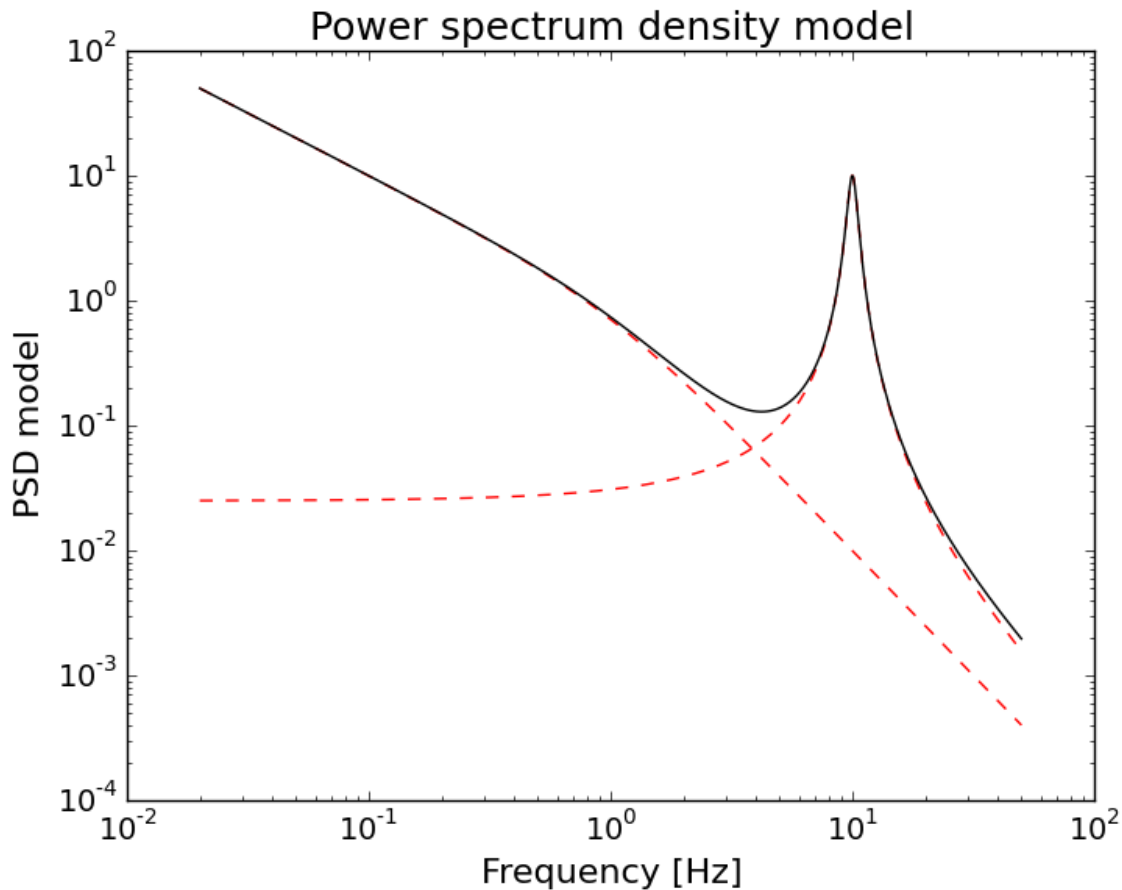
plt.show()
```





The PSD model used in the simulation can be obtained (and plotted) following the next example code:

```
freq_m, model_tot, model_comp = sim.getPSDModel(dt, nbins)
plt.figure()
for mod in model_comp:
    # Plot the various additive component as dashed lines
    plt.loglog(freq_m, mod, ls='dashed', color='red')
# Plot the total model
plt.loglog(freq_m, model_tot)
plt.show()
```



1.7 Example 2

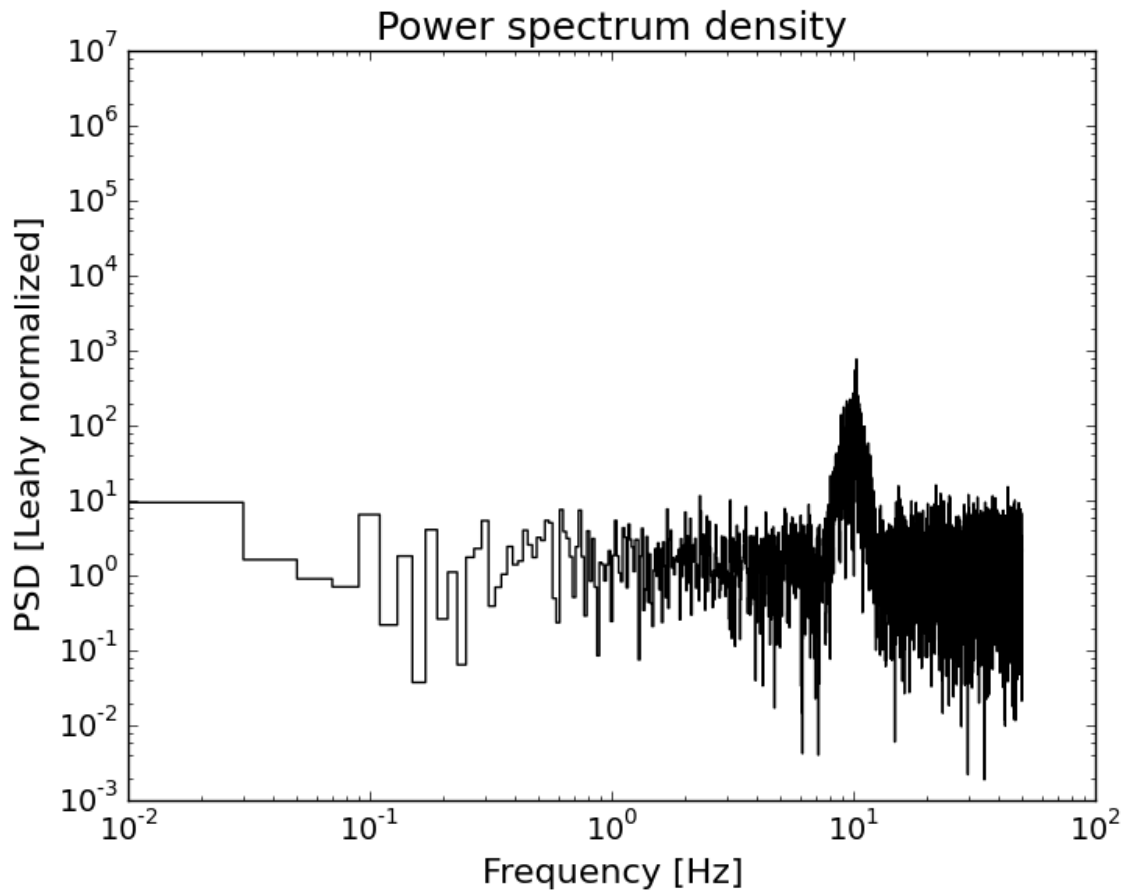
The user can also define his/her own PSD models, simply as python functions. The only caveat is that the function should be positive-valued, and it is suggested to avoid too small output values.

The following example shows a simulation using an user-defined function (a Gaussian centered at 10 Hz, in this case):

```
def myFunc(f, p):
    """
    Example of user-defined function: a Gaussian.
    User-defined PSD models should be positive-valued!
    Moreover, in this example the output is clipped at 1e-32 to avoid too small
    ↪values.
    """
    f = p[0]*np.exp(-(f-p[1])**2/p[2]**2)
    return np.clip(f, 1e-32, np.max(f))

sim = pyLCSIM.Simulation()
sim.addModel('smoothbknpo', [1., 1, 2, 1])
sim.addModel(myFunc, [1000., 10, 1.])

# Run the simulation
sim.run(dt, nbins, rate_src, rms=frms)
```



Additionally, PSD models can be also defined as `astropy.modeling.models` functions.

The following example is equivalent to the previous one (a Gaussian centered at 10 Hz):

```
from astropy.modeling import models

sim = pyLCSIM.Simulation()
sim.addModel('smoothbknpo', [1., 1, 2, 1])
# For astropy.modeling.models, you should define a dictionary of parameters instead_
# of the usual list:
sim.addModel(models.Gaussian1D, {'amplitude':1000., 'mean':10., 'stddev':1.})

# Run the simulation
sim.run(dt, nbins, rate_src, rms=frms)
```

1.8 Example 3

The following example shows the simulation of a coherent signal using a sum of sinusoids:

```
import matplotlib.pyplot as plt
import numpy as np
import pyLCSIM

rate_src = 30000.0
```

```
rate_bkg    = 5000.0
t_exp       = 1.0
dt          = 0.0001
nbins       = t_exp/dt
```

Note the different exposure time (1 s) and time resolution (100 us):

```
# Instantiate a simulation object, this time as coherent
sim = pyLCSIM.Simulation(kind='coherent')

# Run the simulation, using:
# four sinusoidal frequencies: 340, 550, 883, 1032 Hz;
# with pulsed fractions 10%, 5%, 7% and 15% respectively;
# the third frequency has a 35 degree phase shift with respect to the others
sim.run(dt, nbins, rate_src, freq=[340, 550, 883, 1032], amp=[0.1, 0.05, 0.07, 0.15],
→phi=[0., 0, 35., 0.])

# Add Poisson noise to the light curve
sim.poissonRandomize(dt, rate_bkg)

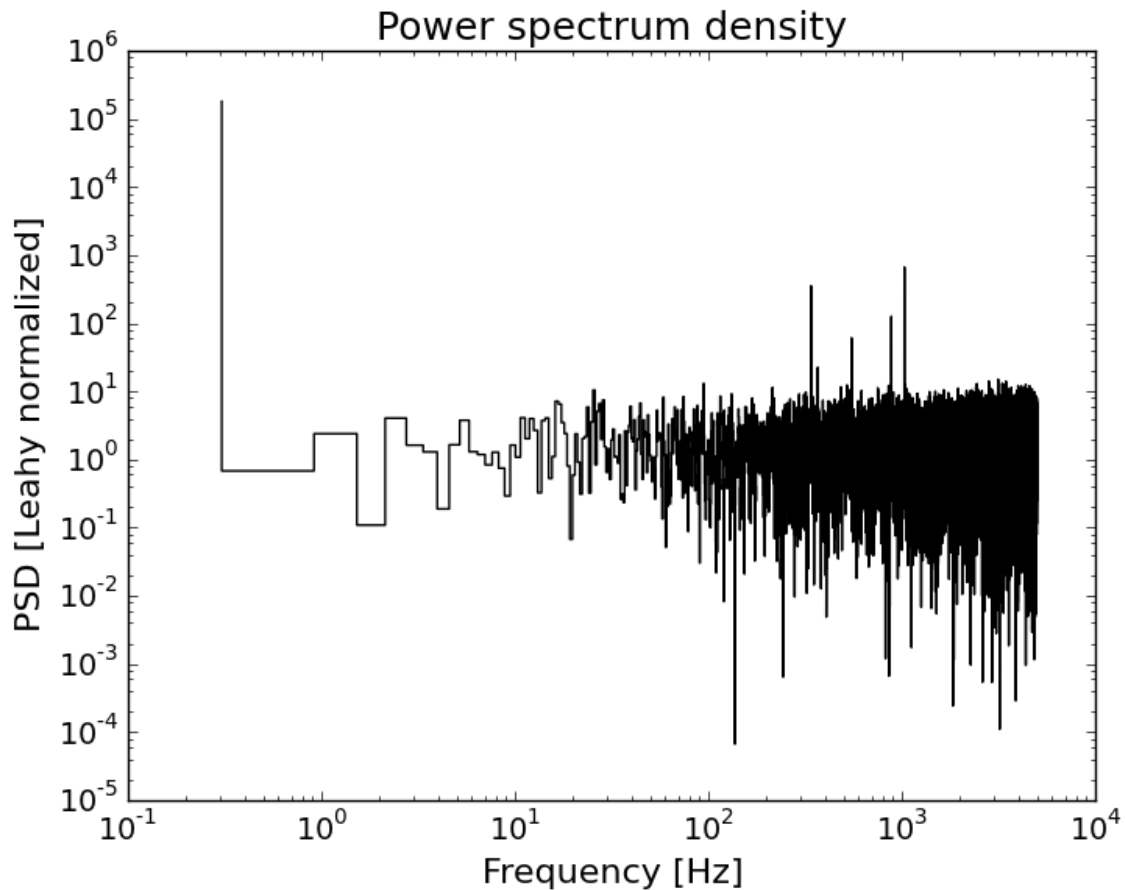
# Get lightcurve and power spectrum as 1-D arrays
time, rate = sim.getLightCurve()
f, psd = sim.getPowerSpectrum()

# Plot the lightcurve and power spectrum
fig0 = plt.figure()
plt.plot(time, rate)
plt.xlabel("Time [s]")
plt.ylabel("Rate [counts/s]")
plt.title("Lightcurve")

fig1 = plt.figure()
plt.loglog(f, psd, drawstyle='steps-mid', color='black')
plt.xlabel("Frequency [Hz]")
plt.ylabel("PSD [Leahy normalized]")
plt.title("Power spectrum density")

# Save FITS files with lightcurve and spectrum
pyLCSIM.saveFITSLC("myLC.fits", time, rate)
pyLCSIM.saveFITSPSD("myPSD.fits", f, psd)

plt.show()
```



1.9 Example 4

Finally, an example with a fundamental frequency and two harmonics:

```
import matplotlib.pyplot as plt
import numpy as np
import pyLCSIM

rate_src = 300000.0
rate_bkg = 3000.0
t_exp = 1.0
dt = 0.0001
phase_shift = 0.
nbins = t_exp/dt

# Instantiate a simulation object, this time as coherent
sim = pyLCSIM.Simulation(kind='coherent')

# Run the simulation:
# Fundamental at 500 Hz, 3 harmonics (500, 1000, 1500 Hz)
# with pulsed fractions 10%, 5% and 15% respectively
sim.run(dt, nbins, rate_src, freq=500, nha=3, amp=[0.1, 0.05, 0.15])
```

```
# Add Poisson noise to the light curve
sim.poissonRandomize(dt, rate_bkg)

# Get lightcurve and power spectrum as 1-D arrays
time, rate = sim.getLightCurve()
f, psd = sim.getPowerSpectrum()

# Plot the lightcurve and power spectrum
fig0 = plt.figure()
plt.plot(time, rate)

fig1 = plt.figure()
plt.loglog(f, psd, drawstyle='steps-mid', color='black')

# Save FITS files with lightcurve and spectrum
pyLCSIM.saveFITS LC("myLC.fits", time, rate)
pyLCSIM.saveFITSPSD("myPSD.fits", f, psd)

plt.show()
```

1.10 Main module

class `pyLCSIM.Simulation` (*kind='psd'*)

Main simulation class.

History: v1.3: Added `getPSDModel` method. Riccardo Campana, 2014.

v1.2: Added `reset` method. Riccardo Campana, 2014.

v1.1: Bugfix. Riccardo Campana, 2014.

v1: Initial python implementation. Riccardo Campana, 2014.

addModel (*modelName, modelParams*)

Append simulation model to model dictionary

getLightCurve ()

Get lightcurve as time and rate arrays

getPSDModel (*dt, nbins, freq=1000*)

Get PSD model Returns a tuple with: frequency array, total model, array with single components

getPowerSpectrum ()

Get power spectrum as frequency and power arrays

info ()

Prints simulation informations

poissonRandomize (*dt, bkg*)

Add Poissonian noise to lightcurve (and background, if present)

reset ()

Reset the simulation, emptying models array and other members

run (*dt, nbins_old, mean, rms=None, freq=None, nha=None, amp=None, phi=None, verbose=False*)

Run the simulation

`pyLCSIM.lcsinusoid` (*dt=1.0, nbins=65536, mean=0.0, freq=None, nha=1, amp=None, phi=None, verbose=False*)

Generate coherent signals as a sequence of sinusoids (if `len(freq) > 1`) or of the fundamental frequency plus `nha-1` harmonics (if `len(freq) == 1`), each with normalized pulsed fraction `amp[i]`.

Kwargs: `dt`: time resolution of the lightcurve to be simulated (default: 1.0).

`nbins`: Number of bins of the simulated lightcurve (default: 65536).

`freq`: if float: frequency of the fundamental harmonic, if array: frequencies of sinusoids.

`nha`: number of harmonics (>1)

`amp`: array with `nha/nfreq` elements; pulsed fraction for each frequency

`phi`: array with `nha/nfreq` elements; phases (in degrees!) for each frequency

Returns: `time`: time array

`rate`: array of count rates

History: v1: Initial python implementation, from the IDL procedure `lcharmonics.pro` v0.0.3 by I. Donnarumma & R. Campana. Riccardo Campana, 2014.

`pyLCSIM.lcpsd` (*dt=1.0, nbins=65536, mean=0.0, rms=1.0, seed=None, models=None, phase_shift=None, time_shift=None, verbose=False*)

Simulate a light-curve with a general power spectrum shape. For the underlying algorithm see: J. Timmer & M. Koenig, "On generating power law noise", *A&A*, 300, 707-710 (1995).

Kwargs: `dt`: time resolution of the lightcurve to be simulated

nbins: Number of bins of the simulated lightcurve (default:65536). Should be power of two for optimum performance (FFT...)

`mean`: Mean count rate of the simulated lightcurve (default: 0.).

`rms`: Total fractional RMS of the simulated lightcurve.

`seed`: Seed for the random number generator.

models: List of tuples, each containing:

1. Name of a function returning the desired PSD shape,
- b. Parameters of the model (argument to model). Total model is the sum of these tuples.

`phase_shift`: Constant phase shift (in degrees) to the FFT.

`time_shift`: Constant time shift to be inserted in the lightcurve, as a frequency-dependent phase shift.

`verbose`: If True, prints some debugging information.

Returns: `time`: time array.

`rate`: array of count rates.

History: v2: Added the possibility to employ user-defined PSD models. Riccardo Campana, 2014.

v1: Initial python implementation, based on AITLIB IDL procedure `timmerlc.pro`. Riccardo Campana, 2014.

`pyLCSIM.poisson_randomization` (*rate, dt=1.0, bkg=0.0, seed=None*)

Poisson randomization of the rate array.

Args: `rate`: input array of count rates (in cts/s).

Kwargs: dt: time resolution of the lightcurve to be simulated.

bkg: Mean count rate of the simulated lightcurve (default: 0.0).

seed: Seed for the random number generator.

Returns: newrate: Array of Poisson randomized count rates of length n.

History: v1: Initial python implementation. Riccardo Campana, 2014.

pyLCSIM.**psd** (*time, rate, norm='leahy'*)

Returns power spectral density from a (real) time series with Leahy normalization.

Args: time: array of times (evenly binned).

rate: array of rate in counts/s.

Kwargs: norm: Normalization (only Leahy for now).

Returns: f: array of frequencies.

p: power spectrum.

History: v1: Initial python implementation. Riccardo Campana, 2014.

pyLCSIM.**rebin** (*x, y, factor, mode='rate', verbose=False*)

Linearly rebins the (x, y) 1-D arrays by factor, i.e. with len(x)/factor new bins, taking for each new element the mean of the corresponding x elements, and the sum (if mode=='counts') or the mean (if mode=='rate') of the corresponding y elements. If the new number of bins is not a factor of the old one, the array is cropped.

Args: x: x array (same length as y)

y: y array (same length as x)

factor: rebinning factor

Kwargs: mode: 'counts' or 'rate'; returns sum or mean of y-array elements

Returns: xreb: rebinned x array

yreb: rebinned y array

History: v2: Switched to rebinning factor instead of number of new bins. Riccardo Campana, 2014. v1: Initial python implementation. Riccardo Campana, 2014.

pyLCSIM.**logrebin** (*x, y, factor, mode='rate', verbose=False*)

Logarithmically rebins the (x, y) 1-D arrays by a constant logarithmic bin $\log(1+1/\text{factor})$, i.e. each new bin has a width $(1+1/\text{factor})$ greater than the preceding; taking for each new element the logarithmic mean of the corresponding x elements, and the sum (if mode=='counts') or the mean (if mode=='rate') of the corresponding y elements.

Args: x: x array (same length as y)

y: y array (same length as x)

factor: logarithmic rebinning factor

Kwargs: mode: 'counts' or 'rate'; returns sum or mean of y-array elements

Returns: xreb: rebinned x array

yreb: rebinned y array

History: v2: Switched to logarithmic rebinning factor. Riccardo Campana, 2014. v1: Initial python implementation. Riccardo Campana, 2014.

pyLCSIM.**saveFITS** (*outfile, time, rate, clobber=True*)

Produce an output FITS file containing a lightcurve.

Args: `outfile`: Name of the output FITS file

`time`: Array of times

`rate`: Array of count rates

Kwargs: `clobber`: if True, overwrites existing files with same name

Returns: none

History: v2: OGIP-compliance (OGIP 93-003). Riccardo Campana, 2014.

v1: Initial python implementation. Riccardo Campana, 2014.

pyLCSIM.`saveFITSPSD` (`outfile`, `freq`, `psd`, `clobber=True`)

Produce an output FITS file containing a power spectrum.

Args: `outfile`: Name of the output FITS file

`freq`: Array of frequencies

`psd`: Array of power spectrum

Kwargs: `clobber`: if True, overwrites existing files with same name

Returns: none

History: v1: Initial python implementation. Riccardo Campana, 2014.

1.11 Submodule: `psd_models`

Contains the analytic models for the power spectrum density.

pyLCSIM.`psd_models.lorentzian` (`x`, `p`)

Generalized Lorentzian function.

(**WARNING:** for $n \neq 2$ the function is no more normalized!)

Args: `x`: (non-zero) frequencies.

`p[0]`: x_0 = peak central frequency.

`p[1]`: γ = FWHM of the peak.

`p[2]`: value of the peak at $x = x_0$.

`p[3]`: n = power coefficient.

The quality factor is given by $Q = x_0/\gamma$.

Returns: `f`: psd model.

History: v1: Initial python implementation. Riccardo Campana, 2014.

pyLCSIM.`psd_models.smoothbknp` (`x`, `p`)

Smooth broken power law.

Args: `x`: (non-zero) frequencies.

`p[0]`: Normalization.

`p[1]`: power law index for $f \rightarrow 0$.

`p[2]`: power law index for $f \rightarrow \infty$.

`p[3]`: break frequency.

Returns: f: psd model.

History: v1: Initial python implementation. Riccardo Campana, 2014.

1.12 Changelog

v0.4.0: Added support for astropy.modeling.models functions.

v0.3.0: Added python 3.x compatibility.

v0.2.3: Minor bugfixes.

v0.2.2: Modified rebinning functions (rebin() and logrebin()).

v0.2.1: Added getPSDModel() method to Simulation. Bugfixes.

v0.2.0: Added the possibility to employ user-defined PSD models.

v0.1.2: Added reset method to Simulation. Lightcurve FITS output is now OGIP-compliant.

v0.1.1: Bugfix. Modified Simulation class.

v0.1.0: Initial release.

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