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# **epos Documentation**

*Release 1.1.0.dev1*

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Detailed Instructions:

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## the Exoplanet Population Observation Simulator

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EPOS is a software package to simulate observations of exoplanet populations. It provides an interface between planet formation simulations and exoplanet surveys such as Kepler. EPOS can also be used to estimate planet occurrence rates and the orbital architectures of planetary systems.

EPOS is written in Python and hosted on [github](#). Follow the instructions there to download and install.

**NEW** You can now install EPOS with pip:

```
pip install epospy
```

(possibly preceded by `sudo -H`)



EPOS runs from the command line. The quickest way to familiarize yourself with the code is to copy the test and example scripts to a local directory:

```
>>> import EPOS
>>> EPOS.scripts.install()
```

These scripts demonstrate some of the basic functionality of EPOS. Output will appear in the terminal and plots in the `png/` folder.

## 2.1 Installation

### 2.1.1 Pip

You can now install epos with `pip`:

```
pip install epospy
```

Depending on your OS, you might have to use `sudo` or:

```
sudo -H pip install epospy
```

You should now be able to import the EPOS module into python:

```
>>> import EPOS
```

### 2.1.2 Github

Download the source from [github](#), preferably using `git`:

```
git clone https://github.com/GijsMulders/epos
```

In the future you can update to the latest version with:

```
git pull
```

You will need to add the EPOS directory to your path if you want to run from outside the main folder.

### 2.1.3 Dependencies

EPOS has the following dependencies:

- python 2.7
- numpy 1.13+
- scipy
- matplotlib 2.0+
- astropy

The following software is required if you want to use the MCMC part of EPOS

- [emcee](#) for the MCMC fitting
- [corner.py](#) for the corner plots

`pip` should take care of these dependencies automatically but if you installed via `github` you will have to install them manually.

### 2.1.4 Testing

To test the basic functionality of EPOS, you can run the test scripts. First, copy the test and example scripts to a local directory:

```
>>> import EPOS
>>> EPOS.scripts.install()
```

Navigate to the scripts directory (`epos-scripts/tests/`) and run each of:

```
./test_1_survey.py
./test_2_montecarlo.py
./test_3_mcmc.py
./test_4_multicore.py
./test_5_occurrence.py
```

If you don't have `ipython` installed, you can also run `python test_1_survey.py` or copy-paste the script into a terminal.

Each command is described in the comments, and provides an introduction to the basic functionality.

## 2.2 Examples

There are a number of example scripts included that demonstrate different functionality. The scripts contains comments describing each command. These scripts are copied to the `epos-scripts/examples/` directory by `EPOS.scripts.install()`.



## 2.2.1 Parametric mode

The first example shows how to fit a parametric function in planet radius and orbital period to Kepler data. The script can be run with:

```
./example_1_parametric_mode.py
```

Here, is a step-by-step description of each set of commands. First, load EPOS and set the output directory name

```
>>> import EPOS
>>> epos = EPOS.epos(name='example_1')
```

Second, load the observations (Kepler DR25 planet candidate list) and survey detection efficiency

```
>>> obs, survey = EPOS.kepler.dr25(Huber=True, Vetting=True, score=0.9)
>>> epos.set_observation(**obs)
>>> epos.set_survey(**survey)
```

Next, define the parametric distribution function that will be fitted to the data. (The example is a broken power-law in both the planet size and distance dimension from fitfunctions.py, but you can define your own)

```
>>> epos.set_parametric(EPOS.fitfunctions.brokenpowerlaw2D)
```

Now initialize the fit parameters with their initial values and limits (min, max). The first parameter is the normalization, defined as the number of planets per star over the simulated radius-period range:

```
>>> epos.fitpars.add('pps', 2.0, min=0)
```

The next six parameters (one break point and two indices for each dimension) control the shape of the period-radius distribution

```
>>> epos.fitpars.add('P break', 10., min=2, max=50, is2D=True)
>>> epos.fitpars.add('a_P', 1.5, min=0, is2D=True)
>>> epos.fitpars.add('b_P', 0.0, dx=0.1, is2D=True)
>>> epos.fitpars.add('R break', 3.0, min=1.0, max=5, is2D=True)
>>> epos.fitpars.add('a_R', 0.0, dx=0.1, is2D=True)
>>> epos.fitpars.add('b_R', -4., fixed=True, is2D=True)
```

Note that the last parameter is fixed and thus not fitted for. `dx` is a parameter that controls the initial distribution of walkers when the initial value is zero.

Next, define the simulation range.

```
>>> epos.set_ranges(xtrim=[0, 730], ytrim=[0.3, 20.], xzoom=[2, 400], yzoom=[1, 6], Occ=True)
```

For transits, `x` refers to orbital period and `y` refers to planet size. The simulated range is that supplied by the detection efficiency grid and trimmed (`trim`) to the given values. For the observational comparison we `zoom` in a bit further.

Now we're ready to go! Run the code once with the initial values:

```
>>> EPOS.run.once(epos)
```

Then run the mcmc chain

```
>>> EPOS.run.mcmc(epos, nMC=1000, nwalkers=100, nburn=200, threads=20, Saved=True)
```

This runs multi-core with 20 threads. `Saved` indicates whether the mcmc will be skipped if a previously saved chain is present on disk. `Saved=False` always reruns the chain.

Define a set of bins where planet occurrence rates are calculated, both from the data and from integrating the fitted planet distributions, and calculate all the rates

```
>>> epos.set_bins(xbins=[[2,400],[0.9*365,2.2*365]], ybins=[[1,6],[0.7,1.5]]) # eta_
↳zoom, eta_earth
>>> EPOS.occurrence.all(epos)
```

Last, plot everything.

```
>>> EPOS.plot.survey.all(epos)
>>> EPOS.plot.input.all(epos)
>>> EPOS.plot.output.all(epos)
>>> EPOS.plot.mcmc.all(epos)
>>> EPOS.plot.occurrence.all(epos)
```

Plots will appear in the png/example\_1/ subfolder

## 2.2.2 Multi-planet Mode

```
./example_2_multiplanet_mode.py
```

In multi-planet mode, the first planet in the system is drawn from a parametric distribution same as above. However, we adjust the initial guess for the slope after the period break

```
>>> epos.fitpars.add('b_P', -1, max=1, dx=0.1, is2D=True)
```

Next we tell epos to draw additional planets in the system assuming the spacing between adjacent planets is drawn from a dimensionless distribution:

```
>>> epos.set_multi(spacing='dimensionless')
```

We generate 10 planets per system.

```
>>> epos.fitpars.add('npl', 10, fixed=True)
```

The fit parameters for the dimensionless distribution are:

```
>>> epos.fitpars.add('log D', -0.3)
>>> epos.fitpars.add('sigma', 0.2, min=0)
```

Other properties of the planetary systems can also be fit for (or not):

```
>>> epos.fitpars.add('dR', 0.01, fixed=True) # Dispersion in planet radii
>>> epos.fitpars.add('inc', 2.0) # mode of mutual inclinations
>>> epos.fitpars.add('f_iso', 0.4) # Fraction of isotropic systems
>>> epos.fitpars.add('f_cor', 0.5, fixed=True) # Correlated noise
```

Then proceed as in single-planet mode.

## 2.2.3 Radial Velocity Surveys

Example 5 shows how to estimate the distribution of planets from a radial velocity survey:

```
./example_5_radial_velocity.py
```

Two commands are different from fitting a transit survey: First, tell epos that we are doing a radial velocity survey (RV=True), that we are not doing the Monte Carlo simulation (MC=False) and that we are fitting for the planet mass distribution (Msini=True)

```
>>> epos= EPOS.epos(name='example_5', RV=True, MC=False, Msini=True)
```

Second, we define the radial velocity survey data, here from Mayor+ 2011

```
>>> obs, survey= EPOS.rv.Mayor2011()
>>> epos.set_observation(**obs)
>>> epos.set_survey(**survey)
```

## 2.2.4 Planet Occurrence Rates

Example 9 shows how to estimate occurrence rates using the inverse detection efficiency method. You can run the entire script with:

```
./example_9_occurrence_rate_inverse.py
```

Here, is a step-by-step description of each set of commands. First, load EPOS and set the output directory name

```
>>> import EPOS
>>> epos= EPOS.epos(name='example_9')
```

Second, load the observations (Kepler DR25 planet candidate list) and survey detection efficiency

```
>>> obs, survey= EPOS.kepler.dr25(Huber=True, Vetting=True, score=0.9)
>>> epos.set_observation(**obs)
>>> epos.set_survey(**survey)
```

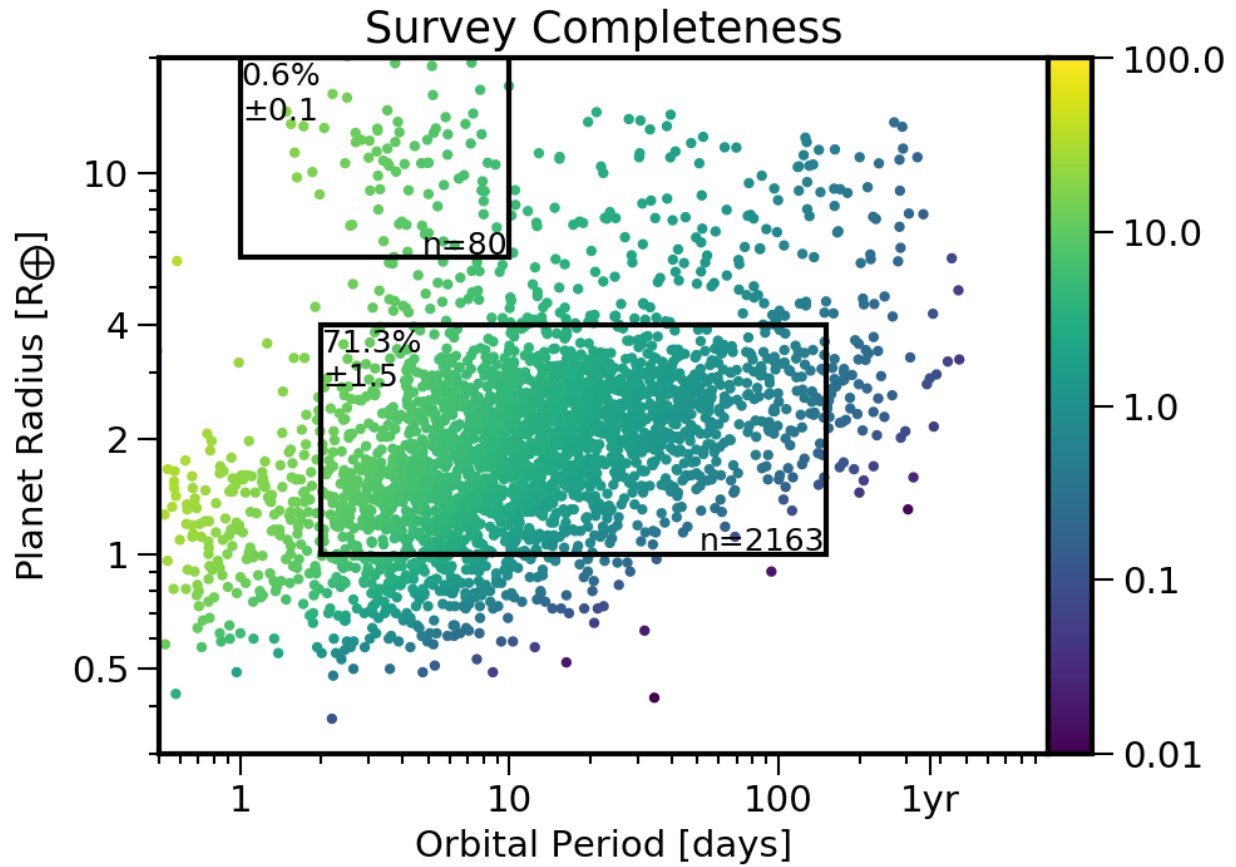
Next, define the occurrence rate bins for hot Jupiters and super-earths/mini-Neptunes:

```
>>> x_HJ= [1,10] # Orbital period range in days
>>> y_HJ= [7,20] # Planet size range in earth radii
>>> x_SEMN, y_SEMN= [2,150], [1.0,4.0] # super-Earths/mini-Neptunes
>>> epos.set_bins(xbins=[x_HJ, x_SEMN], ybins=[y_HJ, y_SEMN])
```

The rates are then calculated, plotted, and saved

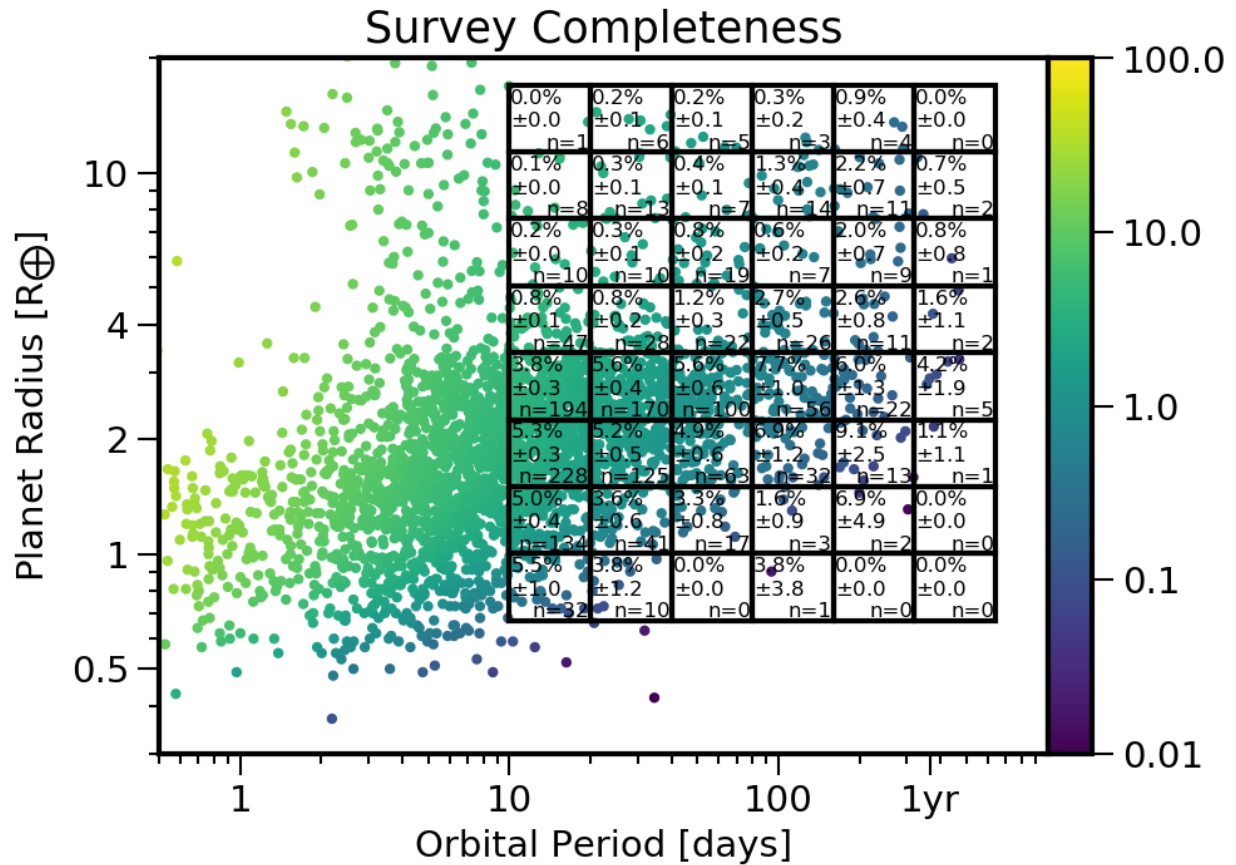
```
>>> EPOS.occurrence.all(epos)
>>> EPOS.save.occurrence(epos)
>>> EPOS.plot.occurrence.all(epos)
```

The output appears in png/occurrence/bins.png and should look like this:



Alternatively, you can generate a 1D or 2D grid of bins, for example the SAG13 grid:

```
>>> import numpy as np
>>> epos.set_bins(xgrid=np.geomspace(10, 640, 7),
                 ybins=np.geomspace(0.67, 17, 9), Grid=True)
```



## 2.3 FAQ

### 2.3.1 Frequently asked questions

If you have any difficulties or questions running EPOS that are not addressed in the documentation or FAQ please contact [gdmulders@gmail.com](mailto:gdmulders@gmail.com)

**I'm getting an AttributeError: 'module' object has no attribute 'geomspace'**

Please upgrade to numpy 1.13 or a more recent version



## 3.1 EPOS API

This generates the API, showing some documented functions

(this is a link to `EPOS.epos`)

### 3.1.1 The epos class

**class** `EPOS.epos` (*name*, *RV=False*, *Debug=False*, *seed=True*, *Norm=False*, *MC=True*, *Msini=False*)

The epos class

**Description:** Initialize

#### Parameters

- **name** (*str*) – name to use for directories
- **RV** (*bool*) – Compare to radial velocity instead of transits
- **MC** (*bool*) – Generate planet population by random draws
- **Msini** (*bool*) – Convert the planet mass distribution into an Msini distribution
- **Debug** (*bool*) – Log more output for debugging
- **seed** (*int*) – Same random number for each simulation? True, None, or int
- **Norm** (*bool*) – normalize pdf (deprecated?)

#### **name**

*str* – name

#### **plotdir**

*str* – plot directory

**RV**

*bool* – Compare to Radial Velocity instead of transit data

**Multi**

*bool* – Do multi-planet statistics

**RandomPairing**

*bool* – multIs are randomly paired

**Isotropic**

*bool* – Assume isotropic mutual inclinations

**Parametric**

*bool* – parametric planet population?

**Debug**

*bool* – Verbose logging

**seed**

Random seed, can be any of int, True, or None

**jsonDir = None**

EPOS mode

**set\_bins** (*xbins=[[1, 10]], ybins=[[1, 10]], xgrid=None, ygrid=None, Grid=False*)

Initialize period-radius (or mass) bins for occurrence rate calculations

**Description:** Bins can be generated from a grid, f.e. *xgrid=[1,10,100]*, or from a list of bin edges, f.e. *xbins= [[1,10],[10,100]]*

**Parameters**

- **xbins** (*list*) – (list of) period bin edges
- **ybins** (*list*) – (list of) radius/mass bin edges
- **xgrid** (*list*) – period bin in interfaces
- **ygrid** (*list*) – radius/mas bin interfaces
- **Grid** (*bool*) – If true, create a 2D grid from bins: *nbins = nx \* ny*. If false, pair x and y bins: *nbins == nx == ny*

**set\_observation** (*xvar, yvar, starID, nstars=168620.0, radiusError=0.1, score=None*)

Observed planet population

**Parameters**

- **xvar** – planet orbital period [list]
- **yvar** – planet radius or  $M \sin i$  [list]
- **ID** – planet ID [list]
- **nstars** – number of stars surveyed

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**Note:** Some pre-defined planet populations from Kepler can be generated from `EPOS.kepler.dr25()`

---

**set\_parametric** (*func*)

Define a parametric function to generate the planet size-period distribution



**Description:** Function should be callable as `func(X, Y, *fitpars2d)` with `X(np.array): period` `Y(np.array): size (radius or mass)` The list of fit parameters `fitpars2d` will be constructed from parameters added using `EPOS.fitparameters.add()` with `is2D=True`

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**Note:** Some pre-defined functions can be found in `EPOS.fitfunctions`

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**Parameters** `func` (*function*) – callable function

**set\_survey** (*xvar, yvar, eff\_2D, Rstar=1.0, Mstar=1.0, vet\_2D=None*)

Survey detection efficiency (completeness) :param xvar: planet orbital period grid [list] :param yvar: planet radius or  $M \sin i$  grid [list] :param eff\_2D: 2D matrix of detection efficiency :param Rstar: stellar radius, for calculating transit probability :param Mstar: stellar mass, for period-semimajor axis conversion

---

**Note:** Some pre-defined detection efficiencies from Kepler can be generated from `EPOS.kepler`

---

**class** `EPOS.fitparameters`

Holds the fit parameters. Usually initialized in `epos.fitpars`

**add** (*key, value, fixed=False, min=-inf, max=inf, dx=None, text=None, is2D=False, isnorm=False*)

Add a fit parameter

**Parameters**

- **key** (*str*) – fit parameter dictionary key
- **value** (*float*) – starting guess
- **fixed** (*bool*) – keep this parameter fixed
- **min** (*float*) – lower bound
- **max** (*float*) – upper bound
- **dx** (*float*) – initial dispersion for MCMC
- **text** (*str*) – plot safe name?
- **is2D** (*bool*) – use this parameter in the 2D parametric `EPOS.fitfunctions()`
- **isnorm** (*bool*) – this parameter is the normalization factor for the number of planet per star `EPOS.fitfunctions()`

### 3.1.2 Fit parameters

**class** `EPOS.fitparameters`

Holds the fit parameters. Usually initialized in `epos.fitpars`

**add** (*key, value, fixed=False, min=-inf, max=inf, dx=None, text=None, is2D=False, isnorm=False*)

Add a fit parameter

**Parameters**

- **key** (*str*) – fit parameter dictionary key
- **value** (*float*) – starting guess
- **fixed** (*bool*) – keep this parameter fixed
- **min** (*float*) – lower bound

- **max** (*float*) – upper bound
- **dx** (*float*) – initial dispersion for MCMC
- **text** (*str*) – plot safe name?
- **is2D** (*bool*) – use this parameter in the 2D parametric `EPOS.fitfunctions()`
- **isnorm** (*bool*) – this parameter is the normalization factor for the number of planet per star `EPOS.fitfunctions()`

## CHAPTER 4

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### License / Attribution

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Copyright 2018 Gijs Mulders

Please cite [Mulders et al. 2018](#) if you use epos. You can also cite the github repository directly



## CHAPTER 5

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### List of Publications

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**Mulders et al. 2018** The Exoplanet Population Observation Simulator. I - The Inner Edges of Planetary Systems

**Pascucci et al. 2018** A Universal Break in the Planet-to-star Mass-ratio Function of Kepler MKG Stars

**Kopparapu et al. 2018** Exoplanet Classification and Yield Estimates for Direct Imaging Missions

**Fernandes et al. 2019** Hints for a Turnover at the Snow Line in the Giant Planet Occurrence Rate



## CHAPTER 6

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### Version Notes:

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- 1.0.1** first public release
- 1.0.2** pip installable version
- 1.1.0** radial velocity without Monte Carlo





## CHAPTER 7

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