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P-pop user documentation

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ABSTRACT

Aims. This user documentation aims to help the reader to get the planet population synthesis tool P-pop running on their own machine. It also defines the format of its output, the planet population table.
Methods. P-pop is a publicly distributed Python tool. It uses planet occurrence statistics, e.g., from the *Kepler* mission, and model distributions for the exoplanet system parameters in order to simulate synthetic planet populations.
Results. P-pop allows to simulate millions of synthetic planets within timescales of hours. These can then be used in order to make yield predictions for future instruments and space missions for example.

Key words. Planets and satellites: detection – Planets and satellites: terrestrial planets – Methods: numerical

1. Introduction

P-pop is a Monte-Carlo tool to simulate exoplanet populations based on planet occurrence statistics, e.g., from the *Kepler* mission. It consists of two Python libraries, P-pop and P-pop Photometry.

P-pop is used to simulate exoplanet populations which are saved in a planet population table which can then be used by other tools. P-pop Photometry is used to compute the photometry for a given planet population table which can then be used to estimate the expected exoplanet yield for future instruments or space missions for example.

P-pop has been used in Kammerer & Quanz (2018), Quanz et al. (2018), and Quanz et al. (2019) to make yield predictions for the LIFE[1] space mission.

2. Installation

P-pop and P-pop Photometry can be downloaded from GitHub[2]. Installation instructions can be found in the readme file.

The provided example only works if P-pop and P-pop Photometry are cloned into the same parent directory. If not, the paths of the planet population table and its photometry might have to be updated.

P-pop and P-pop Photometry have been developed in Python 2.7, but should also be compatible with Python 3.9. Please help to improve the code by reporting any issues on GitHub.

3. Usage

3.1. P-pop

In order to simulate an exoplanet population with P-pop run the script `P-pop.py`. This will first display some informative plots about the star catalog and the different distributions for the physical parameters of the planets. Then, it will simulate a test exoplanet population consisting of 10 universes and write it to a file called `TestPlanetPopulation.txt`.

Various settings can be changed in the „SETUP“ section of the script `P-pop.py` (cf. Figure 1). More detailed information on the available settings can be found in the comments.

3.2. P-pop Photometry

In order to compute the photometry for a given planet population table with *P-pop Photometry* run the script `P-pop_Photometry.py`. This will first display some informative plots about the filters. Then it will compute the photometry for the `TestPlanetPopulation.txt` planet population table and write it to a file called `TestPlanetPopulation_filter.txt`.

Various settings can be changed in the „SETUP“ section of the script `P-pop_Photometry.py` (cf. Figure 4). More detailed information on the available settings can be found in the comments.

4. Planet population table

4.1. Description and format

The output of P-pop is a so-called planet population table. This table contains all information about the simulated planets and its content is described in Table 1.

In general, each line in the planet population table corresponds to one simulated planet. The columns are split by tabs (`\t`) and the column headers are unique and permanent. Hence, you can find a specific column by looking for its permanent header, as it is done in the script `ReadPlanetPopulation.py`. Note that the first two rows of the planet population table are devoted to headers. The second row contains the column names of the new P-pop while the first line contains the column

[1] `https://www.life-space-mission.com/`
[2] `https://github.com/kammerje/P-pop` and `https://github.com/kammerje/P-pop-Photometry`

```
"""
# ============================================================================
# P-pop
# A Monte-Carlo tool to simulate exoplanet populations
#
# Authors: Jens Kammerer, Sascha Quanz, Emile Fontanet
# Version: 1.0.0
# Last edited: 26.02.2026
# ============================================================================
#
# P-pop is introduced in Kammerer & Quanz 2018
# (https://ui.adsabs.harvard.edu/abs/2018A%26A...609A...4K/abstract). Please
# cite this paper if you use P-pop for your research.
#
# P-pop makes use of forecaster from Chen & Kipping 2017
# (https://ui.adsabs.harvard.edu/abs/2017ApJ...834...17C/abstract).
"""


# Don't print annoying warnings. Comment out if you want to see them.
import warnings
warnings.filterwarnings('ignore')


# ============================================================================
# IMPORTS
# ============================================================================

# Import catalogs, distributions, and models here.
import SystemGenerator
from StarCatalogs import alphaCenA,\
                         CrossfieldBrightSample,\
                         ExoCat1,\
                         LTC2,\
                         LTC3,\
                         LTC4,\
                         HPIC_LTC4_combined
from PlanetDistributions import Fressin2013,\
                                Burke2015,\
                                Dressing2015,\
                                SAG13,\
                                SAG13_extrap,\
                                Weiss2018,\
                                Weiss2018KDE,\
                                HabitableNominal,\
                                HabitablePessimistic,\
                                Fernandes2019Symm,\
                                Bryson2021Model1Hab2Low,\
                                Bryson2021Model1Hab2High,\
                                Bergsten2022
from ScalingModels import BinarySuppression
from MassModels import Chen2017
from EccentricityModels import Circular
from StabilityModels import He2019
from OrbitModels import Random
from AlbedoModels import Uniform,\
                         Constant
from ExozodiModels import Ertel2018,\
                          Ertel2020,\
                          Median


# ============================================================================
# SETUP
# ============================================================================
```

Fig. 1. Continued on next page...

```
66
67 # Select the star catalog, the spectral types, the distance range, the
68 # declination range, and the effective temperature range which should be
69 # included here.
70 # StarCatalog = CrossfieldBrightSample # used in Kammerer & Quanz 2018
71 # StarCatalog = ExoCat1 # used by NASA
72 # StarCatalog = LTC2 # LIFE Target Catalog (version 2)
73 # StarCatalog = LTC3 # LIFE Target Catalog (version 3)
74 StarCatalog = LTC4 # LIFE Target Catalog (version 4)
75 Stypes = ['A', 'F', 'G', 'K', 'M'] # list of str
76 Dist_range = [0., 20.] # pc, list of float, [min, max]
77 Dec_range = [-90., 90.] # deg, list of float, [min, max]
78 # Teff_range = [4800., 6300.] # K, list of float, [min, max]
79 Teff_range = None
80
81 # Select the planet distributions, the scenario, and the scaling model which
82 # should be used here. A different planet distribution can be assigned to each
83 # spectral type.
84 # dict, StarCatalog.Stype as keys, PlanetDistribution as data
85 # StypeToModel = {'A': Fressin2013, 'F': Fressin2013, 'G': Fressin2013, 'K': Fressin2013, 'M':
      Fressin2013}
86 # StypeToModel = {'F': Burke2015, 'G': Burke2015, 'K': Burke2015, 'M': Dressing2015}
87 # StypeToModel = {'F': SAG13, 'G': SAG13, 'K': SAG13, 'M': Dressing2015} # used in the ESA
      Voyage 2050 White Paper
88 # StypeToModel = {'F': SAG13, 'G': SAG13, 'K': SAG13, 'M': SAG13}
89 # StypeToModel = {'F': Weiss2018, 'G': Weiss2018, 'K': Weiss2018, 'M': Weiss2018}
90 # StypeToModel = {'F': Weiss2018KDE, 'G': Weiss2018KDE, 'K': Weiss2018KDE, 'M': Weiss2018KDE}
91 # StypeToModel = {'A': SAG13, 'F': SAG13, 'G': SAG13, 'K': SAG13, 'M': Dressing2015}
92 StypeToModel = {'A': SAG13, 'F': SAG13, 'G': SAG13, 'K': SAG13, 'M': SAG13}
93 # StypeToModel = {'A': HabitableNominal, 'F': HabitableNominal, 'G': HabitableNominal, 'K':
      HabitableNominal, 'M': HabitableNominal}
94 # StypeToModel = {'A': HabitablePessimistic, 'F': HabitablePessimistic, 'G':
      HabitablePessimistic, 'K': HabitablePessimistic, 'M': HabitablePessimistic}
95 # StypeToModel = {'A': Fernandes2019Symm, 'F': Fernandes2019Symm, 'G': Fernandes2019Symm, 'K':
      Fernandes2019Symm, 'M': Fernandes2019Symm}
96 # StypeToModel = {'A': Bryson2021Model1Hab2Low, 'F': Bryson2021Model1Hab2Low, 'G':
      Bryson2021Model1Hab2Low, 'K': Bryson2021Model1Hab2Low, 'M': Bryson2021Model1Hab2Low}
97 # StypeToModel = {'A': Bryson2021Model1Hab2High, 'F': Bryson2021Model1Hab2High, 'G':
      Bryson2021Model1Hab2High, 'K': Bryson2021Model1Hab2High, 'M': Bryson2021Model1Hab2High}
98 # StypeToModel = {'A': Bergsten2022, 'F': Bergsten2022, 'G': Bergsten2022, 'K': Bergsten2022, 'M
      ': Bergsten2022}
99 Scenario = 'baseline'
100 # Scenario = 'pessimistic' # for 1-sigma lower error bars on planet distribution
101 # Scenario = 'optimistic' # for 1-sigma upper error bars on planet distribution
102 # Scenario = 'mc' # draw parameters from MCMC posterior for each universe
103 # ScalingModel = None
104 ScalingModel = BinarySuppression
105
106 # Select the mass model, the eccentricity model, the stability model, the orbit
107 # model, the albedo model, and the exozodiacal dust model which should be used
108 # here.
109 MassModel = Chen2017 # Forecaster
110 EccentricityModel = Circular
111 # StabilityModel = None
112 StabilityModel = He2019
113 OrbitModel = Random
114 AlbedoModel = Uniform
115 # AlbedoModel = Constant
116 # ExozodiModel = Ertel2018
117 ExozodiModel = Ertel2020
118 # ExozodiModel = Median
119
120 # Select whether you want to generate summary plots after loading the catalogs,
121 # distributions, and models selected above, how many test draws should be
122 # done for generating these plots, and where you want to save them.
```

Fig. 2. Continued on next page...

```
SummaryPlots = True
# SummaryPlots = False
Ntest = 100000 # int
# Ntest = 10000 # int
# FigDir = None # if you don't want to save the summary plots
FigDir = 'Figures/' # str, should end with a slash ("/")
# block = True # interrupt script and display summary plots
block = False # don't interrupt script, only save summary plots

# Select a name for the output planet population table and how many universes
# should be simulated.
Name = 'TestPlanetPopulation' # str
Nuniverses = 10 # int


# ============================================================================
# P-POP
# ============================================================================

# Don't modify the following code.
SysGen = SystemGenerator.SystemGenerator(StarCatalog,
                                         StypeToModel,
                                         ScalingModel,
                                         MassModel,
                                         EccentricityModel,
                                         StabilityModel,
                                         OrbitModel,
                                         AlbedoModel,
                                         ExozodiModel,
                                         Stypes,
                                         Dist_range, # pc
                                         Dec_range, # deg
                                         Teff_range, # K
                                         Scenario,
                                         SummaryPlots,
                                         Ntest,
                                         FigDir,
                                         block)
SysGen.SimulateUniverses(Name,
                         Nuniverses)
```

Fig. 3. The script `P-pop.py` which can be used to simulate an exoplanet population.

names of the old P-pop (`https://github.com/kammerje/P-pop-first-version`).

4.2. Reading a planet population table

P-pop comes with the class `PlanetPopulation` which is implemented in the script `ReadPlanetPopulation.py` and can be used to read a planet population table including its photometry.

An example of how to use the class `PlanetPopulation` is given in the script `TestPlanetPopulation.py` which reads the test planet population table including its photometry which are provided as part of the P-pop library (cf. Figure 6).

References

Kammerer, J. & Quanz, S. P. 2018, A&A, 609, A4
Quanz, S. P., Absil, O., Angerhausen, D., et al. 2019, arXiv e-prints, arXiv:1908.01316
Quanz, S. P., Kammerer, J., Defrère, D., et al. 2018, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 10701, Proc. SPIE, 107011I

```
"""
# ============================================================================
# P-POP PHOTOMETRY
# A photometry tool for P-POP
#
# Authors: Jens Kammerer, Sascha Quanz, Emile Fontanet
# Version: 5.0.0
# Last edited: 15.04.2020
# ============================================================================
#
# P-pop is introduced in Kammerer & Quanz 2018
# (https://ui.adsabs.harvard.edu/abs/2018A%26A...609A...4K/abstract). Please
# cite this paper if you use P-pop for your research.
#
# P-pop makes use of forecaster from Chen & Kipping 2017
# (https://ui.adsabs.harvard.edu/abs/2017ApJ...834...17C/abstract).
"""


# Don't print annoying warnings. Comment out if you want to see them.
import warnings
warnings.filterwarnings('ignore')


# ============================================================================
# IMPORTS
# ============================================================================

# Import your own filters and photometry tools here.
import PhotometryComputer
from Filters import SVO
from Star import Blackbody
from Planet import Thermal, Reflected


# ============================================================================
# SETUP
# ============================================================================

# Select the filters and photometry tools which you want to use here.

# Select the name of the planet population table for which the photometry
# should be computed here.
PathPlanetTable = '../P-pop/TestPlanetPopulation.txt' # str

# Select the filters for which the photometry should be computed here. You can
# simply use the filter names from the Spanish Virtual Observatory
# (http://svo2.cab.inta-csic.es/theory/fps/).
# list of str
SVOids = ['JWST/MIRI.F560W',\
          'JWST/MIRI.F1000W',\
          'JWST/MIRI.F1500W'] # used for LIFE
# SVOids = ['Paranal/SPHERE.ZIMPOL_V',\
#           'Paranal/SPHERE.IRDIS_B_J',\
#           'Paranal/SPHERE.IRDIS_B_H'] # used for HabEx/LUVOIR

# Select the photometry tools to compute the fluxes from the stars and the
# planets as well as their unit and the wavelength range in which the mission
# is operating here.
Sstar = [Blackbody] # list of Star
Splanet = [Thermal, Reflected] # list of Planet
Unit = 'uJy' # micro-Jansky
# Unit = 'ph' # photons per second per square meter
Mission = 'MIR' # use AgeomMIR for reflected light (used for LIFE)
# Mission = 'VIS' # use AgeomVIS for reflected light (used for HabEx/LUVOIR)
```

Fig. 4. Continued on next page...

```
# Select whether you want to display summary plots after loading the filters
# and models selected above.
SummaryPlots = True
# SummaryPlots = False


# ============================================================================
# P-POP PHOTOMETRY
# ============================================================================

# Don't modify the following code.
Filters = []
for i in range(len(SVOids)):
    Filters += [SVO.getFilter(SVOids[i], SummaryPlots)]

PhotComp = PhotometryComputer.PhotometryComputer(PathPlanetTable,
                                                 Filters,
                                                 Sstar,
                                                 Splanet,
                                                 Unit,
                                                 Mission,
                                                 SummaryPlots)
PhotComp.Run()
```

Fig. 5. The script `P-pop_Photometry.py` which can be used to compute the photometry for a given planet population table.

Table 1. Content of the planet population table.

Header	Header (old)	Content	Unit
Nuniverse	nMC	Number of the universe to which the planet belongs to	–
Rp	Rp	Planet radius	$R_{\rm Earth}$
Porb	Porb	Planet orbital period	d
Mp	Mp	Planet mass	$M_{\rm Earth}$
ep	ecc	Planet orbital eccentricity	–
ip	inc	Planet orbital inclination	rad
Omegap	Omega	Planet longitude of ascending node	rad
omegap	omega	Planet argument of periapsis	rad
thetap	theta	Planet true anomaly	rad
Abond	Abond	Planet Bond albedo	–
AgeomVIS	AgeomVIS	Planet geometric albedo in the visible	–
AgeomMIR	AgeomMIR	Planet geometric albedo in the mid-infrared	–
z	zodis	Exozodiacal dust level	zodi
ap	a	Planet semi-major axis	au
rp	rp	Planet instantaneous separation	au
AngSep	ang_sep	Planet projected angular separation	arcsec
maxAngSep	max_ang_sep	Max planet projected angular separation	arcsec
Fp	Finc	Planet incident host star flux	$S_{\rm Earth}$
fp	f	Planet Lambertian reflectance	–
Tp	Tp	Planet equilibrium temperature	K
Nstar	nstar	Number of the star	–
Rs	Rs	Host star radius	$R_{\rm Sun}$
Ms	Ms	Host star mass	$M_{\rm Sun}$
Ts	Ts	Host star effective temperature	K
Ds	dist	Host star distance	pc
Stype	stype	Host star spectral type	–
RA	ra	Host star right ascension	deg
Dec	dec	Host star declination	deg
lGal	lGal	Host star galactic longitude	deg
bGal	bGal	Host star galactic latitude	deg
WDSsep	WDSsep	Binary star separation from WDS	au
name	name	Host star name from star catalog	–

```
"""
# ============================================================================
# P-pop
# A Monte-Carlo tool to simulate exoplanet populations
# ============================================================================
"""


# ============================================================================
# IMPORTS
# ============================================================================

import matplotlib.pyplot as plt
import numpy as np

import ReadPlanetPopulation as RPP


# ============================================================================
# SETUP
# ============================================================================

# Select the name of the planet population table to be read.
PathPlanetTable = 'TestPlanetPopulation.txt' # str

# Select a model for the computation of the habitable zone.
Model = 'MS'
# Model = 'POST-MS'

# Select the name of the photometry tables to be read and give a tag to each
# of them (leave empty if you don't want to read any photometry tables).
PathPhotometryTable = ['TestPlanetPopulation_MIRI.F560W.txt',
                       'TestPlanetPopulation_MIRI.F1000W.txt',
                       'TestPlanetPopulation_MIRI.F1500W.txt'] # list of str
Tag = ['F560W', 'F1000W', 'F1500W'] # list of str


# ============================================================================
# READ PLANET POPULATION
# ============================================================================

# The next five lines read the planet population table and its photometry.
PP = RPP.PlanetPopulation(PathPlanetTable)
PP.ComputeHZ(Model)
for i in range(len(PathPhotometryTable)):
    PP.appendPhotometry(PathPhotometryTable[i],
                        Tag[i])

print('Number of planets in the planet population table')
print(len(PP.Rp))

print('Planet radius (Rearth) of the first planet in the planet population table')
print(PP.Rp[0])

print('Host star radius (Rsun) of the first planet in the planet population table')
print(PP.Rs[0])

print('Display the header of the '+Tag[0]+' photometry')
print(PP.Phot[Tag[0]]['HEAD'])

print('Display the data of the '+Tag[0]+' photometry of the first planet in the planet
    population table')
for i in range(len(PP.Phot[Tag[0]]['HEAD'])):
    print(PP.Phot[Tag[0]]['HEAD'][i]+': '+str(PP.Phot[Tag[0]]['DATA'][i][0]))

import pdb; pdb.set_trace()
```

Fig. 6. The script `TestPlanetPopulation.py` which reads the test planet population table including its photometry.