Population synthesis of exoplanets

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Population synthesis in astrophysics

A population synthesis is a method of a direct modeling of relatively large populations of weakly interacting objects with non-trivial evolution. As a rule, the evolution of the objects is followed from their birth up to the present moment.

Evolutionary and Empirical

1. **Evolutionary PS.**
   The evolution is followed from some early stage. Typically, an artificial population is formed (especially, in Monte Carlo simulations)

2. **Empirical PS.**
   It is used, for example, to study integral properties (spectra) of unresolved populations. A library of spectra is used to predict integral properties.
Ingredients:
- initial condition
- evolutionary laws
Ingredients for planetary PS

1. The structure and evolution of the protoplanetary gas disk
2. The structure and evolution of the disk of solids (dust, pebbles, planetesimals)
3. The accretion of solids leading to the growth of the planetary solid core
4. The accretion of H/He leading to the growth of the planetary gaseous envelope
5. Orbital migration resulting from the exchange of angular momentum
6. N-body interaction among (proto)planets
In addition, initial positions of embryos is also a random parameter.
The first PS model for exoplanets

Authors modeled formation and migration (I&II) of exoplanets in order to reproduce so-called “desert” in mass-semi-major axis distribution (masses 10-100 Earth mass, and a<3 AU).

Main ingredients:

- Disk model;
- Accretion model;
- Migration model.

The rate of type I migration was significantly reduced to avoid rapid planet displacement.

Red- giants; green – rocky; blue – ice.

Ida, Lin astro-ph/0312144
Individual tracks

Green - rock
Red   - gas
Blue  - ice

\[ \tau_{\text{mig1}} = \frac{a}{\dot{a}} \]

\[ = \frac{1}{C_1} \frac{1}{3.81} \left( \frac{c_s}{a\Omega_K} \right)^2 \frac{M_*}{M_{\text{planet}}} \frac{M_*}{a^2\Sigma_g} \Omega_K^{-1} \]

\[ \simeq 1.5 \times 10^5 \frac{1}{C_1 f_g} \left( \frac{M_c}{M_\odot} \right)^{-1} \left( \frac{a}{1\text{AU}} \right) \]

\[ \times \left( \frac{M_*}{M_\odot} \right)^{3/2} \text{ yrs.} \]

\[ C_1 = 0.1; f_{d,0} = 2 \]

Ida, Lin 2013
Mordasini et al. published a series of papers (0904.2524, 0904.2542, 1101.0513, 1201.1036) on population synthesis of exoplanets, using an approach generally similar to the one by Ida, Lin.

Then this studies were continued in 1206.6103, 1206.3303, 1708.00868. A review is given in 1402.7086.

An important step is to include planet-planet interactions.

A separate subject is to follow long-term evolution.
Alternative variants of hot planets formation
Multi-embryo systems

20 planet embryos with $M=0.1M_{\text{Earth}}$
Mass growth
Mass growth of a single giant planet

Photoevaporation might be important
Peebles and gas accretion
Mass – semi-major axis distribution

Alibert et al. (2013)  
Ida, Lin (2013)

1402.7086
Mass distribution

Thick line – computations;

Thin line – bias-corrected data.

Normalization made for $1M_{\text{Jup}}$

It is still not absolutely clear, if the so-called “planetary desert” exist or not.
Comparison with observations

Observations

Calculations for observable planets
($P_{\text{orb}} < 10$ yrs; $v > 1$ m/s)

Ida, Lin (2013)

1402.7086, see arXiv:1905.0884 for detailed description of comparison methods
Metallicity effect

Solid line – all stars.
Dashed line – stars with at least one giant planet.
Dotted line – stars with at least low-mass planet.
Dependence on the stellar mass
Formation and evolution model allows to estimate the bulk composition of planets.
Mass-radius from data

1911.04745

1911.03582
Another population synthesis model

Simple model with analytical equations.

Model parameters are optimized to fit known data.

Single and four planet cases were studied.
Mass-distance distribution

- Initial Distance (AU)
- Final Mass (Earth = 1)
- Gas accretion
- Disk mass (solar)
- 3-10%
- 1-3%
- 0.3-1%
- 0.1-0.3%
- pebble isolation

- Mass (Earth = 1)
- Distance (AU)
- BD
- Jupiter
- Disk mass (solar)
- 1 m/s

1808.03293
Number of planets and SoSys analogues

Shows how the fit improves with growing number of planets
Role of more complicated migration models

Traps (regions of zero net torque) can slow planet migration (type I).

Traps can be related to peculiarities in density or/and temperature profiles. For example, an ice line can be such critical distance, at which planets are trapped.

Heat transition zone – is another trap. There viscous heating (inside) is changed by irradiation by the star (outer zone).

X-rays due to magnetospheric accretion and cosmic rays ionize the disk. Low ionization produces dead zones in the disk.
Another way to form planets

Gravitational instability in the outer parts of the disc.

Allows to form massive planets out to few tens AU.

 Might also work for brown dwarfs and very light stars.

$Q = \frac{c_s K_G}{\pi G \Sigma} < 1.5 - 1.7$

Some newer results in 1711.05948. See comparison of models in 1901.08089.
Tidal downsizing

Hypothesis by Nayakshin (2010). It is possible to make solid planets at low orbits.

\[ M = M_J = \frac{4\sqrt{2}\pi^3}{3G} \frac{Q^{1/2}c_s^2H}{(1 + \frac{2\pi}{\Sigma})} = \frac{4\sqrt{2}\pi^3}{3G} \frac{Q^{1/2}c_s^2H}{(1 + 4.47\sqrt{\alpha})} \]

**Fragment mass just after fragmentation**

\[ R_H = a_p \left( \frac{q}{3} \right)^{1/3} \]

**Hill radius becomes smaller as a planet migrates towards the star.**

Evolution of a fragment in a disc can result in appearance of a low-mass planet closer to the star, or in appearance of a belt of particles.
Initial and final semi-major axis distribution

45% survived
20% formed solid cores
Mass and semi-major axis distribution
Many brown dwarfs (and even low-mass stars for some parameters) can be produced via this channel.
Role of fragment-fragment interaction

Interaction off

Interaction on
Ejection

Many fragments are ejected. So, this mechanism of planet formation can be an important contributor to the population of free-floating planets and brown dwarfs.
System architecture

Brown – brown dwarfs; Red – gas giants; Blue – rocky (>50%).
Another example of population synthesis of planets formed by instability

Many uncertainties.

This picture summarizes all the models, calculated for different assumptions and parameters.
Population synthesis of satellites

Satellite mass distribution (7500 systems)

Survived satellites (20000 systems)
How to compare calculations with data

After calculations are made it is necessary to compare it with observational data.

For the case of transiting planets a special script was written.
Literature

• 1402.7086 Planet Population Synthesis. W. Benz et al.
• 1804.01532 Planetary population synthesis. C. Mordasini