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Simulating exoplanets in the Milky Way

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Abstract

To simulate a realistic Galactic exoplanet population, we combine a cosmological galaxy formation model tailored to the Milky Way with planetary formation models. We focus on the Solar Neighbourhood exoplanet population as a first step. We present the process of generating a synthetic exoplanet population, from a galactic simulation to the creation of planetary systems, going through the creation of a synthetic stellar population. We consider the stellar multiplicity and the relation between exoplanet occurrence rates and host-star properties. Kepler, PLATO, and other planet-hunting missions are searching for Earth-like exoplanets, which in certain cases could host liquid water and maybe life. From a Galactic evolution point of view, it is interesting to determine if this kind of exoplanet can exist or have existed everywhere in our Galaxy, or if they are preferentially found in certain regions of the Milky Way (the so-called Galactic Habitable Zone). We also provide preliminary statistics on the habitable Earth-like planets in the Solar Neighbourhood.

1 Introduction

Although the number of confirmed detected exoplanets has increased significantly over the past 30 years and now exceeds 5700[1], the observed exoplanet population suffers from a significant observational bias. Firstly, the detected population is restricted to the Solar Neighbourhood

[1]From the NASA Exoplanet Archive, 5766 confirmed exoplanet as of Oct 11, 2024.

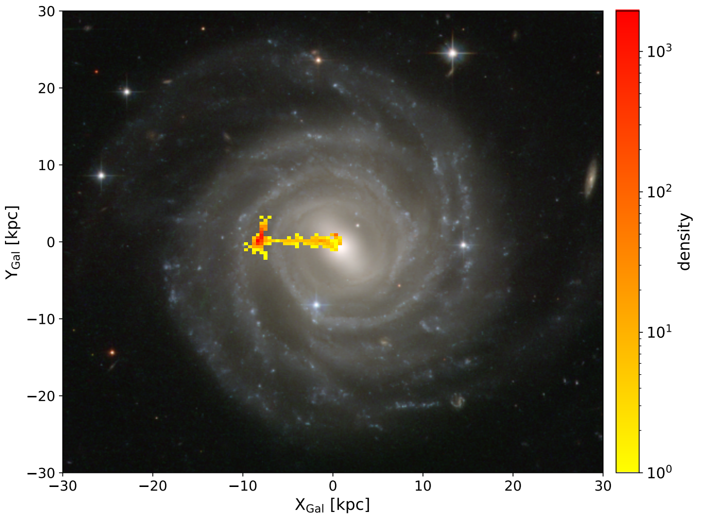

Figure 1: Illustration of the distribution of confirmed exoplanets in the Milky Way, using the galaxy UGC 12158 as a background. Credit of the original image: ESA/Hubble & NASA .

(see Fig. 1): 93% are at less than 2 kpc from the Sun, and less than 2% are more than 6 kpc away, so it may not be representative of the entire exoplanet population of the Milky Way (MW). Secondly, the confirmed population contains an over-representation of massive planets orbiting close to their host star, called "Hot Jupiters" (HJ), and lacks smaller planets more similar to the Earth. This bias is well explained by the employed detection methods (e.g. see [3], [18]) and results in an incomplete and biased exoplanet population.

It has been shown that the occurrence rate of planets is related to the star's properties, like its mass ([6]) or its chemical composition (e.g. [8], [16]). From a Galactic point of view, it is known that stars are not homogeneously distributed in the MW. Firstly in density, the concentration of stars is much higher in the inner Galaxy and decreases exponentially with the distance to the Galactic centre (e.g. [2], [19]). Secondly, the age and chemical composition of stars are also dependent on the distance to the Galactic Centre. The existence of a pronounced negative metallicity gradient of around −0.06 dex/kpc (for young stars, less pronounced for older ones; e.g. [10], [1]) leads to an average stellar metallicity decreasing with increasing Galactocentric distance.

To date, the distribution of exoplanets in the MW remains a poorly explored field: it is still unknown whether their distribution is significantly impacted by Galactic evolution processes like the radial migration of stars. In order to study the impact of Galactic evolution on the exoplanet population, we first need to simulate this population and verify that we are able to generate a realistic sample. In this work, we resume the entire exoplanet generation process, from the galactic simulation to the planetary systems creation. In Section 2 we present the galactic simulation we used to mimic the Milky Way and how we obtained a realistic stellar population from it. In Section 3 we detail the creation of the synthetic exoplanet population and some preliminary results are discussed in Section 4.

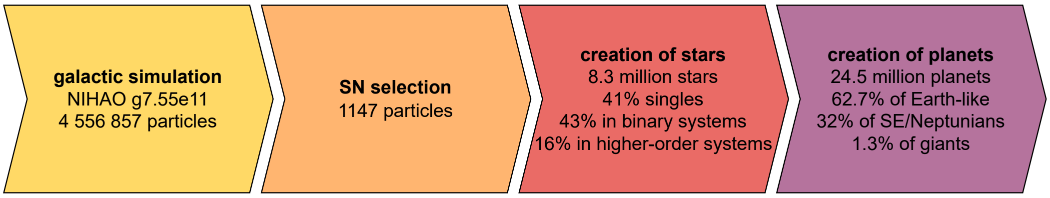

Figure 2: Summary of the developed framework to generate the exoplanet population in the Solar Neighbourhood from a galactic simulation.

2 Galactic simulation and creation of stars

To simulate the exoplanet population in the Milky Way we need a galactic simulation that reproduces the main properties of our Galaxy. For this work, we use the last snapshot of the simulation g7.55e11, taken from the NIHAO-UHD suite of cosmological hydro-dynamical simulations from [5]. We chose this simulation because it has similar properties to the MW, like a similar total stellar mass and a similar metallicity gradient. We use the stellar component of the simulation, constituted by 4 556 857 "stellar particles". Each stellar particle has an associated metallicity, total stellar mass, age, actual position and velocities as well as birth position. The mean stellar mass of the particles is around 5 700 $M_\odot$. As a first step and to be able to compare with actual observations, we focus on the Solar Neighbourhood region in the galactic simulation. We select a region of about 1 kpc^3 around the Galactic position of the Sun (we assumed $R_{Gal} \simeq 8.1$ kpc, [4]) and obtain 1147 stellar particles.

From the stellar particles, we generate a synthetic stellar population, sampling masses following the IMF proposed by [15]. We keep only FGKM-type stars because although OBA stars can host exoplanets (e.g. [12], [13], [9]), we are lacking confirmed observations. We then arrange those stars in stellar systems of one, two or more stars, following the multiplicity fraction derived by [17] as a function of the stellar mass. We obtain 3.4 million single stars, 3.6 million stars in binary systems and 1.3 million in higher-order systems. Those steps and results are summarized in Figure 2.

As predicted and confirmed (e.g. [20]), exoplanets can orbit a binary system or one star in a multiple system. However, given the small number of confirmed cases currently available, as a first approximation, we are considering only exoplanets orbiting single stars.

3 Synthetic exoplanet population

We aim to generate an unbiased exoplanet population. In order to correct the observational bias we combine observational data with results of a planetesimal accretion synthesis model from [7]. We fit the distribution in mass and orbital period of detected exoplanets to describe the distribution of giants (Hot Jupiters and Cold Jupiters) and Super-Earth/Neptunian planets. From the planetary formation model we fit the distribution obtained for Earth-like planets (see Fig. 13 from [7]). The bi-variate Gaussian distributions derived from both observation and models are plotted in the left panel of Fig. 3.

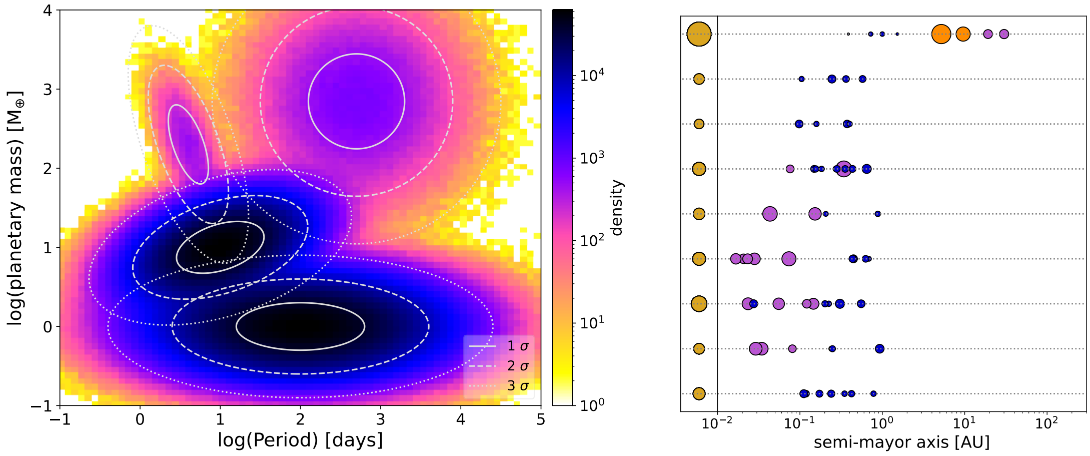

Figure 3: Left panel shows the density distribution in mass and orbital period of the 24.5 million generated exoplanets. The grey lines represent the 4 bi-variate gaussian distributions combined to obtain this distribution. Right panel: Random sample of the generated planetary systems. The top line represent the Solar System as reference. Left part represent the host stars, the right part the planets color-coded by type with in blue the Earth-like planets, in purple the SE/Neptunian planets and in orange the Giant planets.

To generate an exoplanet population in the galactic simulation we assign to each single star a number of planets. First, we determine their probability of harbouring at least one planet of each planet category we consider in this study: Earth-like planets, Super-Earth (SE)/Neptunian planets and Giant planets. To do so, we combine the occurrence rates of these different categories as a function of the stellar mass ([6]) and the metallicity ([16]).

In the Solar Neighbourhood region, we obtain a population of 24.5 million planets distributed in 3.1 million planetary systems (see right panel of Fig. 3 for a random sample of planetary systems we obtained). Among those planets, 62.7% are Earth-like planets, 36% SE or Neptunian planets and 1.3% Giant planets, as resumed in Fig. 4's right panel.

4 Preliminary results

Considering the Early Mars and Recent Venus limits of the Habitable Zone (HZ) of a star from [14], we obtain that 22.5% of our exoplanet sample belong to their host-star HZ, or 24.7% of the Earth-like/Super-Earth planets. We consider all planets to have circular orbits. In Fig. 4 (left panel) we obtain a distribution in agreement with the observational data for the well-sampled regime of inner (mostly giant) planets but with a strongly different density distribution at larger radii and for smaller stars, which are still heavily underrepresented in the present-day exoplanet census. The fraction of planets predicted in the HZ is quite more important than in the observed population, in which only $\sim 7\%$ of the planets lay in the HZ (from [11], considering as belonging to the HZ all exoplanets at least crossing the Optimistic HZ they define).

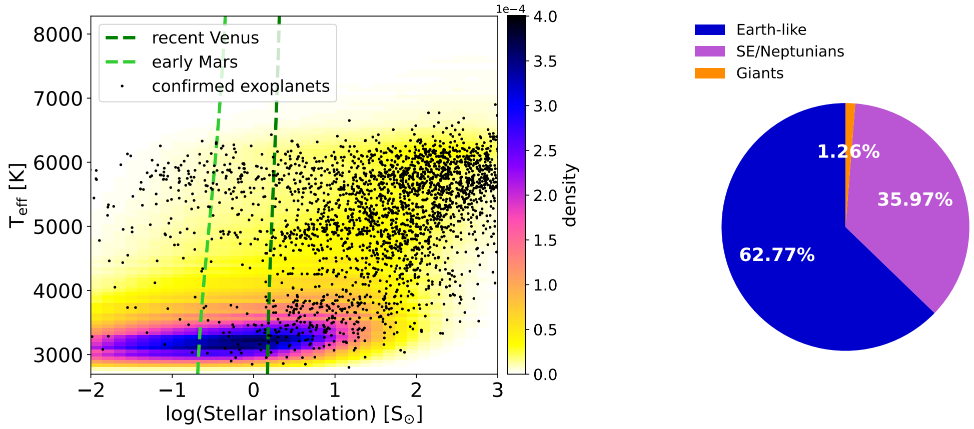

Figure 4: Left panel: Host star effective temperature compared to the instellation received by the exoplanet. The density distribution shows the synthetic exoplanet population we simulated in the Solar Neighbourhood. Black dots are observed exoplanet from the NASA Exoplanet Archive. Right panel: Fraction of each planet type in the generated exoplanet population. We obtain around 2 third of Earth-like planets, almost absent from the observed population.

This difference can be explained by the observational difficulties of detecting low-mass exoplanets close to their host star. Also, there are few observed exoplanets around M-type stars (most confirmed exoplanets orbit F- or G-type stars) while the majority of the synthetic exoplanet population orbit M-type stars, and therefore the majority of our planets predicted in the HZ.

5 Conclusion and future work

We study the exoplanet population from a Galactic point of view. To this end, we developed a framework to generate a synthetic exoplanet population in a galactic simulation reproducing the Milky Way's main characteristics. As a first step, we focused on the region corresponding to the Solar Neighbourhood. After creating a stellar population, including multiple systems, we assigned them a number of planets of different types, organised in planetary systems. Combining observational data with planetary formation models we predict a fraction of 22% of exoplanets belonging to their host star's HZ, more than 3 times higher than the observed fraction.

To continue this work, we will first improve the exoplanet simulation by generating planets in binary systems, adding an eccentricity distribution in the exoplanet population, and by comparing different planetary formation models. We will also apply the exoplanet generation process to other regions of the simulated galaxy, as well as to other galactic simulations to compare the obtained results.

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