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Reproducing the Architecture of TRAPPIST-1 using Global Formation and Evolution Models

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Abstract

The, so far, unique and well constrained TRAPPIST-1 system can be exploited for testing planet formation theories. Because of observational biases, terrestrial planet formation models will, for the next decade, only be testable around low mass stars, showing the need for research in this area. We invoke the Bern model of global planet formation and evolution to conduct population syntheses for 0.1 $M_\odot$ stars and compare the wealth of systems to the TRAPPIST-1 system, finding reasonable consensus for many observables. However, compositions differ significantly.

1 Introduction

Since the discoveries of the first three [7] and later of at least four more [8] planets in the TRAPPIST-1 (T1) system, planet formation theories are challenged by the compactness of the system and the not well studied regime of low mass stars (0.08 $M_\odot$). A universal model of planet formation should be extendable to all regimes. Especially crucial is the extension to late-type stars because the detection probability of the prevalent techniques scales with the mass or radius ratio of the planet and its host star. Thus, the extreme case of T1 is an important benchmark case in terms of how processes are scaling with the stellar mass.

It is generally not expected for giant planets to form around very low mass stars. Therefore, the formation of the T1 system is mainly dependent on the assumed solid accretion and migration model and is not masked by the influence of giant gaseous planets, thus serving as a reference for those processes.

Especially challenging for formation models, even though not well constrained, are the compositions inferred from TTV-masses and the transit radii shown in Grimm et al. [9]. The variability in terms of composition could point to different formation locations, without, however, showing the typical gradient towards more volatile rich compositions with increasing orbital period. We resolve which system-wide compositional features can possibly be inherited from formation.

In contrast to the qualitative study by Ormel et al. [13] that proposes a possible pathway to form compact systems in the pebble accretion scenario, we focus on the planetesimal accretion model and perform quantitative calculations using the classical formation route.

Planet formation models in general are highly dependent on the disk initial conditions and the placement of seeds or embryos. In the population synthesis framework [4, 12], the initial conditions are randomized according to probability distributions suggested by observations of protoplanetary disks [10]. Drawing from this set of initial conditions, we first run our planet formation code for a generic 0.1 $M_\odot$ star. We then develop a criterion for similarity and apply it to search for systems resembling T1.

2 Methods

Our planet formation models are based on the models of Alibert et al. [1], adapted to the case of low mass stars. The models [1, 6, 12] include: an $\alpha = 10^{-3}$ viscous protoplanetary disk with irradiation of the star, type I and II orbital migration of the planets [5], accretion of planetesimals [6], solution of the spherically symmetric internal structure equations of the planets to obtain their gas accretion rate, planetary radius calculation based on the core composition [11], the N-body interaction between the forming (proto-) planets [1] and the evolution over time of the central star [3].

The models are computed for a 0.1 $M_\odot$ central star, which influences a number of processes and features, including the disk structure, the planetary radius during the nebular phase due to the changed Hill radius, migration timescales and the disk mass. Since we consider planets located very close to their parent star, the disk extends down to 0.01 AU in our models.

The initial disk profiles of the 1000 planetary system simulations follow the ones already used in [1], i.e. a power law disk with exponent $\gamma = 0.9$ with an exponential cutoff radius a_C. The total disk mass distribution is derived from observations [2], but it is scaled down compared to the one for solar-type stars following a linear scaling law $M_\mathrm{disk} \propto M_\mathrm{star}$, which in turn scales $a_\mathrm{C} \propto M_\mathrm{disk}^{5/8}$ [2].

To account for small body drift, we use a steeper slope $\gamma_\mathrm{p} = 1.5$ and a lower cutoff radius $a_\mathrm{C,p} = 0.5 a_\mathrm{C}$ for the planetesimal disk than for the gas disk.

The disk lifetime is assumed not to depend on the mass of the central star, we use a mean lifetime of 3 Myr.

We assume that 50 proto-planets grow in the same protoplanetary disk, starting after 200 kyr in which planetesimals had time to form. The initial mass of the planetary embryos is 0.01 $M_\oplus$, and the initial location of each is drawn from a log-uniform distribution within 0.02 AU and 10 AU.

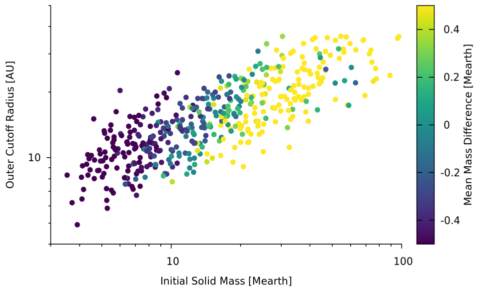

Figure 1: Initial conditions of systems with the mean mass of the synthetic system minus the mean mass of TRAPPIST-1 as color code. Considered were only synthetic planets with masses above 0.1 $M_\oplus$ and semi-major axes lower than 0.1 AU.

3 Results and Conclusions

We compare our synthetic planetary systems to T1 using different measures and find that many features of the T1 systems can be reproduced. We found similar mean motion resonances, mean masses and semi-major axes. For the mean mass, we find a region in initial solid mass and disk dimension that is favorable for the formation of a system similar to T1 (figure 1). This region of the parameter space partially overlaps with favorable regions in terms of other measures. However, the ice mass fraction in the synthetic planets is generally higher than the one inferred from TTV masses for the actual T1 planets [9] due to migration from regions outside the snowline. Matching the ice fractions seems to need fine-tuning of the model or consideration of additional processes, such as a low ice fraction outside the snow line or desiccation of planetesimals by a different heat source.

Acknowledgements

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