Analysis of multiplanetary system population synthesis

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European Research Council
Established by the European Commission

Abstract

Planet formation models have been developed during the past years in order to reproduce and predict observations of the solar system and extrasolar planets. Using a modular planetary system formation model combining an extended core-accretion model including migration, disc evolution and gap formation with an N-Body part for the dynamical interactions we perform population synthesis calculations in order to investigate the effect of the formation of more than one planet in the same protoplanetary disc. We show the modifications of masses, semi-major axes and period ratios through competition and gravitational interactions varying the number of forming planets.

Introduction

In the past 25 years, more than 4000 exoplanet candidates have been detected, already leading to more than 1800 confirmed planets [1], many of which are in multiplanetary systems. In order to understand the formation of these, planet formation models have been developed. For the formation of multiplanetary systems, models describing the formation process of individual planets have to be coupled with the effects caused by the interaction of several planets, among which are:

- Competition for the accretion of gas and solids.
- Perturbation of planetesimals affecting the accretion through solids density waves.
- Gravitational interaction between forming planets modifying the migration and leading to resonant systems.
- Collisions and ejections of planets.
- Modified gap formation and merging of neighbouring gaps.

The 'Bern' model

The 'Bern' model is a modular planetary system formation model combining the initial planet-formation model of Alibert et al. (2005) [2] based on the core-accretion theory by Pollack et al. (1996) [3] with parts that take care of

- migration,
- disc evolution,
- gap formation,
- the calculation of population synthesis (Mordasini et al., 2009a,b) [4, 5], and
- planetesimal accretion rates (Fortier et al., 2013) [6] with
- an N-body module for the dynamical interactions (Alibert et al., 2013) [7].

Presently the model cannot calculate the formation of the embryos from dust but starts by placing moon mass embryos into the protoplanetary disc.

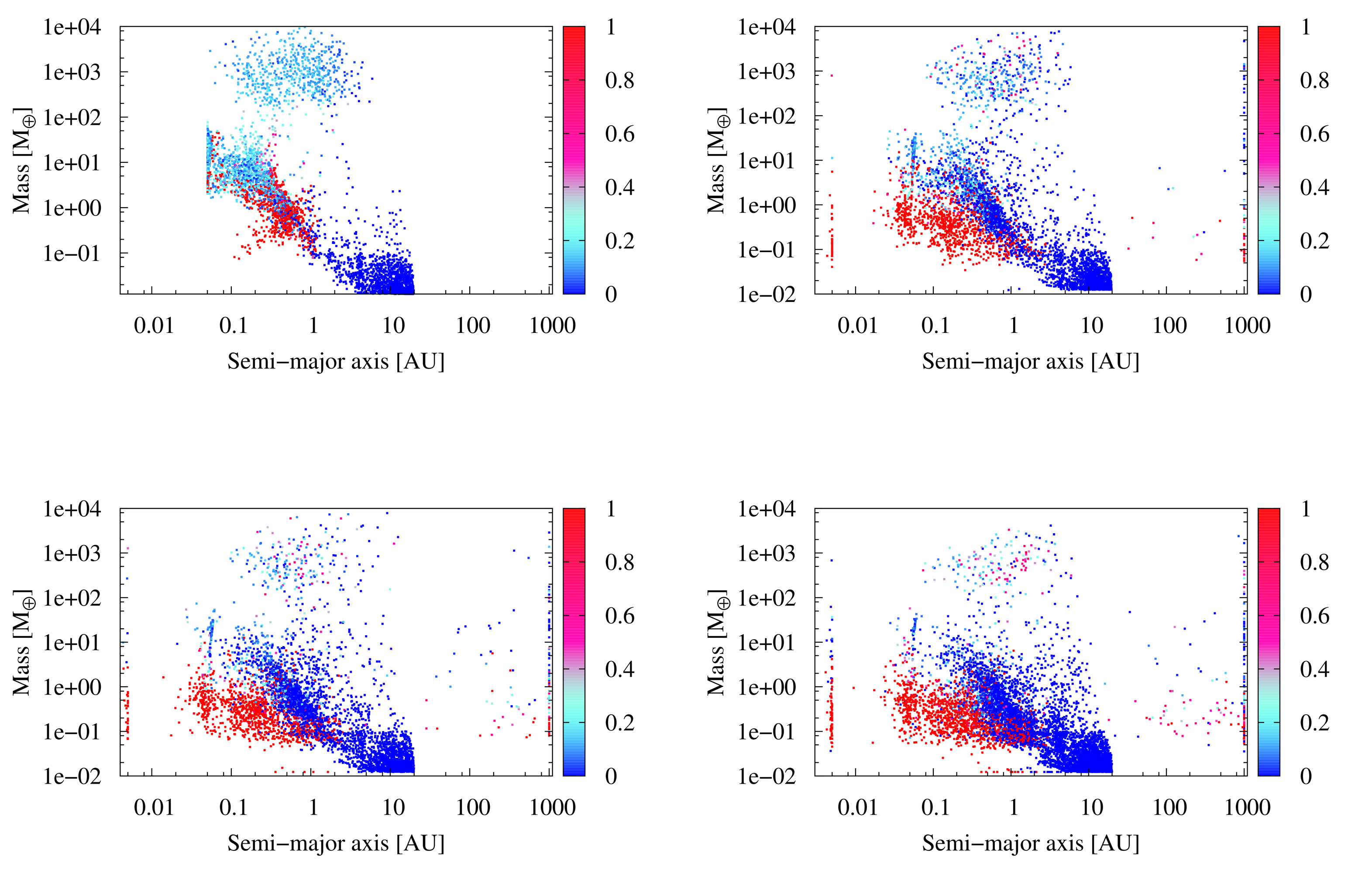

Figure 1: Mass *vs* semi-major axis diagrams for populations of planets. The colour code shows the fraction of rocky planetesimals accreted by the planet, where planets with a core formed through accretion of rocky planetesimals are in red and through accretion of icy planetesimals are in blue. The number of planets assumed to be formed per disc is one (*top left*, 4936 points), five (*top right*, 4875 points), ten (*bottom left*, 5010 points), and twenty (*bottom right*, 5000 points). Planets in the vertical line at 0.05 AU are planets that reached the inner boundary of the computed disc which can presently only be crossed through N-body interactions, whereas planets at 0.005 are assumed to have collided with the star.

Effects of multiplicity

Considering the effects caused by the interactions of several planets forming in the same disc we conducted a number of population synthesis calculations only varying the number of planets forming in each disc. Figures 1 and 2 show the end results for simulations starting with one, two (only Fig. 2), five, ten and twenty embryos per disc. In order to ease the comparison the number of simulations was decreased accordingly to consider a similar amount of planets (ca. 5000) for each population synthesis.

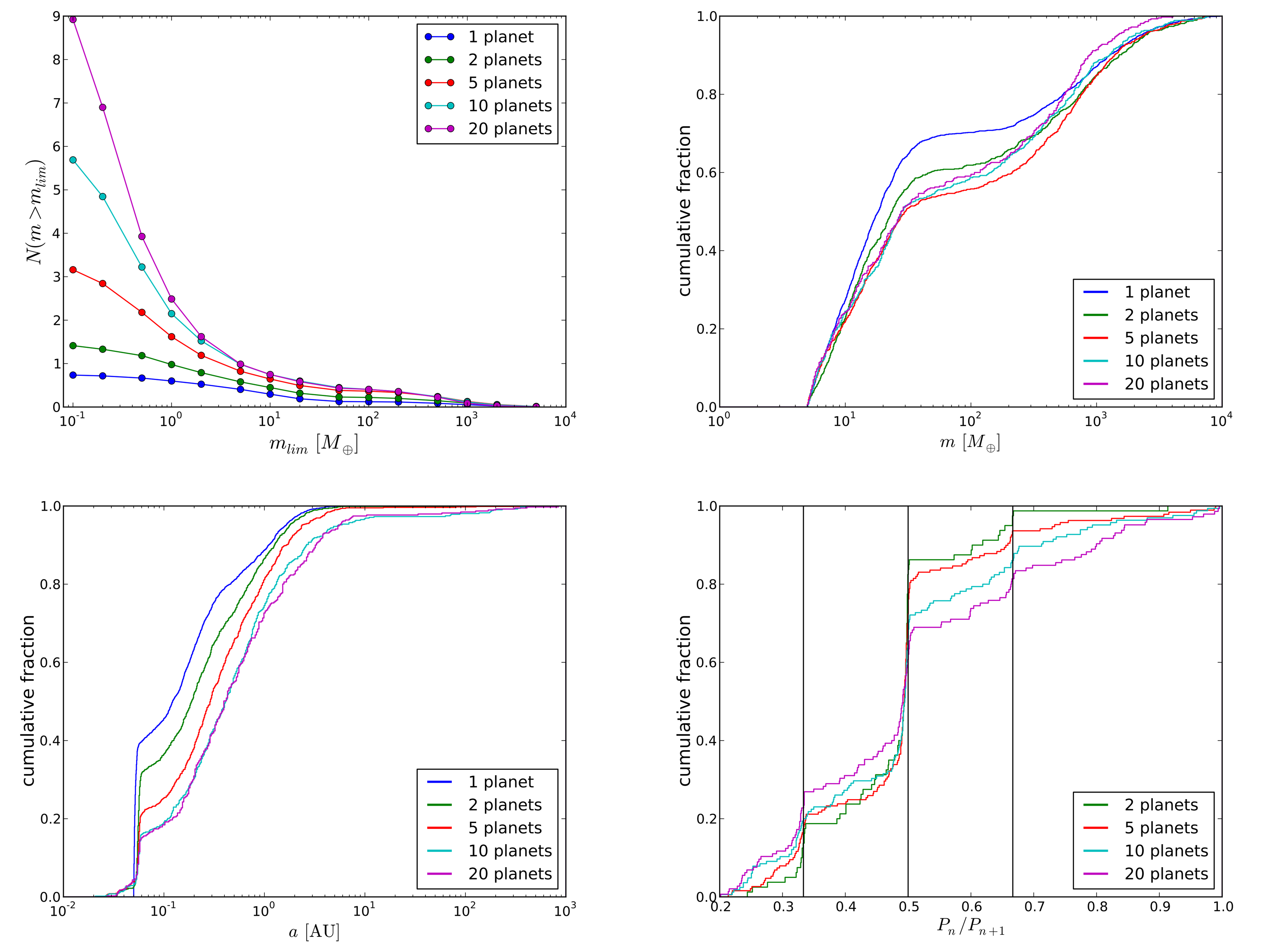

Figure 2: *Top left:* Average number of planets per system that are more massive than a given value. *Top right:* Cumulative mass function, considering only planets more massive than $5\,M_\oplus$ still present in the system at the end of the simulation (planets colliding with the central star or ejected are not considered). *Bottom left:* Cumulative distribution of semi-major axes for the same population as in the top right panel. *Bottom right:* Cumulative period ratios of all adjacent pairs of planets more massive than $5\,M_\oplus$. The vertical lines show the location of the most important mean-motion resonances.

Conclusions

The extension of our planet formation model to include the formation of planetary systems shows that the different number of planets forming simultaneously can result in very important modifications in the overall result of the formation process. In particular, gravitational interactions result in significant changes in the final mass and semi-major axis:

- The sub-populations of massive planets are affected less by the interactions, yet an increasing number of planets forming simultaneously leads to slightly lower masses. The growth of planets is delayed by the competition for the accretion of solids.
- The more planets are forming simultaneously the higher are the distances of the more massive planets from the star. On one hand this is caused by the delayed development and on the other hand by the increased interactions.
- A sub-population of close-in Earth- to Super-Earth mass planets appears when interactions between planets are considered. These are pushed inwards by gravitational interactions. (See also the close-in tail for all but the one-planet case in the bottom left panel of Fig. 2, where planets are pushed over the inner disc boundary.)
- The curves for the average number of planets per system that are more massive than a given value converge for higher masses (roughly $> 20\,M_\oplus$).
- Additionally the cumulative distributions of semi-major axes and masses converge for a higher number of embryos.
- The number of mean-motion resonances decreases with the increasing number of planets per systems.

References

[7] Alibert, Y., Carron, F., Fortier, A., et al. 2013, *A&A*, 558, A109
[2] Alibert, Y., Mordasini, C., Benz, W. & Winisdoerffer, C. 2005, *A&A*, 434, 343
[6] Fortier, A., Alibert, Y., Carron, F., Benz, W., & Dittkrist, K.-M. 2013, *A&A*, 549, A44
[4] Mordasini, C., Alibert, Y., & Benz, W. 2009a, *A&A*, 501, 1139
[5] Mordasini, C., Alibert, Y., Benz, W., & Naef, D. 2009b, *A&A*, 501, 1161
[3] Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, *Icarus*, 124, 62
[1] Schneider, J., Dedieu, C., Le Sidaner, P., Savalle, R. & Zolotukhin, I. 2011, *A&A*, 532, A79

Acknowledgments

This work was supported by the European Research Council under grant 239605, the Swiss National Science Foundation, and the Alexander von Humboldt Foundation.