国立天文台天文シミュレーションプロジェクト成果報告書

Terrestrial planet formation and delivery of water/volatiles

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I performed hundreds of computer simulations to better understand the planetesimal disk conditions that formed the four terrestrial planets in the solar system. In particular, I investigated terrestrial planet formation by testing the influence of the disk mass and disk spatial structure, the orbital architecture of the Jupiter and Saturn, the source region and delivery of water to the terrestrial planets during their formation, and other parameters.

As explained in the PC cluster application for H29, to achieve the two main goals of 1) consistent formation of the four terrestrial planets, and 2) understanding the origin of water and organics delivered to these planets, the expected total time for the conclusion of this project is approximately 2 years. All the simulations finished by the end of the H29 calendar. Although I have already produced the auxiliary codes needed to extract the desired output data for analysis of the results, analysing the tons of data produced by simulations is going to take at least a whole year in the H30 calendar (as expected for a 2-yr project). Also, considering I am on a parental leave since April 1st 2018, I have not been able yet to perform a detailed analysis that is necessary to summarize the main results into scientific papers. The analysis of water/organics delivery to the formed terrestrial planets is also missing here.

Taking these facts in mind, the following results are preliminary and are in need of a deeper analysis. They also comprise only the formed planets in the systems whose simulations finished earlier during H29. So, the following results do not represent yet all the parameters tested in this project.

- The following disk properties tend to produce systems containing planets that could reproduce the terrestrial planets in terms of orbits and masses:
  - mass distribution described by $r = 1, 4$, where r represents the ratio of disk mass distributed between embryos and planetesimals at the beginning of the simulations;
  - embryos/planetesimals concentrated at $a = 0.7$–1.0 au in orbitally compact disks, rather than 0.7–1.2 au or more extended disks;
  - Jupiter and Saturn placed on more excited orbits ($e \sim 0.05$–0.1), rather than on near circular orbits ($e \sim 0$).
- The only Grand Tack disk setup with potential to reproduce the terrestrial planets had

mass concentration at 0.7–1.0 au and $r = 4$. The other setups with mass concentration 0.7–1.2 au and/or $r = 1$, 8 yielded systems inconsistent with the solar system terrestrial planets.

- The formation of Mercury analogs considering both masses and orbits may require the existence of a mass depleted inner region inside 0.7 au. Given the great difficulty in probing this region and consistently forming a very small Mercury well separated from Venus, it is the formation of Mercury (rather than that of Mars) that offers the best constraints for any model that aims at reproducing the terrestrial planets in terms of their orbits, masses, and other key properties.
- The orbital spacing of the terrestrial planets and Ceres may require a mass depleted component beyond 1.0 au, as Ceres-like objects tend to remain in the systems that formed from disks that contained initially very small embryos in that farther region.

These results were summarized in a poster presented at the wakuseigakkai 2017. Although these results are preliminary, they can provide very important new constraints on terrestrial planet formation. Our simulations also suggest that the formation of Mercury and Mars analogs should be considered consistently, not separately as commonly seen in the literature. Indeed, forming the four terrestrial planets simultaneously remains a tremendous challenge, but fortunately some of our simulations have yielded quite similar systems! For this reason, further data analysis have the potential to reveal systems that could satisfy that goal for the first time in planetary sciences.

Thank you for the opportunity to use the General Purpose PC cluster to pursue this (ongoing) project!