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 in the framework of the depleted disk model

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Background

To date, there are many dynamical models available in the literature to study the formation process of the terrestrial planets. With specific initial conditions, most of these models claim to be able to reproduce the mass distance relationship of the terrestrial planets, and sometimes additional dynamical properties. However, given the fact that these models call for different processes in the protoplanetary disc, they cannot all be true at the same time. It is therefore imperative to test and distinguish between them using new constraints and a different approach.

There is abundant data from cosmochemistry that, combined with the dynamics, could offer us a fresh perspective. High-precision measurements of isotopic anomalies in meteorites reveal dissimilarity in the isotopic composition of the Earth and Mars, indicating that, to a first approximation, they are not made up of the same building materials. Using numerical simulations, the feeding zones and the isotopic compositions of the terrestrial planets can be computed by means of tracking the materials that went into each planet. By comparing the results of the models with the data, we will be able to identify models that better explain the formation process of the terrestrial planets and rule out those that do not.

Approach

Building on the results of previous works to identify a model that is consistent with the data, we tested a fairly new and unexplored dynamical model—the depleted disc model—in this work. We have performed 144 simulations to study the evolution of a system of embryos and planetesimals to fully-grown terrestrial planets. The simulations were run for a total of 154 Myr with the first 4 Myr including the effects of a gas disc.

Results

We find that, in the framework of this model, the terrestrial planets accrete material mostly locally and have distinct feeding zones. This means that Earth and Mars can be isotopically distinct if there is an isotopic gradient in the inner protoplanetary disc where the planets sourced their building blocks from. Our results imply that the terrestrial planets likely accreted material from the vicinity of their current orbits and the material was not thoroughly mixed during the accretion process.

Conference participation

Name of meeting: Solar System Symposium in Sapporo 2020

Meeting website: https://3s2020.webnode.com/general-information/

Date: 17 - 19 Feb 2020

Type of presentation: Oral

Abstract: Combining isotopic constraints from meteorite data with dynamical models of planet formation proves to be advantageous in identifying the best model for terrestrial planet formation. Prior studies have shown that the probability of reproducing the distinct isotopic compositions of the Earth and Mars for both classical and Grand Tack models is very low. For Mars to be isotopically different from the Earth, it had to form under very specific conditions in the framework of the Grand Tack model. The depleted disc model is an alternative to the Grand Tack model for the formation of Mars with the correct mass without relying on the migration of the gas giants. It presupposes that the region in the inner protoplanetary disc from Mars' orbit and beyond is depleted in mass such that Mars is left with insufficient material to grow to much larger sizes. The reason for the depletion is left unspecified and requires further investigation. Our aim is to test the predictions of this model on the isotopic compositions of the terrestrial planets, and determine if the predictions for Earth and Mars' compositions are consistent with them potentially being a mixture of various meteorites. We employed N-body simulations to integrate the evolution of a system of planetary embryos and planetesimals for 154 Myr, with the first 4 Myr including the effects of a dissipating gas disc. The successful terrestrial planet analogues formed at the end of the simulations had their accretion histories tracked to compute their feeding zones, i.e., the region from where they sourced their building blocks. We found that the terrestrial planets accrete mostly locally in the framework of the depleted disc model and thus can have distinct isotopic compositions if there is a gradient in isotopic composition of the materials in the feeding zones of the terrestrial planets. This is in contrast to the Grand Tack model where the feeding zones are nearly identical due to mixing of the materials by Jupiter's migration. Despite the rather ad-hoc requirement for the mass depletion in the depleted disc model, its predictions for the isotopic compositions of the Earth and Mars show a trend with meteorite data. This suggests that the materials in the inner Solar System most likely did not undergo substantial mixing that homogenised the potential isotopic gradient.

Journal publication

A manuscript regarding the above work has been submitted for review in *Icarus*.