Dynamical and chemical modeling of terrestrial planet accretion

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The "Grand Tack" dynamical model

The classic dynamical models of terrestrial planet formation, starting from a disk of planetesimals extended from the Sun to the current orbit of Jupiter, typically produce in ~ 100 Ma a few planets in the terrestrial zone on orbits comparable to the real ones [1], but the synthetic planets located near 1.5 AU are systematically more massive than Mars. The large Earth/Mars mass ratio seems to require a strong depletion of solid mass beyond ~1 AU [2]. The "Grand Tack" model [3] explains such a depletion by coupling the early orbital migration of the giant planets with the terrestrial planets accretion process. More precisely, the model assumes that, when the giant planets formed in a proto-planetary disk still dominated by gas, Jupiter first migrated towards the Sun and then, as a consequence of the formation of Saturn, reversed its migration and spiralled outwards. This possibility is supported by hydro-dynamical simulations [4]. If the reversal (or tack) of Jupiter's migration occurred when the planet was at ~ 1.5 AU, the region beyond 1 AU would have been strongly depleted by the passage of Jupiter. The simulations in [3] show that this model is consistent with the existence and the structure of the asteroid belt between 2 and 4 AU, it produces in 30-50 Ma terrestrial planets on orbits consistent with the real ones and, in particular, it explains why Mars is 10 times smaller than the Earth and formed 10 times faster [5]. Thus, the Grand Tack model is so far the most successful model of terrestrial planet formation from the dynamical point of view.

Chemical modelling

To test the Grand Tack model further, we are now applying geochemical constraints. The model is consistent with the delivery of 2000 ppm of water to the Earth from planetesimals of chondritic composition, which agrees with recent estimates of the Earth's water budget and its isotopic composition [6]. Moreover, we are modeling core-mantle differentiation [7] using the accretion history of the planets obtained in the Grand Tack simulations. Assuming that the material originally inside ~1.5 AU had a reduced composition and that beyond this threshold was oxidized, our chemical models result in a FeO content of 8 wt% for the Earth's mantle and ~18 wt% for the Martian mantle, results that are consistent with observed concentrations [8,9]. In the future we will extend our analysis to include more elements (e.g. sulphur, volatile elements, HSEs and water) and we will use more than two initial bulk compositions for accreting material.

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