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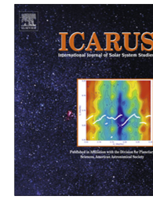

Accretion and differentiation of the terrestrial planets with implications for the compositions of early-formed Solar System bodies and accretion of water

D.C. Rubie [a,*], S.A. Jacobson [a,b], A. Morbidelli [b], D.P. O'Brien [c], E.D. Young [d], J. de Vries [a], F. Nimmo [e], H. Palme [f], D.J. Frost [a]

[a] Bayerisches Geoinstitut, University of Bayreuth, D-95490 Bayreuth, Germany
[b] Laboratoire Lagrange, Universite' de Nice - Sophia Antipolis, Observatoire de la Cote d'Azur, CNRS, 06304 Nice, France
[c] Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85719, USA
[d] Dept. of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095, USA
[e] Dept. of Earth & Planetary Sciences, UC Santa Cruz, CA 95064, USA
[f] Forschungsinstitut und Naturmuseum Senckenberg, 60325 Frankfurt am Main, Germany

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In order to test accretion simulations as well as planetary differentiation scenarios, we have integrated a multistage core–mantle differentiation model with N-body accretion simulations. Impacts between embryos and planetesimals are considered to result in magma ocean formation and episodes of core formation. The core formation model combines rigorous chemical mass balance with metal–silicate element partitioning data and requires that the bulk compositions of all starting embryos and planetesimals are defined as a function of their heliocentric distances of origin. To do this, we assume that non-volatile elements are present in Solar System (CI) relative abundances in all bodies and that oxygen and H_2O contents are the main compositional variables. The primary constraint on the combined model is the composition of the Earth's primitive mantle. In addition, we aim to reproduce the composition of the martian mantle and the mass fractions of the metallic cores of Earth and Mars. The model is refined by least squares minimization with up to five fitting parameters that consist of the metal–silicate equilibration pressure and 1–4 parameters that define the starting compositions of primitive bodies. This integrated model has been applied to six Grand Tack N-body accretion simulations. Investigations of a broad parameter space indicate that: (1) accretion of Earth was heterogeneous, (2) metal–silicate equilibration pressures increase as accretion progresses and are, on average, 60–70% of core–mantle boundary pressures at the time of each impact, and (3) a large fraction (70–100%) of the metal of impactor cores equilibrates with a small fraction of the silicate mantles of proto-planets during each core formation event. Results are highly sensitive to the compositional model for the primitive starting bodies and several accretion/core-formation models can thus be excluded. Acceptable fits to the Earth's mantle composition are obtained only when bodies that originated close to the Sun, at <0.9–1.2 AU, are highly reduced and those from beyond this distance are increasingly oxidized. Reasonable concentrations of H_2O in Earth's mantle are obtained when bodies originating from beyond 6–7 AU contain 20 wt% water ice (icy bodies that originated between the snow line and this distance did not contribute to Earth's accretion because they were swept up by Jupiter and Saturn). In the six models examined, water is added to the Earth mainly after 60–80% of its final mass has accreted. The compositional evolution of the mantles of Venus and Mars are also constrained by the model. The FeO content of the martian mantle depends critically on the heliocentric distance at which the Mars-forming embryo originated. Finally, the Earth's core is predicted to contain 8–9 wt% silicon, 2–4 wt% oxygen and 10–60 ppm hydrogen, whereas the martian core is predicted to contain low concentrations (<1 wt%) of Si and O.

* Corresponding author.
E-mail address: dave.rubie@uni-bayreuth.de (D.C. Rubie).

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1. Introduction

It is widely recognized that the four terrestrial planets of our Solar System, Mercury, Venus, Earth and Mars, formed over a time period on the order of up to 100 Myr (e.g. Jacobson et al., 2014). According to current astrophysical theories, these planets formed in three stages: (1) planetesimal formation. During this stage, dust condensed from the solar nebula, a disk of gas and dust rotating around the growing Sun, settled to the midplane of the disk and coagulated to form km- to multi-km-size solid planetesimals. (2) Planetary embryo formation. In a disk of planetesimals, the largest bodies grow fastest due to gravitationally enhanced mutual collisions creating a population of embryos (Greenberg et al., 1978). By the end of this stage, a population of oligarchic planetary embryos, lunar to Mars-mass objects, has emerged amongst the swarm of remnant planetesimals (Kokubo and Ida, 1998). (3) Planet formation. The final stage of accretion was dominated by the mutual gravitational interactions of the embryos and was characterized by large, violent collisions (e.g. Benz et al., 1989). In recent years, there has been significant progress in modelling this giant impact stage. For example, the numerical *N-body accretion* simulations of O'Brien et al. (2006), starting with embryos and planetesimals initially located in the region between 0.3 and 4 astronomical units (AU), resulted often in the formation of 3–4 planets that provide a reasonable match to many characteristics of the terrestrial planets in the Solar System. The resulting planets are generally distributed between 0.5 and 2 AU and have masses ranging from 0.3 to 1.6 M_e (where M_e = mass of the Earth).

An outstanding problem in modelling the formation of the terrestrial planets has been to reproduce the small mass of Mars ($\sim$0.1 M_e). Classical simulations, in which the giant planets form on or near their current orbits (i.e. no giant planet migration), have generally produced a Mars-like planet that is too massive and located too far from the Sun. An important insight into this problem has been made based on the idea of Hansen (2009). A small Mars can form if the planetesimal disk becomes truncated at 1–1.5 AU. The Grand Tack model of Walsh et al. (2011) achieves this truncation by invoking the large-scale radial gas-driven migration of Jupiter and Saturn. First, they migrate inwards toward the Sun during the early stages of Saturn's growth (such radial migration is common for giant planets discovered around other stars). Once Saturn achieved a critical mass and was in resonance with Jupiter, these planets then migrated back outwards. This inward-then-outward migration (the "Grand Tack") truncated the disk of planetesimals and planetary embryos at around 1 AU and subsequent accretion in this truncated disk then results in a system of planets matching the terrestrial planets of the Solar System including, in particular, a Mars-like planet with a correct mass.

At present, the main constraints on the validity of accretion models are the masses and orbital characteristics of the final planets in comparison with the actual terrestrial planets of the Solar System. On the other hand, considerable information is available concerning the chemistry of the silicate mantles of the Earth and, to a lesser extent, Mars, Venus and Mercury (e.g. McDonough, 2003; Palme and O'Neill, 2013; Dreibus and Wänke, 1985; McSween, 2003; Taylor, 2013; Righter and Chabot, 2011; Treiman, 2009; Robinson and Taylor, 2001; Taylor and Scott, 2003). Combining core–mantle differentiation with accretion modelling can provide important new constraints on both processes.

There have been no attempts to comprehensively integrate geochemical evolution models with the N-body accretion simulations. Although several studies have considered the accretion of water-bearing material onto the terrestrial planets (e.g. Morbidelli et al., 2000; O'Brien et al., 2014), only two studies have attempted to address the bulk composition of accreted material and its implications for the final compositions of the planets (Bond et al., 2010; Elser et al., 2012). In these studies, predictions of equilibrium solar-nebula condensation models were combined with the results of N-body simulations in order to estimate the bulk chemistry of planets as a function of their final locations (heliocentric distances) in the Solar System. There are a number of problems with this approach. In particular, no account is taken of core–mantle differentiation even though this has a large influence on the chemistry of planetary mantles – on which the observational constraints are based.

In this study we combine N-body accretion and core–mantle differentiation models following the approach of Rubie et al. (2011). We thus model differentiation and geochemical evolution of all the terrestrial planets simultaneously. Such an approach provides an important additional test of the viability of N-body simulations. In addition, models of planetary core formation can be significantly improved and refined. Note that the aim is not to define the exact conditions and processes of accretion and differentiation – which is clearly impossible for such stochastic and complex events. Instead we aim to provide robust indications of the likely ranges of conditions and processes.

Here we describe the methodological approach in detail and discuss results from six Grand Tack accretion simulations. In a subsequent paper (Jacobson et al., in preparation) the method described here will be applied to a large number of accretion simulations in order to examine the results statistically.

2. Methodology

2.1. N-body simulations

We derived the accretion history of each planet from six Grand Tack N-body simulations. Each simulation run is integrated with Symba (Duncan et al., 1998) tracking both embryos, which interact with all particles in the simulation, and planetesimals, which interact only with the Sun, embryos and the giant planets (for a review of similar simulations see Morbidelli et al., 2012). These simulations assume perfect accretion and are run for 150–200 Myr with the effects of gas included for the first 0.6 Myr. Since these are Grand Tack simulations, the giant planets do not begin near their current orbits and they migrate during the gas phase of the disk. Here we follow the prescription set out in the supplementary material of Walsh et al. (2011) in the section "Saturn's core growing in the 2:3 resonance with Jupiter". In brief, Jupiter and Saturn begin at 3.5 and 4.5 AU on circular orbits, respectively, then over 0.1 Myr migrate inward to 1.5 and 2 AU. Meanwhile, Saturn's mass grows linearly from 10 M_e to its current mass, and when it reaches a mass close to its current mass the migration physics in the resonance changes and the giant planets then migrate outwards (Masset and Snellgrove, 2001; Morbidelli and Crida, 2007; Pierens and Nelson, 2008). They continue to migrate outwards as the gas in the disk dissipates exponentially over the next 0.5 Myr. Once the gas is gone, they are then stranded on orbits with semi-major axes of 5.25 and 7 AU, respectively. These locations are appropriate for a late giant planet instability at $\sim$500 Myr (Nice model; Morbidelli et al., 2007) that will place them and the outer ice giants (Neptune and Uranus) on their current orbits (Levison et al., 2011). The treatment of the nebula gas and the giant planets are identical in each of the six simulations.

Only the initial locations and masses of the embryos and planetesimals distinguish the six simulations. All simulations begin with an inner disk of embryos and planetesimals and an outer disk of planetesimals, which are scattered inwards by the outward migration of the giant planets. Table 1 lists the parameters of these disks for each simulation (the parameters for the inner planetesimal disk