Earth and Planetary Science Letters 392 (2014) 28–38

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Dynamics of the terrestrial planets from a large number of *N*-body simulations

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ARTICLE INFO

Article history:
Received 6 September 2013
Received in revised form 26 January 2014
Accepted 3 February 2014
Available online 25 February 2014
Editor: T. Elliott

Keywords:
accretion
N-body simulations
terrestrial planets
Mars
late veneer

ABSTRACT

The agglomeration of planetary embryos and planetesimals was the final stage of terrestrial planet formation. This process is modeled using *N*-body accretion simulations, whose outcomes are tested by comparing to observed physical and chemical Solar System properties. The outcomes of these simulations are stochastic, leading to a wide range of results, which makes it difficult at times to identify the full range of possible outcomes for a given dynamic environment. We ran fifty high-resolution simulations each with Jupiter and Saturn on circular or eccentric orbits, whereas most previous studies ran an order of magnitude fewer. This allows us to better quantify the probabilities of matching various observables, including low probability events such as Mars formation, and to search for correlations between properties. We produce many good Earth analogues, which provide information about the mass evolution and provenance of the building blocks of the Earth. Most observables are weakly correlated or uncorrelated, implying that individual evolutionary stages may reflect how the system evolved even if models do not reproduce all of the Solar System's properties at the end. Thus individual *N*-body simulations may be used to study the chemistry of planetary accretion as particular accretion pathways may be representative of a given dynamic scenario even if that simulation fails to reproduce many of the other observed traits of the Solar System.

1. Introduction

The canonical view of terrestrial planet formation in our Solar System consists of accretion of increasingly larger bodies in a series of stages. This process began with the collisional and gravitational accumulation of dust and pebbles into planetesimals, bodies measuring tens to hundreds of kilometers in radius (e.g., Cuzzi et al., 2001; Johansen et al., 2007; Weidenschilling, 2003; Youdin and Shu, 2002). Gravitational forces and collisions between these bodies led to the formation of approximately lunar to Mars-mass planetary embryos by runaway accretion (e.g., Wetherill, 1980). The resulting embryos and remaining planetesimals continued to accrete stochastically in a series of large and violent collisions to form the terrestrial planets (e.g., Chambers, 2004; Morbidelli et al., 2012).

The final properties of the planets that form are determined by the ensemble of these various stages of growth. The last stage of planet formation is typically modeled using *N*-body accretion simulations, which begin with a swarm of embryos and planetesimals in orbit around a star, then calculate how their gravitational interactions and collisions lead to the formation of larger planets. This allows us to determine the provenance and timing of accretion of the planetary building blocks, as well as the physical and orbital properties of the resulting planets and how these are set by the dynamic properties of the early Solar System. These results can then be compared to the properties of our terrestrial planets to better understand this process.

Ideally, we could constrain the early dynamical history of the Solar System (e.g., orbital properties of the giant planets) by determining which initial configuration is best able to reproduce all of the properties of the planets. The key properties that were targeted to be reproduced in previous studies included the number, masses, semimajor axes, eccentricities, inclinations, formation timescales, and water contents of the terrestrial planets, as well as the angular momentum deficit (AMD) and radial mass concentration (RMC) of the bulk planetary system, and the mass stranded in the asteroid belt (Raymond et al., 2009). Early low-resolution simulations (e.g., Agnor et al., 1999; Chambers, 2001) with relatively few initial embryos and planetesimals ($<$160 bodies) were able to approximately reproduce the number, masses, and semimajor axes of the terrestrial planets, despite different initial configurations of the planetary building blocks and the giant planets, suggesting that such outcomes did not depend sensitively on the early dynamics of

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http://dx.doi.org/10.1016/j.epsl.2014.02.011

the Solar System. However, these systems tended to produce planets with larger eccentricities and inclinations than the terrestrial planets in our Solar System. O'Brien et al. (2006) and Raymond et al. (2006) demonstrated that similar configurations run at higher resolution (∼50–100 embryos along with >1000 planetesimals) exhibit greater dynamical friction, which damps the eccentricities and inclinations of the embryos and planets, leading to formation timescales and orbital parameters that are more in line with those of the Solar System. Thus it appears that a mix of massive embryos and low mass planetesimals were responsible for producing the planets we see today.

Each of these early studies was able to produce planets that were 'Earth-like' to some extent, in that most simulations produced one planet with nearly the same mass and semimajor axis as that of the Earth. However, it was found that the initial orbital architecture for the planetary building blocks and giant planets used in the simulations had a dramatic effect on other key properties of the planetary system (O'Brien et al., 2006; Raymond et al., 2009). In the cases where Jupiter and Saturn were assumed to exist on their current orbits, the numbers and masses of the terrestrial planets were more easily reproduced, though the planets tended to accrete very little water-bearing materials from the outer edge of the asteroid belt. In those cases where more circular orbits of the giant planets were assumed, consistent with the Nice model (Gomes et al., 2005; Morbidelli et al., 2005; Tsiganis et al., 2005), more water-bearing materials were accreted by the planets, though the masses and numbers did not match the current Solar System. Thus the configuration of the giant planets at the time of terrestrial planet accretion remains uncertain.

While early studies of planet formation largely focused on matching the physical and orbital properties of the planets in our Solar System, the chemical consequences of planetary accretion have also been studied with these same *N*-body simulations. Two recent studies (Bond et al., 2010; Elser et al., 2012) calculated the compositions of simulated planets to further explore the chemical consequences of planetary accretion, focusing on properties such as their bulk elemental compositions and oxidation states, volatile loss, water delivery, and geochemical ratios. These studies found that the bulk elemental abundances and water contents of the terrestrial planets could be broadly matched in their dynamical studies, though they used only two simulations each, leaving it unclear whether such properties would always be reproduced. When comparing a larger number of simulations or comparing the detailed compositions of the cores and mantles of the simulated planets, even greater variation is expected from simulation to simulation, as a result of the timing of when materials with different compositions were accreted (Rubie et al., 2011). The scatter in accretion histories is thus important to understand in detail as the results of planetary accretion models are highly stochastic, with the final outcomes being strongly dependent on the initial locations of the planetary embryos and planetesimals even in cases where the same general dynamical setting is assumed (e.g., Lissauer, 2007).

Because of the stochastic nature of accretion, it is difficult to evaluate how representative any single run is of the possible accretion histories, and thus final chemical properties, for a resulting planet in a given dynamic scenario. Previous studies performed a small number of *N*-body simulations, typically four or fewer for each set of initial conditions (Chambers, 2001; Chambers and Wetherill, 1998; Morishima et al., 2010; O'Brien et al., 2006; Raymond et al., 2004, 2006, 2009) and no more than twelve (Raymond et al., 2009). Such a small number of runs is understandable as much earlier studies were limited by computational power, while more recent studies concentrated on exploring parameter space instead of running a large number of simulations per set of conditions (Morishima et al., 2010). Given the range of outcomes that are seen in such simulations, it is not always clear from a limited sample whether a particular constraint is consistently reproduced within a given dynamical environment or if it was a low probability event.

Fully understanding how the early dynamic environment of the Solar System controls the properties of a planetary system or the chemical evolution of a single planet requires that we quantitatively evaluate the range of accretional outcomes and most likely results expected for a particular orbital architecture. This can only be done by performing a statistical analysis of these various starting conditions: rather than focusing on reproducing all observables simultaneously, it is important to know which of the constraints are easily reproduced as well as which constraints are correlated with others for a given dynamical environment. This necessitates performing a large number of simulations in order to determine the probability distribution functions (PDFs) of any given outcome for a given dynamic environment. Only then can we begin to understand the initial configuration of the planetary building blocks in our Solar System.

As our goal is ultimately to utilize *N*-body simulations to investigate the physical and chemical evolution of the Earth during its formation and early evolution, we want to understand the plausible range of accretion histories of the terrestrial planets in different dynamic settings. Here we carry out a large number of simulations (fifty) for a given set of initial conditions, to quantify the probabilities of reproducing various aspects of the early evolution of the Solar System and especially of the Earth. These simulations provide greater robustness in our evaluation of terrestrial planet accretion models, allowing us to develop a more statistically significant database for analyzing the dynamical outcomes; in particular, it increases our chances for observing low-probability events. Further, our goal is not to reproduce all attributes of the Solar System with these simulations, but instead to determine the correlative relationships between various Solar System properties for different dynamic environments. This allows us to evaluate in detail what this means in terms of using *N*-body simulations as tools for examining the chemical evolution of the planets in the Solar System. While we focus on just a subset of plausible dynamic environments in the early Solar System, the methodology used here is readily adopted in any other study of planetary accretion.

2. Methods

We performed 100 *N*-body simulations using the MERCURY code (Chambers, 1999) for two different dynamical environments for the early Solar System (fifty simulations each). The two most commonly tested orbital configurations for the gas giant planets in previous studies are the Eccentric Jupiter and Saturn (EJS) case, where the giant planets are given the orbits that they have today, and the Circular Jupiter and Saturn (CJS) case, where the giant planets are put on non-eccentric orbits as is expected as the starting point in the Nice Model (Gomes et al., 2005; Morbidelli et al., 2005; Tsiganis et al., 2005). These two situations were previously studied by O'Brien et al. (2006) and Raymond et al. (2009), and we follow their approach in setting up the initial conditions for each model, though we increase the resolution slightly by assuming a lower mass for, and thus greater number of, planetesimals. More recent studies have suggested different initial orbital configurations for reproducing the properties of the Solar System (Hansen, 2009; Walsh et al., 2011), which can be explored in future studies. We focus on the EJS and CJS cases to compare and contrast our results with previous studies, which mostly use these configurations. The methodology used here can readily be applied to any other dynamical environment of interest.

Each simulation began with ∼80 embryos, following a solid disk surface density profile of $\Sigma(r) = \Sigma_0(r/1\ \text{AU})^{-3/2}$ (Weidenschilling, 1977), with $\Sigma_0 = 10\ \text{g/cm}^2$. There were also ∼2000 plan-