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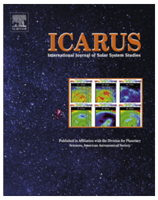

A collisional origin to Earth's non-chondritic composition?

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ABSTRACT

Several lines of evidence indicate a non-chondritic composition for bulk Earth. If Earth formed from the accretion of chondritic material, its non-chondritic composition, in particular the super-chondritic ^{142}Nd/^{144}Nd and low Mg/Fe ratios, might be explained by the collisional erosion of differentiated planetesimals during its formation. In this work we use an *N*-body code, that includes a state-of-the-art collision model, to follow the formation of protoplanets, similar to proto-Earth, from differentiated planetesimals (>100 km) up to isolation mass (>0.16 $M_\oplus$). Collisions between differentiated bodies have the potential to change the core–mantle ratio of the accreted protoplanets. We show that sufficient mantle material can be stripped from the colliding bodies during runaway and oligarchic growth, such that the final protoplanets could have Mg/Fe and Si/Fe ratios similar to that of bulk Earth, but only if Earth is an extreme case and the core is assumed to contain 10% silicon by mass. This may indicate an important role for collisional differentiation during the giant impact phase if Earth formed from chondritic material.

1. Introduction

A basic premise when estimating elemental budgets of planets is that they were constructed from material represented by our collection of undifferentiated, chondritic meteorites. This assumption has recently come under close scrutiny due to the super-chondritic ^{142}Nd/^{144}Nd composition of the accessible Earth (Boyet and Carlson, 2005). This observation has generally been explained by one of two scenarios for generating elevated ^{142}Nd/^{144}Nd as a result of radiogenic ingrowth from the short-lived ^{146}Sm. [1] Namely, either the Earth has an untapped, hidden reservoir, most likely located at the bottom of the mantle (Boyet and Carlson, 2005; Labrosse et al., 2007), leaving the observable, outer silicate Earth super-chondritc, or the bulk composition of Earth is inherently non-chondritic (O'Neill and Palme, 2008; Caro et al., 2008). The former explanation has long been popular in accounting for other planetary mass-balance problems (Allègre et al., 1996; Rudnick et al., 2000; Blichert-Toft and Albarède, 1997), but for the neodymium isotope case it requires an uncomfortably early formation and subsequent isolation of the putative hidden reservoir (Bourdon et al., 2008). Thus, there is an impetus to explore different models.

One alternative notes that samarium and neodymium isotopic compositions of different chondrite types show mass independent variations that reflect an inhomogenous distribution of pre-solar materials in the nebular disk (Andreasen and Sharma, 2006). Some have thus argued that the elevated ^{142}Nd/^{144}Nd of Earth represents such nucleosynthetic heterogeneity (Huang et al., 2013) rather than the result of radiogenic ingrowth. However, the few chondrites so far analysed that have Sm and Nd isotopes within the error of measured terrestrial values (Gannoun et al., 2011) have other chemical characteristics that are inappropriate for them to represent the bulk Earth (e.g. Fitoussi and Bourdon, 2012).

Thus, attention has focused on how collisions during the accretion history of Earth could have altered the Earth's composition from a chondritic starting point (e.g. Palme and O'Neill, 2003). This has many similarities with a hidden reservoir model, except that material is lost from the Earth, rather than irrevocably buried within. If the process of accretion commonly results in bodies with different compositions than the precursor materials, models of planetary compositions require significant revision.

It is now well documented that planetesimals can differentiate within the first few million years of the Solar System's evolution

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[1] For example, $^{142}\mathrm{Nd}/^{144}\mathrm{Nd} = (^{142}\mathrm{Nd}/^{144}\mathrm{Nd})^{\circ} + (^{144}\mathrm{Sm}/^{144}\mathrm{Nd})(^{146}\mathrm{Sm}/^{144}\mathrm{Sm})^{\circ}(1 - e^{-\lambda t_1})$ for a reservoir formed as a closed system t_1 years after the start of the Solar System with super chondritic ^{144}Sm/^{144}Nd (proportional to bulk Sm/Nd). The symbol ° indicates initial values at the start of the Solar System inferred from primitive meteorites, λ is the decay constant of $^{146}\mathrm{Sm} \sim 1.02 \times 10^{-7}\ \mathrm{yr}^{-1}$ (Kinoshita et al., 2012).

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(Kleine et al., 2005; Scherstén et al., 2006; Markowski et al., 2006; Kruijer et al., 2014). As the terrestrial planets are thought to form from the accretion of planetesimals, it seems inevitable that the planets formed from objects that were already differentiated. Terrestrial planet formation is dominated by collisions, most of which are accretional, but some of which are disruptive. During the course of accretion, compositionally distinct parts of the differentiated colliding bodies might be preferentially lost (Marcus et al., 2009, 2010). Indeed, collisional loss of crust during planetary formation has been invoked to be the cause of super-chondritic ^{142}Nd/^{144}Nd on Earth (O'Neill and Palme, 2008; Caro et al., 2008). To date, however, attempts to investigate this suggestion quantitatively have been minimal. In part this has been a consequence of the assumption of perfect merging in traditional *N*-body collision models (e.g. Chambers, 2001; Kokubo and Ida, 2002; O'Brien et al., 2006; Raymond et al., 2009).

In this work we take a first step towards examining the chemical consequences of imperfect accretion using the parameterisation of collisional out-comes of Leinhardt and Stewart (2012), coupled with the *N*-body gravity code PKDGRAV (Richardson et al., 2000; Stadel, 2001). Rather than address the isotopic differences in ^{142}Nd/^{144}Nd, which rely on rather subtle fractionations between the volumetrically small crust and underlying silicate-dominated mantle, in this initial study we examine the gross compositional differences between the metallic core and silicate shell (mantle and crust) of planetesimals. Preferential loss of the outer, silicate portion of a planetesimal during collision, increases the fractional mass of its metallic core. Estimates of terrestrial Mg/Fe suggest that it is lower than any chondritic value (Palme and O'Neill, 2003). This has been explained as a consequence of accretional erosion (Palme and O'Neill, 2003) but the hypothesis has not been quantitatively tested. Here we examine the importance of preferential mantle erosion during the initial stages of accretion and test if this process can bias the core fraction of planets away from that predicted from the chondritic model.

2. Numerical method

Terrestrial planet formation is dominated by collisions between planetesimals, both accretional and erosive. In the canonical model of terrestrial planet formation, km-sized bodies grow into protoplanets via runaway and oligarchic growth (Kokubo and Ida, 1998). Due to practical numerical constraints, in this work we track the formation of protoplanets from planetesimals that are initially larger than 100 km in diameter.

Our simulations use a modified version of the parallelized *N*-body code, PKDGRAV (Richardson et al., 2000; Stadel, 2001). PKDGRAV employs a hierarchical tree to calculate inter-particle gravity and a second-order leap frog integrator for time evolution. The code has been modified to include a state-of-the-art collision model from Leinhardt and Stewart (2012). Unlike many other *N*-body simulations of terrestrial planet formation that assume perfect merging (the projectile is completely accreted by the target) as the only collision outcome (e.g. Kokubo and Ida, 2002; Raymond et al., 2009), this code includes a range of collision types in addition to perfect merging, such as, partial accretion (a fraction of the projectile is accreted by the target), hit-and-run (scattering or bouncing collisions in which the target remains intact, although the projectile may be disrupted and no material is exchanged between the target and projectile), and erosive collision outcomes (the target looses mass or is fully disrupted).

The outcomes of each individual collision, including the size and velocity distribution (in 3D) of the fragments, are calculated based on the impact parameter and collision velocity, using analytic laws derived from simulations of individual collisions (Leinhardt and Stewart, 2012; Stewart and Leinhardt, 2012). This collision model produces results that broadly match those of previous work.

The aim of the simulations in this work is to produce a suite of protoplanets that have the potential to become Earth-like planets. For this reason, and to follow previous work, we focus on the region around 1 AU and use a disc with a surface density of the Minimum Mass Solar Nebula (MMSN) (Kokubo and Ida, 2002; Leinhardt and Richardson, 2005; Leinhardt et al., 2009). The mass of the planetesimal disk should not greatly affect our conclusions, having the largest influence on the number of protoplanets formed. The initial conditions for our simulations are summarised in Table 1. The simulations are repeated 9 times, with different randomised initial conditions, in order to produce a statistical sample of protoplanets. Each simulation took a few months to complete on 16 2.6 GHz Intel Sandybridge processors.[2]

Due to the vast difference in orbital and collisional dynamical timescales we employ a two rung multistepping procedure. The major step of 0.01 yr is used to resolve the orbit of the planetesimals while a much smaller minor step of 1.5×10^{-4} yr is used to resolve planetesimal collisions (see Leinhardt and Richardson, 2005, for details). However, even with a highly efficient paralleized *N*-body code and multistepping we are forced to "trick" time in order to reach oligarchic growth in a practical time frame. Following previous work (Kokubo and Ida, 2002; Leinhardt and Richardson, 2005; Leinhardt et al., 2009), we assumed a radial expansion factor, f, of 6 and, thus, an initial planetesimal density (ρ) of 0.00925 g cm^{-3} and a radius of 1000 km, instead of a density of $\rho = 2$ g cm^{-3} and a radius of 160 km. As a consequence, the evolution of the planetesimals is accelerated by a factor of $f^2 = 36$. The expansion parameter does not adversely effect the collision model that has been implemented from Leinhardt and Stewart (2012) because this model already includes a density normalization (to $\rho = 1$ g cm^{-3}); thus, the collision outcome is determined based on the mass of the colliders not the density/radius.

Kokubo and Ida (1996) showed that radial expansion of this order did not change the growth mode of planetesimals as long as there was still a sufficiently massive background population of smaller planetesimals to dominate the velocity dispersion of all bodies via dynamical friction. In other words, using a radial expansion factor should only change the timescale of evolution as long as the velocity dispersion of the bodies is not dominated by gravitational scattering due to the protoplanets. Thus, our simulations lose validity as we approach the giant impact phase.

We have chosen to simplify the evolution scenario further, as we have done in the past, by ignoring the presence of any remaining gas disc. This assumption is reasonable for the directly resolved planetesimals as they are large (~100 km), and the effect of aerodynamic drag is negligible.

In order to create a more realistic size distribution than the equal-mass planetesimals used in previous work, and to avoid an unrealistic number of hit-and-run collisions, the initial size distribution is determined from the outcome of perfectly merging 5×10^5 equal-mass planetesimals, until only 10^5 planetesimals remain. The initial size distribution is shown as the black line in Fig. 2.

Our simulations allow erosion, and track the fragments produced in erosive collisions. To stop exponential growth in the number of particles, we do not resolve fragments below a mass of 2×10^{22} g ($10^{-11}\ M_\odot$), which is just under the mass of our initial planetesimals. Fragments smaller than this value are considered to be unresolved material and the mass is added to one of ten cylindrical annuli, depending on the radial location at which the fragments are realised and assumed to be dynamically cold. The resolved planetesimals

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[2] https://www.acrc.bris.ac.uk/hpc.htm.