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Melting and mixing states of the Earth's mantle after the Moon-forming impact

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ABSTRACT

The Earth's Moon is thought to have formed by an impact between the Earth and an impactor around 4.5 billion years ago. This impact could have been so energetic that it could have mixed and homogenized the Earth's mantle. However, this view appears to be inconsistent with geochemical studies that suggest that the Earth's mantle was not mixed by the impact. Another outcome of the impact is that this energetic impact melted the whole mantle, but the extent of mantle melting is not well understood even though it must have had a significant effect on the subsequent evolution of the Earth's interior and atmosphere. To understand the initial state of the Earth's mantle, we perform giant impact simulations using smoothed particle hydrodynamics (SPH) for three different models: (a) standard: a Mars-sized impactor hits the proto-Earth, (b) fast-spinning Earth: a small impactor hits a rapidly rotating proto-Earth, and (c) sub-Earths: two half Earth-sized planets collide. We use two types of equations of state ($MgSiO_3$ liquid and forsterite) to describe the Earth's mantle. We find that the mantle remains unmixed in (a), but it may be mixed in (b) and (c). The extent of mixing is most extensive in (c). Therefore, (a) is most consistent and (c) may be least consistent with the preservation of the mantle heterogeneity, while (b) may fall between. We determine that the Earth's mantle becomes mostly molten by the impact in all of the models. The choice of the equation of state does not affect these outcomes. Additionally, our results indicate that entropy gains of the mantle materials by a giant impact cannot be predicted well by the Rankine–Hugoniot equations. Moreover, we show that the mantle can remain unmixed on a Moon-forming timescale if it does not become mixed by the impact.

1. Introduction

The so-called giant impact hypothesis is a widely accepted explanation for the origin of the Moon (Hartmann and Davis, 1975; Cameron and Ward, 1976). According to the standard version of this hypothesis, a Mars-sized impactor hit the proto-Earth and created a disk around the planet from which the Moon accreted. This hypothesis has been favored because it can explain the Moon's mass, iron depletion, and the angular momentum of the Earth–Moon system. However, this model has difficulty in explaining the fact that the Earth and Moon have nearly identical isotopic ratios (e.g. oxygen, silicon, and tungsten, Wiechert et al., 2001; Herwartz et al., 2014; Armytage et al., 2012; Touboul et al., 2007). The typical outcome of a giant impact simulation is that the disk materials are derived mainly from the impactor (e.g., Benz et al., 1986), which is often assumed to have had different isotopic ratios given that the oxygen isotopic ratios between the Earth and Mars differ by 0.321‰ (Franchi et al., 1999). Reufer et al. (2012) report that an impact at a high impact velocity and steep impact angle would deliver more Earth's mantle materials to the disk, but it is still difficult to explain the identical isotopic ratios.

Pahlevan and Stevenson (2007) have suggested that turbulent mixing in the Earth's atmosphere and the disk homogenized the isotopic ratios of the two reservoirs. This model could potentially solve the isotopic problem, but it has several shortcomings. This mechanism may not work for all of the observed isotope systems, such as Si (Pahlevan et al., 2011; Armytage et al., 2012). Furthermore, this mixing would have required the Earth's whole mantle convection during the Moon formation, but such convection may not have occurred due to the thermally stratified structure of the mantle after the impact (discussed in Sections 2.4 and 3.3). Even if the post-impact mixing caused the disk to have the same isotopic reservoir as, say, the outer 80% of the mantle but failed to equilibrate with the inner 20%, then the Earth and Moon could still be isotopically different if there had been a subsequent mixing of the Earth's mantle after the Moon formation. At present, there is no detectable oxygen isotopic difference (with respect to the three

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isotopes, which are referred to as $\Delta^{17}O \equiv \delta^{17}O - 0.52\delta^{18}O$) among Earth rocks.

The possibility that the impactor had a similar oxygen isotopic ratio to the Earth has been recently revisited. Kaib and Cowan (2015a) investigate feeding zones of terrestrial planets based on orbital calculations and predict that this possibility is ~5% or less. Mastrobuono-Battisti et al. (2015) have performed similar analyses and report that the possibility could be as high as 20–40% if its standard deviation ($\pm\sigma$) is included. This discrepancy may originate from their different criteria to choose Earth and Mars analogues in their simulations (Kaib and Cowan, 2015b). It is also possible that the impactor could have been compositionally similar to enstatite chondrites (e.g., Herwartz et al., 2014), whose compositions are much more similar to those of the Earth than those of Mars. Alternatively, a recent model of planet formation, the so-called Grand Tack model (Walsh et al., 2011), may suggest a different outcome. This Grand Tack model suggests that the planetesimal disk was truncated at 1 AU due to migration of gas giants and, as a result, terrestrial planets mainly formed from the inner part of the disk. This model may increase the chance of having an impactor with a composition similar to the Earth (personal communications with Alessandro Morbidelli). This increased probability may arise possibly because the main source of the Earth's materials was confined to a limited region of distances from the Sun, or perhaps because of more efficient mixing of the source materials than the standard models predict (discussed in Section 4.4). In either case, this finding would imply that the Earth is different from Mars but not necessarily different from the terminal giant impacting body that led to the formation of the Moon (often called as "Theia"). It should be noted that having the same oxygen isotopic ratios for the proto-Earth and impactor does not necessarily explain the nearly identical tungsten and silicon isotopic ratios of the two (Dauphas et al., 2014; Fitoussi and Bourdon, 2012).

New giant impact models have been suggested as alternatives. Ćuk and Stewart (2012) propose that an impactor hit a rapidly rotating proto-Earth (called the "fast-spinning Earth"), whereas Canup (2012) suggests a giant impact between two half-Earth-mass objects (here we call this "sub-Earths", and the model is also called "large impactor" and "half Earth" in other literatures). In these cases, the composition of the disk would have been similar to that of the Earth's mantle; therefore, the models could explain the isotopic similarities. In these models, the angular momentum of the Earth–Moon system after the impact was 2–3 times as large as today's value. Ćuk and Stewart (2012) suggest that the evection resonance between the Moon and the Sun could have transferred the excess angular momentum of the Earth–Moon system to the Sun–Earth system. This resonance occurs when the period of precession of the pericenter of the Moon is equal to the Earth's orbital period (Touma and Wisdom, 1998). It is also possible that there is some other resonance that yields the same result, but it is not clear if these resonances could efficiently remove the excess of the angular momentum once the thermal evolution of the Moon is considered (Wisdom and Tian, 2015). The existence of a resonance does not imply the removal of a large amount of angular momentum because that would depend on a particular and possibly narrow choice of tidal parameters.

These new models are indistinguishable in terms of the oxygen isotopic ratios, but additional geochemical constraints may differentiate these models. For example, it has been suggested that the Earth's mantle may not have been completely mixed by the giant impact. This has been drawn from various isotopic studies, especially those on the Hf–W system. Hf is a lithophile ("rock-loving") element, whereas W is a moderately siderophile ("iron-loving") element. ^{182}Hf decays to ^{182}W with a 9 Myr half-life; thus, the mantle of a planet would have an enhanced ^{182}W/^{184}W if differentiation occurred while Hf was still alive (within the first ~60 Myr after CAI formation). Most terrestrial rocks have similar values of ^{182}W/^{184}W (Lee and Halliday, 1996), but Willbold et al. (2011) and Touboul et al. (2012) find that some 2.8 and 3.8 billion years old rocks have elevated ^{182}W/^{184}W ratios. This finding may indicate that the early mantle was heterogeneous (while ^{182}Hf was still present) and that the signature was preserved at least until 2.8 billion years ago. Determining the cause of the heterogeneity is an active area of research. It should be noted that the chemical heterogeneity could take many forms, including a non-uniformity of noble gas mole fraction (e.g., Mukhopadhyay, 2012) or a discrete layer of denser mantle material at the base of the mantle because of the formation of a basal magma ocean (e.g., Labrosse et al., 2007).

Regardless of the cause or form, the Earth's mantle may not have been mixed even by the giant impact given that the mantle heterogeneity formation predated the Moon-forming impact. Previous studies based on the lunar ^{182}W/^{184}W ratio suggest that the Moon formed as early as 30 Myr after CAI formation (e.g., Lee et al., 1997), whereas Touboul et al. (2007) propose that ~60% crystallization of the lunar magma ocean occurred after ~60 Myr by taking into account the excess of ^{182}W formed by neutron capture of ^{181}Ta. This is consistent with the age estimate based on other systems (e.g., Sm–Nd, Carlson and Lugmair, 1988, and recent studies on orbital dynamics, Jacobson et al., 2014). Although the age of the Moon is still under debate, recent work tends to suggest a young age of the Moon (>60 Myr). Herein, we focus on the scenario in which the mantle heterogeneity predated the formation of the Moon.

In addition to mantle mixing, mantle melting is important because the extent of melting affected the evolution of the Earth's interior and atmosphere (e.g., Abe and Matsui, 1986; Tonks and Melosh, 1993; Elkins-Tanton, 2008). When the Earth grew through collisions with numerous impactors, these impactors melted part of the Earth's mantle and delivered their metallic iron to the Earth. The metallic iron of small impactors (at least up to a few hundred kilometers in size) would have been dispersed as droplets and the resulting rainfall would have led to metal–silicate equilibration during the descent to the metal pond at the base of the magma ocean (Stevenson, 1990). The iron might have passed through the solid-rich deeper mantle without further equilibration with the ambient mantle. If the abundance of siderophile elements in the mantle recorded the metal–silicate equilibrium at the base of the magma ocean, the magma ocean depth would have been approximately around 28–40 GPa (700–1200 km deep) (e.g., Li and Agee, 1996; Righter et al., 1997). However, this model may be too simplistic because it assumes that the core formation occurred by a single stage process, but the Earth's core must have formed though multiple impacts processes (Wade and Wood, 2005; Rubie et al., 2015). Thus, the mantle geochemistry is not likely to have recorded the single impact event. The concentrations of siderophile elements in the mantle reflect very complex processes of the core formation (e.g., Stevenson, 1989; Zimmerman et al., 1999; Rubie et al., 2003; Dahl and Stevenson, 2010; Shi et al., 2013).

Analytical and numerical studies suggest that a significant fraction of the mantle would have experienced melting by the Moon-forming impact (e.g., Tonks and Melosh, 1993; Canup, 2008; de Vries et al., 2014). A simple estimate can be described as follows; for an impacting body with velocity 10 km/s, the specific kinetic energy carried by the body is 5×10^7 J/kg. The latent heat of melting is about 1×10^6 J/kg (for a mean temperature of 2500 K). Therefore, a Mars-mass projectile would deliver several times more energy than that needed to melt the entire mantle, assuming that the pre-impact state is near the solidus. Of course, this does not indicate that the entire mantle is in fact melted upon impact because the heating is heterogeneous and because part of the impact-induced energy is partitioned to the kinetic energy of the

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