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Zirconium isotope constraints on the composition of Theia and current Moon-forming theories

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ABSTRACT

The giant impact theory is the most widely recognized formation scenario of the Earth's Moon. Giant impact models based on dynamical simulations predict that the Moon acquired a significant amount of impactor (Theia) material, which is challenging to reconcile with geochemical data for O, Si, Cr, Ti and W isotopes in the Earth and Moon. Three new giant impact scenarios have been proposed to account for this discrepancy – hit-and-run impact, impact with a fast-spinning protoEarth and massive impactors – each one reducing the proportion of the impactor in the Moon compared to the original canonical giant impact model. The validity of each theory and their different dynamical varieties are evaluated here using an integrated approach that considers new high-precision Zr isotope measurements of lunar rocks, and quantitative geochemical modelling of the isotopic composition of the impactor Theia. All analysed lunar samples (whole-rock, ilmenite and pyroxene separates) display identical Zr isotope compositions to that of the Earth within the uncertainty of 13 ppm for $^{96}Zr/^{90}Zr$ (2σ weighted average). This 13 ppm upper limit is used to infer the most extreme isotopic composition that Theia could have possessed, relative to the Earth, for each of the proposed giant impact theories. The calculated Theian composition is compared with the Zr isotope compositions of different solar system materials in order to constrain the source region of the impactor. As a first order approximation, we show that all considered models (including the canonical) are plausible, alleviating the initial requirement for the new giant impact models. Albeit, the canonical and hit-and-run models are the most restrictive, suggesting that the impactor originated from a region close to the Earth. The fast-spinning protoEarth and massive impactor models are more relaxed and increase the allowed impactor distance from the Earth. Similar calculations carried out for O, Cr, Ti and Si isotope data support these conclusions but exclude a CI- and enstatite chondrite-like composition for Theia. Thus, the impactor Theia most likely had a Zr isotope composition close to that of the Earth, and this suggests that a large part of the inner solar system (or accretion region of the Earth, Theia and enstatite chondrites) had a uniform Zr isotope composition.

1. Introduction

The giant impact theory – a collision between a late-accretion stage planet (protoEarth) and a smaller Mars-sized impactor (Theia) approximately 4.5 billion years ago – is the leading theory to explain the origin of the Moon (Hartmann and Davis, 1975; Cameron and Ward, 1976; Benz et al., 1986). Underlying models reveal that the energy released during this impact is sufficient to vaporize and eject material (>1 Moon mass) into Earth's orbit, which later re-accretes to form the Moon. This theory successfully reproduces key dynamical and geochemical constraints unique to the Earth–Moon system, including the relatively high specific angular momentum of the system and the small iron core of the Moon. The *canonical* subset of giant impact model simulations (Canup and Asphaug, 2001; Canup, 2004) further predict that the majority (≤70%) of the Moon's mass originates from the impactor Theia. However, the similar isotopic compositions of the Moon and bulk silicate Earth (BSE) reported for several elements – O ($\Delta^{17}O$ – Wiechert et al., 2001; Spicuzza et al., 2007; Hallis et al., 2010; Young et al., 2016), Si (Georg et al., 2007; Fitoussi and Bourdon, 2012), Cr (Lugmair and Shukolyukov, 1998), Ti (Zhang et al., 2012), Zr (Schönbächler et al., 2005a, 2005b) and W (Touboul et al., 2007, 2015; Kruijer et al., 2015) – sug-

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gests that the dominant fraction of the Moon derived from the protoEarth. Five potential solutions to this irregularity can be proposed: taking the giant impact model at face value, (1) the isotopic composition of Theia was comparable to that of the Earth (Ringwood, 1979; Wiechert et al., 2001; Meier et al., 2014; Dauphas et al., 2014) or (2) chemical equilibration between the vapour phases of the protoEarth atmosphere and the lunar forming disk occurred by post-impact processes (Pahlevan and Stevenson, 2007). Alternatively, by increasing the collisional angular momentum, the simulation parameter space (e.g., impact velocity and collisional mass) can be extended to include further variants of the giant impact models. These new models significantly lower the predicted amounts of impactor material ending up in the Moon. These models are: (3) hit-and-run impact (Reufer et al., 2012), (4) impact with a fast-spinning protoEarth (Ćuk and Stewart, 2012) and (5) a collision between two roughly equal-sized massive impactors (Canup, 2012). The excess angular momentum is removed from the system by invoking different post-impact mechanisms, such as mass loss to space (Reufer et al., 2012) or evection resonance between the Earth, Moon and Sun (Ćuk and Stewart, 2012).

The first solution (case (1) above – identical building materials for the protoEarth and the impactor) is difficult to test due to the absence of direct isotopic measurements of Theia, while in case (2), the large uncertainties on the thermodynamic quantities (e.g. temperature) and formulations (e.g. equation of state), which are necessary for the thermal equilibration calculations, hinder the validation. Semi-empirical arguments against the first two cases can be raised and are discussed elsewhere (e.g. see Pahlevan and Stevenson, 2007; Ćuk and Stewart, 2012). In the present study, we focus on determining the isotopic compositions of Theia to verify case (1), examine the significance of case (2) and evaluate the newly proposed giant impact scenarios (cases (3)–(5)) in the context of new (Zr) and existing isotopic data from various elements (O, Cr, Ti, Si, W). Each element has its own advantages and disadvantages, which are discussed in the following section.

Oxygen. Herwartz et al. (2014) identified small (up to 15 ppm, 95% confidence level) differences in the O isotope compositions ($\Delta^{17}O$) of the BSE and Moon. These results are contested by Young et al. (2016) who report identical terrestrial and lunar O isotope compositions within analytical uncertainties, as with other previous works (e.g., Wiechert et al., 2001). Young et al. (2016) argue for isotopic homogenisation through violent post-impact mixing (cf. Pahlevan and Stevenson, 2007), while Wiechert et al. (2001) attribute the homogeneous O isotope composition of the Earth–Moon system to Theia forming at a similar heliocentric distance as the protoEarth. This debate about possible O isotope differences between Earth and the Moon as well as the unique O isotope composition observed for each planetary body except for the Earth–Moon system raises the important question of whether isotopic differences between the Earth and Moon may exist for other elements, but have been concealed within the analytical uncertainties. Such compositional differences would provide crucial constraints for the evaluation of different giant impact theories. The identification of such small differences (≈10 ppm level), however, requires a careful consideration of the isotopic data.

Tungsten. In the case of the W isotope similarity, the effect of the short-lived ^{182}Hf–^{182}W decay system is considered. New studies show that W isotopes display an actual difference of 20–30 ppm ($\varepsilon^{182}W$) between the BSE and the bulk silicate Moon (Touboul et al., 2015; Kruijer et al., 2015). This difference was attributed to the late veneer, which affected the Moon and the Earth differently. In light of these new findings, it is not possible to unambiguously exclude the possibility that the BSE and the Moon had slightly different W isotope compositions.

Silicon. The similarity in Si isotopes refers to isotopic effects that are induced by chemical mass-dependent isotope fractionation (e.g. see Young et al., 2002). The complication here is that this type of isotope fractionation can occur during various geological processes such as core formation or magmatic differentiation that take place on rocky planets during or after its accretion.

Chromium, Titanium, Zirconium. Nucleosynthetic isotope variations (non-mass-dependent effects), instead, are robust indicators of the source materials from which a planet or small rocky body formed. These intrinsic anomalies reflect incomplete mixing of presolar components and are inherited from the building materials of a planetary body. They are characteristic for each planetary body and, most importantly are not affected by subsequent geological processing. High-precision nucleosynthetic data are available for Cr, Ti and Zr isotopes. Unfortunately, the Cr and Ti isotope compositions can be modified by the long lasting cosmic ray irradiation on the lunar surface (Zhang et al., 2012; Qin et al., 2010). Zhang et al. (2012) provide evidence that the difference between lunar and terrestrial samples of up to 23 ppm in $\varepsilon^{50}Ti$ is due to cosmic ray irradiation of the lunar surface, while Herwartz et al. (2014) argued for a true difference between BSE and the Moon. This illustrates the need for an element that shows nucleosynthetic effects, but is not significantly affected by the cosmic rays. A very promising element to fill this gap and address all the above-mentioned complications is Zr.

The element Zr is naturally suited to search for nucleosynthetic isotope differences between the Earth and Moon. Zirconium is an ultra-refractory element (half-mass condensation temperature of 1736 K; Lodders, 2003), and therefore very unlikely to be equilibrated isotopically between the Earth and Moon in the aftermath of the giant impact (cf. O, Si, Cr). Its isotopes receive minimal contributions from (i) galactic cosmic rays (Leya et al., 2003; Schönbächler et al., 2003; cf. Ti), (ii) radioactive decay (cf. Cr, W), and (iii) as a lithophile element it is very abundant in the silicate fraction of a planet and thus not significantly affected by the late veneer (cf. W), all of which point to Zr as an ideal system for this study. The five naturally occurring Zr isotopes are predominantly synthesized by slow – ($^{90,91,92,94}Zr$) and rapid – (^{96}Zr) neutron-capture processes. The s-process largely occurs during the thermally pulsating phases of asymptotic giant branch stars, while the r-process may occur in core-collapse supernovae. Charged particle reactions (fusion of light charged nuclei), principally occurring in core-collapse supernovae environments, also contribute to the synthesis of Zr isotopes (e.g. Farouqi et al., 2010; Akram et al., 2013). Nucleosynthetic Zr isotope variations are reported for different bulk solar system materials: (i) $^{96}Zr/^{90}Zr$ enrichments in carbonaceous chondrites relative to the Earth, which scale with the abundance of ^{96}Zr enriched Calcium–Aluminium-rich inclusions (CAIs; Schönbächler et al., 2003; Akram et al., 2013, 2015) and potential correlated $^{96}Zr/^{90}Zr$–$^{91}Zr/^{90}Zr$ variations in primitive and differentiated meteorites, which arise from the addition/removal of different s-process phases relative to the Earth (Akram and Schönbächler, 2013; Akram et al., 2015). Due to this nucleosynthetic Zr isotope heterogeneity between different solar system materials, it is likely that Theia and the protoEarth exhibited distinct Zr isotope compositions. Since the Earth and the Moon reflect different mixtures of these two bodies, isotopic differences in the precursor material should lead to distinct mass-independent isotope compositions for the Earth and the Moon.

Previous work (Schönbächler et al., 2005a) did not identify such differences. Therefore, the aim of this study is to determine the Zr isotope composition of lunar rocks and minerals to a higher precision (<13 ppm for $^{96}Zr/^{90}Zr$, using 2σ weighted average uncertainties; Section 2.1). These data are utilised to assess the plausibility of each of the giant impact models from a mass-balance