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Radial mixing and Ru–Mo isotope systematics under different accretion scenarios

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ABSTRACT

The Ru–Mo isotopic compositions of inner Solar System bodies may reflect the provenance of accreted material and how it evolved with time, both of which are controlled by the accretion scenario these bodies experienced. Here we use a total of 116 *N*-body simulations of terrestrial planet accretion, run in the Eccentric Jupiter and Saturn (EJS), Circular Jupiter and Saturn (CJS), and Grand Tack scenarios, to model the Ru–Mo anomalies of Earth, Mars, and Theia analogues. This model starts by applying an initial step function in Ru–Mo isotopic composition, with compositions reflecting those in meteorites, and traces compositional evolution as planets accrete. The mass-weighted provenance of the resulting planets reveals more radial mixing in Grand Tack simulations than in EJS/CJS simulations, and more efficient mixing among late-accreted material than during the main phase of accretion in EJS/CJS simulations. We find that an extensive homogeneous inner disk region is required to reproduce Earth's observed Ru–Mo composition. EJS/CJS simulations require a homogeneous reservoir in the inner disk extending to ≥3–4 AU (≥74–98% of initial mass) to reproduce Earth's composition, while Grand Tack simulations require a homogeneous reservoir extending to ≥3–10 AU (≥97–99% of initial mass), and likely to ≥6–10 AU. In the Grand Tack model, Jupiter's initial location (the most likely location for a discontinuity in isotopic composition) is ∼3.5 AU; however, this step location has only a 33% likelihood of producing an Earth with the correct Ru–Mo isotopic signature for the most plausible model conditions. Our results give the testable predictions that Mars has zero Ru anomaly and small or zero Mo anomaly, and the Moon has zero Mo anomaly. These predictions are insensitive to wide variations in parameter choices.

1. Introduction

The bulk chemical and isotopic compositions of the terrestrial planets are largely controlled by the original location of material from which these planets accreted (their provenance). Different proposed accretion scenarios (which differ primarily by the behavior of Jupiter and Saturn during terrestrial planet accretion) produce different degrees of radial mixing and predict different provenance histories. A body's ruthenium–molybdenum isotopic signature can act as a fingerprint of its source material and how that source evolved, due to correlated nucleosynthetic variations in Ru and Mo stable isotopes. These variations are likely caused by variable addition of s-process material in different regions of the initial disk (e.g., Dauphas et al., 2004; Chen et al., 2010; Fischer-Gödde and Kleine, 2017).

Siderophile ("iron loving") elements partition preferentially into iron-rich metal more than into silicates. Highly siderophile elements (including Ru) in Earth's mantle are thought to have been delivered in a "late veneer," since they should have been stripped from the mantle during core formation (e.g., Kimura et al., 1974). Therefore, the mantle Ru isotopic composition is sensitive only to the last accreted material. On the other hand, Mo is moderately siderophile, so the mantle Mo isotopic composition is dominated by the main phase of accretion (Dauphas, 2017). Comparing mass-independent Ru and Mo isotopic variations can thus inform our knowledge of the feeding zones of the Earth and other terrestrial planets and their changes with time (Dauphas et al., 2004). However, the initial distribution of Ru–Mo isotopes in the disk is unknown.

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Ru and Mo isotopic anomalies are often reported as:

$$\varepsilon^{100}\text{Ru} = \left[\frac{(^{100}\text{Ru}/^{101}\text{Ru})_{sample}}{(^{100}\text{Ru}/^{101}\text{Ru})_{standard}} - 1 \right] * 10{,}000$$
$$\varepsilon^{92}\text{Mo} = \left[\frac{(^{92}\text{Mo}/^{96}\text{Mo})_{sample}}{(^{92}\text{Mo}/^{96}\text{Mo})_{standard}} - 1 \right] * 10{,}000 \quad (1)$$

The Earth's mantle has $\varepsilon^{100}\text{Ru} = \varepsilon^{92}\text{Mo} = 0$. Meteorite groups form a linear trend with negative ε^{100}Ru and positive ε^{92}Mo, with the Earth as one endmember (Dauphas et al., 2004, 2014a; Fischer-Gödde et al., 2015; Walker et al., 2015; Dauphas and Schauble, 2016; Fischer-Gödde and Kleine, 2017). There are subtle variations in trend slope between carbonaceous and non-carbonaceous material (Budde et al., 2016). Since ruthenium and molybdenum isotopes sample different temporal phases of accretion, in principle the bulk Earth need not fall on this cosmic trend. But it does, implying that material accreted by the Earth at different times came from the same isotopic reservoir (Dauphas et al., 2004; Dauphas, 2017). Two martian crustal samples have been analyzed for mass-independent Mo isotopic variations (Burkhardt et al., 2011), but not for Ru. These analyses indicate consistency with zero ε^{92}Mo anomaly, though at least one of the two samples may have experienced terrestrial weathering (Burkhardt et al., 2014).

The Moon has an identical or very similar isotopic composition to the Earth for many elements (e.g., Dauphas and Schauble, 2016, and references therein), which is striking considering the range in isotopic compositions exhibited by meteorites. Theories to explain this phenomenon include: 1) isotopic equilibration between the Earth and Moon via the proto-lunar disk (Pahlevan and Stevenson, 2007), which may not explain isotopic similarities in refractory elements; 2) collisions that result in the Earth and Moon containing similar fractions of the proto-Earth and the Moon-forming impactor, "Theia" (e.g., Canup, 2012; Ćuk and Stewart, 2012), which require specific dynamical conditions; or 3) the proto-Earth and Theia having identical isotopic compositions, which either requires them to have similar provenance/location (e.g., Quarles and Lissauer, 2015; Kortenkamp and Hartmann, 2016) or requires isotopic homogeneity in the inner disk (e.g., Dauphas et al., 2002a, 2014a, 2014b). However, the latter theory does not explain the nearly-identical lunar and terrestrial ^{182}W isotopic anomalies as these anomalies are sensitive to differentiation timescales (Dauphas and Schauble, 2016; Dauphas et al., 2014a; Nimmo and Kleine, 2015).

Previous studies have used various isotopic systems to probe heterogeneity and mixing in the disk and address this Earth–Moon isotopic conundrum. Kaib and Cowan (2015a) and Mastrobuono-Battisti and Perets (2015) used N-body simulations of terrestrial planet accretion to assess the probability of the proto-Earth and Theia having the same oxygen isotopic composition. Kaib and Cowan (2015a) concluded that no initial isotopic distribution succeeds and so there remains no probable explanation for the Moon's oxygen isotopic composition, in agreement with earlier work by Pahlevan and Stevenson (2007). Mastrobuono-Battisti et al. (2015) found success at producing isotopically similar proto-Earths and Theias with a 20–40% probability, or 5–18% in a follow-up study (Mastrobuono-Battisti and Perets, 2017) (but see also Kaib and Cowan, 2015b). The model of Young et al. (2016) favors mixing during the giant impact to produce an Earth and Moon with identical oxygen isotopes. Alexander et al. (2012) used H, N, and O isotopes to constrain the source regions of Earth's volatiles, arguing against an outer disk origin. Differences between ^{142}Nd/^{144}Nd of Earth and chondrites may be of nucleosynthetic origin (Burkhardt et al., 2016), with the Earth as one endmember in terms of Sm–Nd isotopes. The similarity in isotopic composition of the Earth and enstatite meteorites, and its difference from other meteorites, has also been used to argue for isotopic homogeneity in the inner disk (e.g., Dauphas et al., 2002a, 2014b).

The goal of this study is to evaluate and quantify the homogeneity of the inner disk by analyzing the provenance of terrestrial planets formed in N-body simulations, and using Ru and Mo isotopes as specific tracers of mixing to model the isotopic evolution of Earth, Mars, and Theia analogues. Unlike oxygen isotopes, the Ru–Mo system is sensitive to temporal changes in source material provenance because Ru was predominantly delivered in the late veneer. Using these methods, the degree of homogeneity required to match observational constraints for the Earth can be assessed, and testable predictions can be made for the Ru–Mo isotopic compositions of Mars and the Moon. A homogeneous isotopic reservoir has previously been proposed (e.g., Dauphas et al., 2002a, 2014b) but not constrained quantitatively using dynamics.

After discussing methods in the following section, Section 3 focuses on extracting and quantifying planetary provenance and mixing in the disk from N-body simulations. Section 4 presents isotopic modeling calculations, beginning with one example case (Section 4.1) where the two compositional endmembers are the Earth and the most anomalous composition reported in meteorites. Then, we discuss what happens when we let one endmember composition vary (Section 4.2), then both (Section 4.3). Section 4.4 shows a full exploration of parameter space, including compositions with positive ε^{100}Ru and negative ε^{92}Mo that are not present in the meteorite record. Finally, Section 5 discusses the limitations and complications of the model, followed by conclusions (Section 6).

2. Methods

2.1. N-body simulations

This study utilizes two pre-existing suites of N-body simulations. Fischer and Ciesla (2014) ran fifty simulations with Jupiter and Saturn on slightly eccentric orbits (Eccentric Jupiter and Saturn, EJS) and fifty with the giant planets on non-eccentric orbits (Circular Jupiter and Saturn, CJS) predicted by the Nice model (e.g., Tsiganis et al., 2005). O'Brien et al. (2014) ran sixteen simulations extending previous models of the proposed Grand Tack event (Walsh et al., 2011), in which the giant planets migrate inward and then outward to truncate the disk of embryos (larger bodies) and planetesimals (smaller bodies). For more details, see the Supplemental Text.

Earth and Mars analogues were defined by their final semimajor axes only (Earth: 0.75–1.25 AU, Mars: 1.25–2 AU) (similar to Raymond et al., 2009), and must have late veneers to calculate their Ru–Mo anomalies. Planetary mass was not considered in the definition because no single simulation reproduces all Solar System properties, and here the focus is not on the simulations' success but rather their implications for radial mixing. Theia analogues were defined as the last large body (containing at least one embryo) to hit an Earth analogue (e.g., Mastrobuono-Battisti et al., 2015). Any planetesimals accreted to the Earth after the collision with Theia are considered to comprise the late veneer, regardless of mass. It is critical to use a large number of simulations for statistical analyses due to stochastic variations in accretion that can transform the resulting planetary chemistry (e.g., Fischer et al., 2017). Here the provenance of surviving bodies was quantified using their mass-weighted average semimajor axis:

$$\text{MWSMA} = \frac{\sum_i m_i a_i}{\sum_i m_i} \quad (2)$$

where m_i and a_i are the mass and initial semimajor axis of each accreted body i (e.g., Kaib and Cowan, 2015a).