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Tungsten isotopic evolution during late-stage accretion: Constraints on Earth–Moon equilibration

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ABSTRACT

We couple the results of N-body simulations of late-stage accretion (O'Brien et al., 2006) to a hafnium–tungsten (Hf–W) isotopic evolution code to investigate the evolution of planetary bodies in the inner solar system. Simulations can simultaneously produce planets having Earth- and Mars-like masses and Hf–W systematics by assuming that the tungsten partition coefficient decreases with increasing semi-major axis (e.g. due to increasing oxidation). Simulations assuming that Jupiter and Saturn occupy circular orbits are more successful at reproducing the Hf–W systematics than those assuming present-day Jupiter and Saturn orbits. To generate Earth-like tungsten anomalies, 30–80% of each impactor core is required to re-equilibrate with the target mantle. Some model outcomes yield a target and final impactor having similar (Earth- and Moon-like) tungsten anomalies. However, in no case can the inferred lunar Hf/W ratio be simultaneously matched. This result suggests that the Moon isotopically equilibrated with the Earth's mantle in the aftermath of the giant impact (cf. Pahlevan and Stevenson, 2007). Alternatively, either the dynamical models which show the Moon being derived primarily from the impactor mantle, or the accretion timescales obtained by the N-body simulations, are incorrect.

1. Introduction

The hafnium–tungsten (Hf–W) isotopic system provides a powerful constraint on the timing of planetary core formation, and thus of planetary accretion (e.g. Jacobsen, 2005; Kleine et al., 2009). Other things being equal, a higher abundance of ^{182}W in the mantle indicates that accretion finished earlier (see Section 2.2). Measurements of the tungsten isotope systematics of the Earth, Mars, the Moon and asteroids thus allow a chronology of solar system accretion to be established (e.g. Kleine et al., 2009).

Late-stage accretion inevitably involves large collisions (Agnor et al., 1999), which in some cases appear to have resulted in the formation of satellites such as the Moon. The Moon is thought to have formed from the re-accretion of hot material originating from the mantle of a Mars-sized impactor that struck the Earth (e.g. Canup, 2008). From an isotopic point of view, the two key aspects of this story are that: 1) the impactor was differentiated prior to encountering the Earth; and that 2) the bulk of the Moon was derived from impactor mantle material. The first factor is required to explain the apparently low mass of the lunar core and the low Fe content of the Moon: in simulations, the impactor core is rapidly accreted into the target core (Canup and Asphaug, 2001). The second factor implies that the Moon should resemble the composition of the impactor's mantle, not that of the Earth. However, terrestrial and lunar samples display a surprising similarity in isotope compositions of elements that show variations among other solar system bodies. These elements include O (Wiechert et al., 2001), Cr (Lugmair and Shukolyukov, 1998; Trinquier et al., 2008), Ti (Leya et al., 2008) and W (Touboul et al., 2007, 2009). The similarity in O (and Cr and Ti) isotopes could in principle arise if two bodies contained a similar mix of nucleosynthetic and solar nebula components and perhaps formed at similar heliocentric distances (Wiechert et al., 2001), although the probability of such an occurrence is small (Pahlevan and Stevenson, 2007). However, the indistinguishable W isotopic compositions of the terrestrial and lunar mantles presents more of a problem, because variations in the $^{182}W/^{184}W$ ratio cannot be produced by varying proportions of different nucleosynthetic components but rather reflect the different timescales and conditions of core formation (Touboul et al., 2007).

There are three possible explanations for the W isotopic similarities of the Earth and Moon. First, the impactor just happened to have identical isotopic signatures to the Earth. Second, the bulk of the Moon was derived largely from the proto-Earth, implying that there is a fundamental error in current models of lunar origin. Third, the Moon isotopically re-equilibrated with the Earth following the giant impact, as has recently been proposed to account for the O isotope similarity of the Earth and Moon (Pahlevan and Stevenson, 2007).

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Below we investigate the first of these possibilities for tungsten. Qualitatively, our argument is as follows. Lunar- to Mars-mass embryos generally form within a few Ma (Kokubo and Ida, 2000), while their growth into Earth-mass planets takes ~10–100 Ma. Other things being equal, the Mars-mass moon-forming impactor should therefore develop more radiogenic mantle tungsten than the target (Earth). Since the present-day Moon actually has a higher Hf/W ratio than the Earth, it should have even more radiogenic mantle tungsten. Thus, the fact that the Moon and Earth have identical mantle tungsten isotopic signatures is a potential argument for post-impact re-equilibration. To quantify this argument, we resort to dynamical N-body simulations in which tungsten isotopic evolution is tracked. We find that impactors having Moon-like Hf/W ratios always acquire more radiogenic mantle tungsten than the present-day Moon. Having examined various mixing scenarios to reduce this mismatch, we conclude that post-impact re-equilibration is required to explain the present-day observations (unless the N-body accretion timescale or the lunar impact simulations are incorrect).

One advantage of this approach is that we can use physical (mass, semi-major axis) as well as isotopic observations to help reduce the non-unique nature of the Hf–W constraint. We also require our models to simultaneously produce both Earth-like and Mars-like bodies, since these are the only two major bodies for which we have isotopic measurements. To test the robustness of our results, we adopt several different models for how the Hf/W ratio varies between bodies (Section 4.1). We find that the results are very similar, because the logic outlined in the preceding paragraph does not depend on the model details. We also investigate (Section 3.3) the extent to which addition of proto-Earth (target) material to the impactor could result in more Moon-like results.

2. Methods

2.1. N-body accretion model

The tungsten isotope calculations, described below, are carried out as a post-processing step on the results from a series of N-body simulations performed by O'Brien et al., (2006); hereafter OML06. These simulations are initiated with 25 Mars-mass (0.093 M_E, where M_E is the present-day mass of the Earth) planetary embryos and ~1000 planetesimals 1/40th as massive spanning 0.3 AU to 4 AU in distance. Half the initial mass is contained in the embryos and half in the planetesimals. The orbits of all these bodies are tracked, with the small planetesimals perturbing the orbits of the embryos but not each other. When collisions occur they result in perfect mergers with angular momentum conserved. The orbits were tracked for 250 Ma. Surviving massive bodies are typically comprised of a few to ~10 embryos and several tens of planetesimals.

Two different suites of simulations were run. In the first suite (EJS1-4) Jupiter and Saturn are included on their current orbits. In the second suite (CJS1-4), Jupiter and Saturn are closer together and on zero-eccentricity orbits, to reproduce their hypothesized configuration prior to the Late Heavy Bombardment (Gomes et al., 2005). For both configurations, roughly half of the initial mass ends up in planets, with the remainder either ejected from the system or hitting the Sun. Both sets of simulations result in 2–4 roughly Earth-mass planets closer than 2.5 AU. The main differences between the two suites are that the EJS runs result in earlier termination of accretion, planets with lower eccentricities, a smaller planet near the position of Mars, and less mixing of material from the outer asteroid belt into the terrestrial planet zone.

Our N-body code neglects the effect of fragmentation. Impact erosion can lead to changes in bulk planetary chemistry (O'Neill and Palme, 2008), while fragmentation causes both the timescale of accretion and the final planet masses to change (Chambers, 2008). Although not included here, the chemical consequences of these processes are in principle easy to investigate.

2.2. The ^{182}Hf–^{182}W system: definitions and observational constraints

Hafnium is lithophile and W is siderophile, resulting in strong fractionation during core formation, while ^{182}Hf is unstable and decays to ^{182}W with a half-life of 9 Ma. As a result, early core formation results in mantles with excess ^{182}W (i.e. a positive tungsten anomaly), with the magnitude of the excess depending on the timing of the event and the degree of fractionation (Kleine et al., 2009, e.g.). Tungsten isotopic evolution depends not only on when core formation happened but also on how efficiently the impactor material re-equilibrates with the target's mantle during each individual impact, and on how strongly tungsten is subsequently partitioned into the target's core (Jacobsen, 2005; Halliday, 2004; Kleine et al., 2004b; Nimmo and Agnor, 2006).

There are two main observational constraints provided by Hf–W data. The first is the ratio of Hf to W in the planetary mantle. Here we will define this ratio relative to a chondritic reference as follows:

$$f^{\mathrm{Hf/W}} = \frac{\left(C^{180\mathrm{Hf}}/C^{183\mathrm{W}}\right)}{\left(C^{180\mathrm{Hf}}/C^{183\mathrm{W}}\right)_{\mathrm{CHUR}}} - 1 \quad (1)$$

where $C^{180\mathrm{Hf}}$ and $C^{183\mathrm{W}}$ are the mantle concentrations of the two isotopes, and CHUR refers to an undifferentiated (chondritic) ratio.

The second is the mantle tungsten anomaly ε_W, defined here as

$$\varepsilon_W = \left[\frac{\left(C^{182\mathrm{W}}/C^{183\mathrm{W}}\right)}{\left(C^{182\mathrm{W}}/C^{183\mathrm{W}}\right)_{\mathrm{CHUR}}} - 1\right] \times 10^4. \quad (2)$$

In the remainder of this work, “tungsten anomaly” will be assumed to refer to the mantle of the body in question. A chondritic body has $f^{\mathrm{Hf/W}} = \varepsilon_W = 0$ by definition.

We take the chondritic ^{180}Hf/^{183}W ratio to be 2.627 (equivalent to an Hf/W ratio of 1.04) (Kleine et al., 2009, 2004a). The bulk silicate Earth $f^{\mathrm{Hf/W}}$ value is based on the Th/W ratio of Earth's mantle (Newsom et al., 1996) and is 13.6 ± 4.3 (Kleine et al., 2009). For the bulk silicate Moon, the corresponding $f^{\mathrm{Hf/W}}$ value is based on the U/W ratio of the lunar mantle (Palme and Rammensee, 1982) and is 21.4 ± 1.7. The FeO content of the lunar mantle is probably ≈13 wt.% (Jones and Palme, 2000), while the lunar core size is uncertain, but is unlikely to exceed 2% of the lunar mass (Wieczorek et al., 2006). As discussed by Nimmo and Kleine (2007), the Hf/W for bulk silicate Mars is uncertain. Assuming Hf and Th are present in carbonaceous chondrite relative abundances, $f^{\mathrm{Hf/W}} = 2.4 \pm 0.9$ (note that (Nimmo and Kleine, 2007) use a different definition of $f^{\mathrm{Hf/W}}$ to that employed here).

The present day tungsten anomaly for the Earth is $\varepsilon_W = 1.9 \pm 0.1$ (Yin et al., 2002; Kleine et al., 2002; Schoenberg et al., 2002; Kleine et al., 2004a). Interpretation of the lunar ε_W has been bedevilled by cosmogenic effects (e.g. Leya et al., 2000), but it has been shown that lunar metals preserve the indigenous W isotopic composition of their host rocks (Touboul et al., 2007; Kleine et al., 2005b). The lunar metal data reveal that the lunar mantle has a tungsten anomaly of $\varepsilon_W = 2.0 \pm 0.1$, which is identical within error to the terrestrial value (Touboul et al., 2007, 2009). For Mars, the shergottites yield a tungsten anomaly of $\varepsilon_W = 2.3 \pm 0.2$ (Kleine et al., 2004a; Foley et al., 2005). Nakhlites have larger ^{182}W excesses but these most likely stem from an early differentiation within the Martian mantle and hence do not only result from core formation (Kleine et al., 2004a; Foley et al., 2005). Hence, we take the tungsten anomaly of shergottites to represent that of the bulk Martian mantle.

2.3. Isotopic calculations

Isotopic evolution is calculated using an approach based on Nimmo and Agnor ((Nimmo and Agnor, 2006); hereafter NA06). The evolution of four isotopes (^{182}Hf, ^{182}W, ^{180}Hf and ^{183}W, where the