TUNGSTEN ISOTOPIC EVOLUTION AND MANTLE EQUILIBRATION IN GRAND TACK ACCRETION SIMULATIONS.

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Summary: The evolution of the Hf/W isotopic system is followed through the accretionary collisions of 28 N-body simulations using the Grand Tack scenario, during which the target cores are assumed to experience partial mantle re-equilibration. The simulations are able to reasonably reproduce the measured tungsten isotope values for resulting Earth and Mars-sized bodies.

Introduction: Measurements of the radioisotopic Hf/W system found in meteorites and the Earth can be used to place constraints on the timescales of core formation and accretion [1]. Calculations of the tungsten isotopic evolution of planetesimals in "classical" accretion models have been able to produce physical and chemical values close to those measured presently on the Earth [1,2]. The classical models' difficulty in reproducing the correct mass for Mars inspired the creation of the Grand Tack scenario [3,4]. In this study we examine whether the Grand Tack simulations are able to reproduce the measured tungsten anomalies in final planets resembling Earth and Mars.

Mantle Equilibration: Hf is a lithophile and W a siderophile element, resulting in fractionation during core formation. The decay of ^{182}Hf into ^{182}W with a half life of 9 My causes mantles with early core formation to develop a large positive tungsten anomaly [5]. The tungsten evolution of a mantle depends on how impactor core material re-equilibrates during each individual impact with a target [1,2]. The equilibration factor k is defined as the fraction of impactor core not directly added to target core, where $k = 0$ indicates core merging, and $k = 1$ indicates complete re-equilibration. For the results in this study, an intermediate $k = 0.5$ was used for comparison with past analyses on the classical accretion scenario [1,5].

Isotopic Results: Table 1 summarizes the results of surviving bodies from the 28 N-body simulations.

	Mantle fractionation	Tungsten anomaly	Accretion Time (My)	N
Earth	**13.6 ± 4.3**	**1.9 ± 0.1**	-	-
Earth-like (8:1)	16.1 ± 3.1	5.0 ± 2.3	39 ± 45	26
Earth-like (4:1)	16.1 ± 1.7	5.4 ± 2.1	17 ± 6	18
Mars	**2.4 ± 0.9**	**2.3 ± 0.2**	-	-
Mars-like (8:1)	11.4 ± 6.5	12.0 ± 7.1	1 ± 3	13
Mars-like (4:1)	2.9 ± 0.8	2.9 ± 2.1	4 ± 6	7

Table 1: Summary of results. Mean and standard deviation for final values of bodies are displayed for objects that meet Earth-like or Mars-like criteria (mass within a factor of 2 of actual, Earth-like semi-major axis between 0.387 and 1.524 AU, Mars-like semi-major axis between 1 and 2.3 AU). Measured Earth and Mars are values from [6], [7], [8] Accretion time refers to the time when the body reached 90% of final mass.

Fig. 1 shows the mantle fractionation factor as a function of semi-major axis, with the solid line representing the initial assumed values (from [5]). An initial variation in $f^{\mathrm{Hf/W}}$ is one way of explaining the different values measured for Earth and Mars. The initial variation is not completely destroyed, despite the significant radial mixing caused by Jupiter's inwards-then-outwards migration.

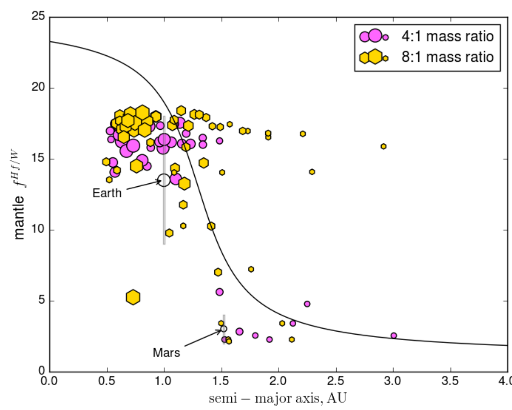

Figure 1: Mantle fractionation factor of surviving bodies as a function of final semi-major axis, for 28 Grand Tack simulations [3]. The solid line denotes initial assumed variation in $f^{\mathrm{Hf/W}}$ [5]. Mass ratio refers to the distribution of initial mass in Mars-sized embryos vs. smaller planetesimals. The size of the markers are scaled to the object's final mass.

In Fig. 2, the variation in mantle fractionation $f^{\mathrm{Hf/W}}$ against tungsten anomaly ε^{W} is shown. Tungsten anomaly increases with increased $f^{\mathrm{Hf/W}}$ but decreases with longer accretion timescales, as expected. Although most model Earth-mass bodies develop large $\varepsilon^{182\mathrm{W}}$ values, because of their rapid accretion, some take longer to complete accretion and produce Earth-like values. Mars analogues accrete rapidly but can develop Mars-like ε^{182W} values because of lower $f^{\,Hf/W}$ values. Smaller values of k (less equilibration) result in isotopic anomalies which are too large.

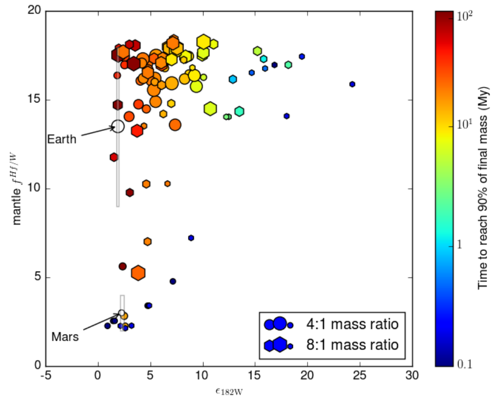

Figure 2: Mantle fractionation factor of surviving bodies as a function of tungsten anomaly. Color scale shows approximate time of last giant impact. Earth and Mars values (shergottite source) are plotted as rectangles, with circles shown for mass comparison.

In Fig. 3 tungsten anomaly ε^{W} is plotted against semi-major axis. Accretion terminates earlier at larger semi-major axes, but the resulting tungsten anomalies of these outer bodies are highly variable, because of the varying $f^{\,Hf/W}$ values. The actual tungsten anomalies for both Earth and Mars sit towards the lower end of the envelope of model values, perhaps suggesting more re-equilibration than assumed here (k>0.5).

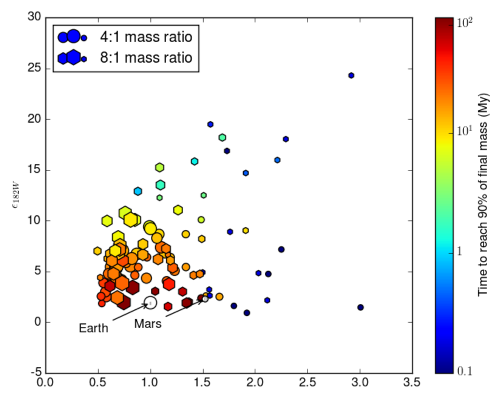

Figure 3: Tungsten anomaly of surviving bodies as a function of final semi-major axis. Color and size are formatted as in Fig. 2. The uncertainties of tungsten anomaly for Earth and Mars are smaller than the circle markers.

Discussion: The study suggests that the Grand Tack scenario is able to construct an Earth and Mars that have both physical and chemical characteristics that reasonably agree with measured values, assuming that there is a spatial variation in $f^{\,Hf/W}$ and that mantle re-equilibration occurs with a factor of around $k = 0.5$. Future work should focus on exploring different prescriptions for k, which is likely to depend on the details of individual impacts [9], and on more sophisticated treatments of how $f^{\,Hf/W}$ is likely to vary (for instance, as a function of the oxidation state of the starting material [10]).

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