EPSC Abstracts
Vol. 13, EPSC-DPS2019-977-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Metal-silicate partitioning of Mo and W in Earth's mantle during core formation

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Abstract

We are able to reproduce the W and Mo mantle abundances in an astrophysical-geological model of terrestrial planet accretion and core formation using a new parameterization of metal-silicate partitioning developed from new and published high pressure laboratory experiments. We find that this is only possible when Earth's mantle grows carbon-enriched and sulfur-depleted. Ultimately, the model produces simulated Earth-like planets matching 17 elemental mantle abundances including S, C, Mo, and W.

1. Introduction

The moderately siderophile elements molybdenum and tungsten are important constraints on the processes of accretion and core formation during Earth's earliest history. In particular, the details of tungsten partitioning between mantle and core determine the final radiogenic 182-tungsten anomaly generated by the ^{182}Hf-^{182}W radioactive decay system, which has been used to infer the history of Earth's core formation since the 1990s [1]. The partitioning of both W and Mo have been the focus of a number of previous experimental investigations [2-16], however these studies have produced varying and inconsistent models, thereby making extrapolations to realistic mantle-silicate equilibration conditions difficult. The liquid-liquid metal-silicate partition coefficients D_{Mo} and D_W have variously been suggested to depend on pressure, temperature, silicate and metal compositions. Indeed, the high cationic charges of W and Mo in silicate melts make their partition coefficients particularly sensitive to oxygen fugacity.

2. High pressure laboratory metal-silicate partitioning experiments

We combined 48 new high pressure and temperature experimental results with a comprehensive database of previous partitioning experiments [2-16] to re-examine the systematics of Mo and W partitioning. From this database, we selected 68 Mo and 57 W experiments with pyrolite-like silicate compositions because Mo has a 4+ and W has a 6+ oxidation state in terrestrial magma ocean conditions and their partitioning is sensitive to silicate and metallic melt compositions. Fitting to the selected data, we present a new partitioning model in the form of a parameterized activity-corrected observed concentration ratio [5]:

$$\log_{10} K = a + b\frac{1}{T} + c\frac{P}{T} \quad (1)$$

We find that Mo becomes more siderophile with increasing temperature but less siderophile with pressure such that the fitting parameters are $a = 1.47 \pm 0.44$, $b = -1448 \pm 851$, and $c = -67.1 \pm 20.9$. We also find that W becomes more siderophile with increasing temperature but has no resolvable dependence on pressure such that the fitting parameters are $a = 0.61 \pm 0.28$ and $b = -4091 \pm 670$. Both W and Mo become more siderophile with increasing C content of the metal: we therefore performed experiments with varying C concentrations and fit epsilon interaction parameters $\varepsilon_C^{Mo} = -7.03 \pm 0.30$ and $\varepsilon_C^{W} = -7.38 \pm 0.57$.

3. Numerical planetary accretion and core formation simulations

W and Mo along with C (which is assumed to have $D_C = 1000$, but the results are insensitive to this choice), are incorporated into a combined N-body accretion and differentiation model, which already includes the major rock-forming elements as well as moderately and highly siderophile elements and sulphur [17-18]. In this model, oxidation and volatility gradients extend through the protoplanetary disk so that Earth accretes heterogeneously. These gradients as well as the equilibration pressure (temperature is assumed to lie along the peridotite melting curve) are fitted using a least squares optimisation so that the model Earth-like planet reproduces the composition of the Bulk Silicate Earth (BSE) across 17 simulated element concentrations (Mg, Fe, Si, Ni, Co, Nb, Ta, V, Cr, S, Pt, Pd, Ru, Ir, W, Mo, and C). We also included the interaction parameters of W and Mo with Si, S, O, and C in the model.

Across six separate terrestrial planet formation simulations, we discovered that W and Mo require the early accreting Earth to be sulphur-depleted and carbon-enriched so that W and Mo are efficiently partitioned into Earth's core and do not accumulate in the mantle. If this is the case, the produced Earth-like planets possess mantle compositions matching the BSE across all simulated elements. However, there are two distinct estimates of the mantle's C abundance: ~70 ppm [19] and ~770 ppm [20], and all six models are consistent with the higher [20] estimated carbon abundance.

Acknowledgements

We acknowledge financial support from the European Research Council (ERC) Advanced Grant "ACCRETE" (Contract No. 290568) and the German Science Foundation (DFG) Priority Programme SPP1833 "Building a Habitable Earth" (RU 1323/10-1) and SPP1385 "The First 10 Million Years of the Solar System – a Planetary Materials Approach" (RU 1323/2).

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