EXTENT OF ISOTOPIC FRACTIONATION DUE TO METAL-SILICATE EQUILIBRATION DURING CORE FORMATION. G. Nathan[1] (nathanga@msu.edu), S. A. Jacobson[1],
[1]Department of Earth and Environmental Sciences, Michigan State University, 288 Farm Ln, East Lansing, MI 48824

Introduction: Explaining the bulk silicate isotopic composition of Solar System bodies is an outstanding goal of planetary science. One potential mechanism for the isotopic fractionation of planetary mantles is metal-silicate equilibration during core formation. Here, we present the results of a generalizable computational model of isotopic fractionation due to individual impact-induced core formation events. Specifically, we explore the parameter space in the context of the ^{56}Fe isotopic composition of the bulk silicate Earth.

Metal-silicate equilibration during core formation is responsible for depleting planetary mantles of siderophile elements and may be additionally responsible for establishing its isotopic composition. For instance, terrestrial oceanic basalts have isotopically distinct δ^{56}Fe anomalies relative to chondritic material [1], while abyssal peridotites appear indistinguishable from chondrites [2]. Some studies have concluded that isotopic fractionation during metal-silicate equilibration is too small at the high temperatures and pressures of core formation to account for terrestrial Fe isotopic variations and the observed isotopic signature of the mantle [3], contradicting others that came to the opposite conclusion [4]. Prior works assume single-stage core formation models which unphysically assert that the entire bulk silicate Earth and entire core equilibrated in one event at a mid-mantle pressure and temperature. Astrophysical models of planet formation instead suggest that terrestrial bodies experience multiple episodes of core formation driven by many large accretionary impacts. These events occur as a planet grows, and so equilibration between silicate and core-forming liquids covers a wide range of PT conditions, and each accretion event may involve only a small fraction of the planet's mantle and, perhaps, not even all of each projectile's core (for review, see [5]).

To understand multi-stage core formation, it is essential to understand the effects of individual impactors of varying size and composition on the subsequent isotopic fractionation of a planet's mantle. A range of scenarios are of interest: chondritic bodies (C) represent non-differentiated bodies present early in the formation history of the Solar System, while non-chondritic bodies (NC) are established by past episodes of core formation and metal-silicate equilibration that resulted in elevated δ^{56}Fe signatures. In a multi-stage core formation scenario, a growing planet would experience multiple metal-silicate equilibration events caused by impacts both from already differentiated (NC) and still undifferentiated (C) planetesimals.

Model description: While our model will be extended to other isotopic systems in the future, here we focus on the isotopic evolution of Fe, the primary core forming element. Our model analytically calculates the δ^{56}Fe isotopic composition of a terrestrial body following metal-silicate equilibration resulting from a projectile planetesimal striking a target planetary embryo, considering mass balance and isotopic abundances in the Fe system. This explores the effect(s) of the amount of equilibrating target mantle, isotopic fractionation factor, and initial isotopic compositions of the colliding planetesimals on the resulting isotopic composition. Only a fraction of the larger target body's mantle equilibrates with the projectile, but nearly the entire projectile mantle equilibrates, which is consistent with laboratory fluid experiments of post-impact turbulent mixing [6].

The fractionation factor $\Delta^{56}Fe_{Mantle\text{-}Core}$ is the isotopic difference between mantle and core material following metal-silicate equilibration, and it is a key input to the model and determined by laboratory measurements. Liu et al (2017) measured $\Delta^{56}Fe_{Mantle\text{-}Core}$ and predicted the resultant terrestrial silicate mantle δ^{56}Fe composition to be between -0.01 and +0.03 per mil, depending on the composition of the metallic melt and the temperature and pressure of core formation [3], where chondritic δ^{56}Fe composition is the isotopic standard of 0.0 per mil. However, for the purposes of this exploratory study, we impose a fractionation factor, $\Delta^{56}Fe_{Mantle\text{-}Core}$, of +0.06 per mil, the largest possible value implied by values from [4], representing fractionation between basalt and an FeH_x alloy at conditions of 2,000 K and 40 GPa. These equilibration conditions and particular alloy are chosen to maximize the fractionation factor and exaggerate effects to best identify them, rather than for realistic conditions of equilibration.

Results: We explored the isotopic fractionation in δ^{56}Fe due to core formation for a variety of chondritic (starting at δ^{56}Fe = 0.0) and non-chondritic (starting at δ^{56}Fe = +0.03) target-projectile combinations, shown in Fig.1. For a chondritic target, impacted by a chondritic projectile, there is an increase in mantle δ^{56}Fe composition following impact induced metal-silicate equilibration. This effect increases with a larger projectile to total mass ratio and is greater if the projectile is non-chondritic. However, this effect is still minimal, on the order of +0.01 to +0.03 per mil, depending on the size of the projectile. In the case of a non-chondritic target mantle impacted by a chondritic

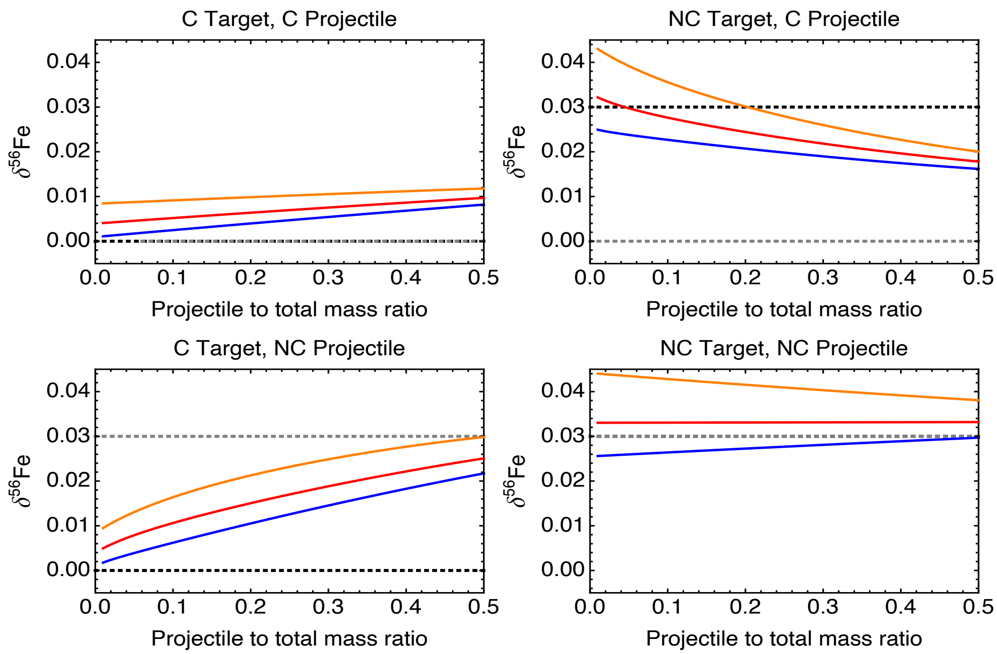

Figure 1: Resulting mantle δ^{56}Fe anomalies after metal-silicate equilibration of chondritic (C) and non-chondritic (NC) target and projectile pairs. δ^{56}Fe is shown as a function of the projectile-to-total-mass ratio (0.01 is a very small projectile, 0.5 is an equal-sized projectile and target). Blue, red, and orange lines respectively represent 5, 20, and 40% of the target's mantle equilibrating during a post-impact core formation event. Black and grey lines represent initial compositions of the target and projectile, respectively.

projectile, subsequent metal-silicate equilibration will decrease mantle δ^{56}Fe. Equilibration between a non-chondritic target and planetesimal will result in very little change in mantle isotopic composition (≤ 0.01 per mil).

Colored lines indicate how much of the target mantle equilibrates in the simulated metal-silicate equilibration event. Note the orange lines, which represent 40% of the target mantle equilibrating post impact. With more of the target mantle equilibrating, less unequilibrated material mixes with and dilutes the equilibrating material, resulting in fractionation closer to the imposed factor, $\Delta^{56}Fe_{Mantle-Core}$, of +0.06 per mil. However, a high percentage of target mantle equilibration is unphysical, especially in the case of a collision between a small projectile and much larger target. Thus, the resulting fractionation in this scenario should be considered an extreme upper limit.

Discussion: The effects of isotopic fractionation due to metal-silicate equilibration on δ^{56}Fe are small, regardless of the combination of chondritic or non-chondritic projectile and target. Of course, this is in part due to the small fractionation factors measured by laboratory experiments. However, it is also due to dilution during the mixing between equilibrating and non-equilibrating projectile and target reservoirs. This important diluting effect means that the effective fractionation following an impact is ~5x smaller than a corresponding measured $\Delta^{56}Fe_{Mantle-Core}$ factor.

Such small fractionation means that each core formation event will not significantly alter the composition of terrestrial Fe. The delivery of a chondritic projectile to a chondritic target could not raise the target's isotopic composition by much more than +0.01 per mil (see top left panel of Fig.1). That signature, at its highest, would be indistinguishable from (and still lower than) the estimated terrestrial mantle δ^{56}Fe composition (+0.025 per mil, [1]).

Even in the multi-stage scenario, subsequent collision-induced core formation events are unlikely to result in measurable isotopic fractionation. In fact, such events are likely to counteract any prior isotopic enrichment. In the case where the target body has a non-chondritic composition, the delivery of smaller chondritic projectiles drives the target mantle δ^{56}Fe closer to the chondritic value (see top right panel of Fig.1). Additionally, because all the effects modeled here are exaggerated by the choice of the highest conceivable fractionation factor, in reality the effects would be even smaller.

However, this does constrain Earth's building blocks as likely chondritic in δ^{56}Fe. Even multiple stages of core formation cannot shift then δ^{56}Fe isotopic composition by a measurable amount. Thus, given that the estimate from abyssal peridotites that Earth's mantle composition is consistent with chondritic [1] and it likely was not altered by metal-silicate equilibration, Earth's δ^{56}Fe signature must have been established as chondritic. The combined effect (or lack thereof) of small fractionation factors and mixing dilution means core formation cannot be the source of varied and non-chondritic terrestrial δ^{56}Fe.

References: [1] Craddock, P. R. et al. (2013) *Earth and Planet. Sci. Lett.*, *365*, 63-76. [2] Teng, F. Z., et al. (2013) *Geochimica et Cosmochimica Acta*, *107*, 12-26. [3] Liu, J. et al. (2017) *Nature communications*, *8*, 14377. [4] Shahar, A., et al. (2016) *Science*, *352*(6285), 580-582. [5] Rubie, D. C., & Jacobson, S. A. (2016) *Deep Earth: Physics and Chemistry of the Lower Mantle and Core*, *217*, 181-190. [6] Deguen, R. et al. (2011) *Earth and Planet. Sci. Lett.*, *310*(3-4), 303-313.