Short-lived Lunar Dynamos Driven by the Accretion of Cold Impactor Material. Fiona Nichols-Fleming[1*], Alexander J. Evans[1], and Brandon C. Johnson[2], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI ([*]fiona_nichols-fleming@brown.edu), [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN.

Introduction: Measurements of the lunar crust and samples suggest that the Moon likely had an early magnetic field with high surface field intensities of 40 to 110 μT between 4.3 and 3.5 Ga followed by a period of weak field intensities on the order of a few μT that may have persisted for several billion years [1-7]. This history of the lunar dynamo poses a unique problem as no model has yet been able to explain the inferred lunar paleointensity record [8]. Previous studies have investigated several mechanisms for producing a lunar magnetic field to match the inferred lunar paleorecord including models of core convection [9-15], mechanical mixing driven by differential rotation of the mantle and core due to large impacts [16], and mantle precession [17-18]. To date, none of these mechanisms are able to reproduce both the intensity and lifetime of the inferred lunar magnetic field.

Furthermore, models of thermochemical core convection – the process most commonly recognized to sustain dynamos within planetary cores of rocky bodies – are substantially underpowered and have been unable to produce field intensities greater than ~1 μT [10]. Here we investigate whether the period of high surface field intensities between ~3.9 and ~3.5 Ga could have been caused by episodic and vigorous thermochemical convection of the lunar core caused by cold, dense material from an impactor sinking to the lunar core-mantle boundary (CMB), see Figure 1. This mechanism could result in short-lived periods of high surface magnetic field intensities that could conceivably explain the unusually high field intensities suggested by the early lunar paleorecord.

Methodology: For the nominal range of viscosities expected for the lunar mantle (10^{18}-10^{22} Pa s) [19-20], impactor material will descend through the mantle in the Stokes regime and will therefore remain intact [21]. The impactor core is assumed to be less dense than the lunar core due to compositional variations from the inclusion of sulfur or some amounts of rocky material, allowing the impactor material to remain in a layer above the CMB. Additionally, to maintain uniform heat flow across the entire CMB and allow for the use of the simplified dynamo scaling relation of [10], we assume that the cold impactor material surrounds the core uniformly. We extrapolate from the size of the impactor material at the CMB to the initial impactor size by assuming that the impactor material at the CMB represents the entire core of a differentiated impactor with a ratio of 30 to 70 weight percent for the core and mantle, respectively [22].

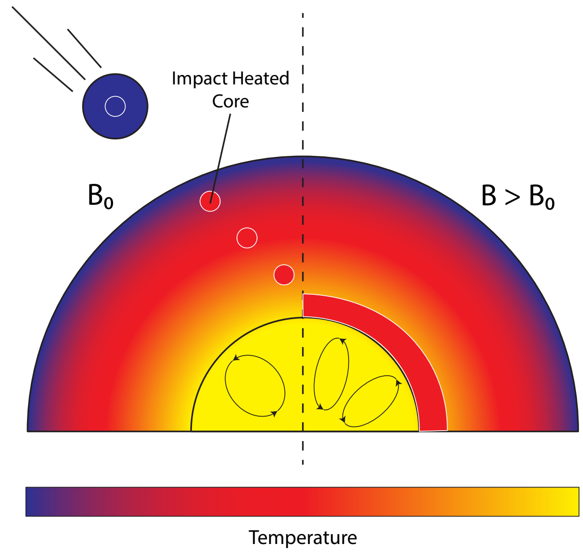

Figure 1: Schematic illustrating a pre-impact (left) and post-impact (right) temperature of the Moon. Left: The impact-heated core material from the impactor descends through the lunar mantle. Right: impactor core material is distributed laterally across the CMB. Convection cells inside the lunar core are shown. As the cold impactor material remains above the lunar core (right), more vigorous thermochemical convection within the core is driven by the large temperature difference and higher heat flow at the CMB resulting in a larger magnetic field intensity.

For impactor core material to promote more vigorous convection within a lunar core at a temperature of 1800 K, the post-impact temperature of the impactor core material must be lower than 1800 K [9, 10, 23]. Using the ANEOS equation of state for iron [24] and the planar impact approximation, we find that this condition is met when the vertical component of the impact velocity is lower than 7.5 km/s. Thus, impactor core material is able to promote more vigorous core convection for approximately 30% of all lunar impacts.

The amount of additional energy transported across the CMB due to the cooler surrounding impactor material is given by the thermal energy of cooling the lunar core by some difference in temperature. To quantify the maximum effect of the impactor material on the lunar core dynamo, the impactor material at the CMB is assumed to be exclusively heated by the core.

We employ the dynamo scaling law of [24] as modified by [10] to approximate the field lifetime for a given surface field intensity and the heat flux across the CMB, where the heat flux across the CMB is directly proportional to the temperature increase of the impactor core material at the CMB. To maximize the potential lifetimes of the calculated dynamos, we presume that the magnetic field produced is purely dipolar.

To match measured paleointensities, we find the lifetime for a given surface intensity for a range of CMB temperature differences and impactor material radii and find the minimum size that will support the field for more than two days – the amount of time for the sample to cool [1, 4] – as function of CMB temperature difference.

Results & Discussion: Based on the above relations, we determine a relationship between the minimum required impactor sizes and the temperature difference between the lunar core and the impactor material for surface intensities of 50 and 110 μT, as shown in Figure 2. Figure 2 also shows required impactor sizes for supporting 50 and 110 μT fields for one year.

Overall, we find that minimum impactor diameters of about 1 – 10 km are able to produce short-lived fields with strengths between 20 and 110 μT for the assumed two-day-field threshold. We expect that most differentiated impactors will have diameters larger than 40 km [26], and therefore we expect that any differentiated impactor with a vertical component of the impact velocity less than 7.5 km/s should be able to promote a strong, short-lived field.

The relatively small impactor sizes required to produce short-lived fields of high intensity suggest that impacts with a vertical velocity below 7.5 km/s may have a signature in the lunar paleorecord. Additionally, as 4.3 to 3.5 Ga is a period in lunar history with a high impact flux, the timing of these high field intensities could be the result of more frequent impacts. Overall, this method has the potential to explain the unexpectedly high field intensities found in the early lunar paleorecord.

Future work will include the effects of different lunar core temperatures as well as the addition of heat to the impactor material as it descends through the lunar mantle. It is expected that mantle heating will be of greater importance for smaller amounts of impactor material as the thermal diffusion timescale is smaller than or on the order of the amount of time for the material to reach the CMB in these cases.

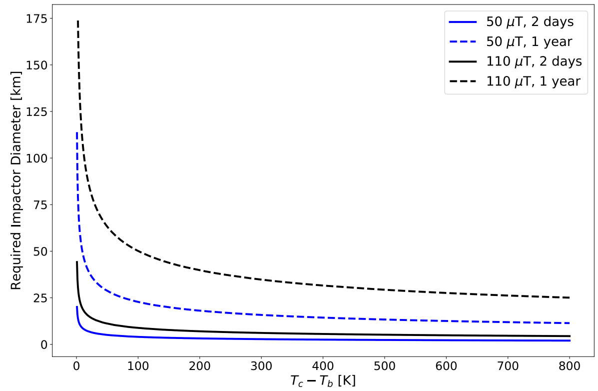

Figure 2: Minimum required diameters of differentiated impactors as a function of the temperature difference between the core and the impactor material for particular surface field strengths. The required diameter is defined as the smallest impactor which can support the given field strength for over two days or one year represented by the solid and dashed lines, respectively.

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