A LUNAR DYNAMO POWERED BY CORE CONVECTION AND A BASAL MAGMA OCEAN. S. S. Hamid[1]*, J. G. O'Rourke[1], and K. M. Soderlund[2], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (*sshamid1@asu.edu), [2]Jackson School of Geosciences, University of Texas at Austin, Austin, TX.

Introduction: Remnant magnetization of the lunar crust and returned Apollo lunar samples indicate that an ancient, internally generated magnetic field existed on the Moon. Paleomagnetic analyses of returned Apollo samples revealed a high-intensity field that persisted ~4.2–3.6 billion years ago (Gyr) followed by a weakened field that persisted until ~1.92–0.80 Gyr [1, 2, 3]. Previous studies, however, have challenges identifying the mechanism(s) that can explain both the high- and low-intensity dynamo epochs.

The timing and intensity of the Moon's magnetic field are dictated by the structure of its interior. Vigorous convection of an electrically conductive fluid can generate a strong magnetic field via dynamo action. An internal energy source is required to drive these convective motions. In a previous study [4], Apollo seismic data were reanalyzed to search for layering deep within the Moon that may be associated with the lunar core. Findings revealed the presence of a solid inner core, a fluid outer core, and possibly an overlying partially molten boundary layer. Furthermore, analyses of Gravity Recovery and Interior Laboratory (GRAIL) mission data constrained values of the Moon's mean density and moment of inertia as well as the tidal Love number, which constrains the dependency of density on depth and the rigidity of the body, respectively. Calculated models of the mission data supported the presence of a fluid outer core and were compatible with a solid inner core within the Moon's interior [5].

Previous studies have demonstrated that core convection alone would not have been able to produce inferred paleofields. Available energy sources—thermal, gravitational, and latent heat—produce insufficient energy to sustain the high-intensity field for its observed duration [1]. One recent study suggested that convection in a basal magma ocean (BMO) produced the high-intensity field [2]. Although liquid silicates generally would not have sufficient electrical conductivity to sustain a dynamo under lunar conditions, the lunar BMO may have had a particularly high titanium and iron content. However, that study did not examine the transition from a BMO-hosted dynamo to a potential core-hosted dynamo. In this study, we test the hypothesis that an early BMO dynamo in combination with a later thermo-compositional core dynamo driven primarily by inner core solidification may help explain the history of the lunar magnetic field and the modern core structure.

We calculate the energetics of the core during the solidification of the BMO and beyond to determine the sensitivity of the model to parameters such as the abundances of sulfur ([S]) and potassium ([K]) in the bulk core, thermal conductivity (k_c), and the heat flow across the core-mantle boundary (Q_C), to help constrain which parameters promote convection, and thus a dynamo, in the lunar core.

Methods: In this study, we model the thermal evolution of the core using a thermochemical core convection model. The model starts 4.2 billion years before today, covering the evolution of the BMO and the time after the BMO has solidified. Using the nominal model output from [2] (i.e., V19K50p54 in their Table 2), the model calculates the core energetics and structure using the temperature at the top of the BMO and Q_C when the basal magma ocean was >1700 K. At lower temperatures, when the BMO has presumably solidified, Q_C goes linearly to a value that we specify for present day.

Initial conditions: As initial conditions, we begin our simulations with a few assumptions [2]: 1) the surficial lunar magma ocean has solidified, 2) mantle density overturn has occurred, leaving some potassium, rare earth elements, and phosphorus (KREEP) material beneath the plagioclase crust, and 3) the dense KREEP material that overturned and sunk to the bottom of the mantle is 1700 K and molten due to radiogenic heating. We further assume that the iron-rich core starts fully liquid and chemically homogeneous.

Results: Simulations were run under a range of values of [S], [K], Q_C, and k_c and were then compared against a reference simulation with [K] = 50 ppm, $Q_C = 10^9$ W at present day, and k_c = 40 W/m/K. We test values of [S] ranging from 1 to ≥6 wt%.

Heat budget: In our model, the temperature at the CMB begins at ~1700 K and quickly spikes to ~1900 K due to radiogenic heating. The core then begins to cool as radiogenic heating in the BMO declines over time. The heat budget of the core initially includes secular cooling (Q_S) and radiogenic heating (Q_R). Once the inner core nucleates, latent heat (Q_L) and the gravitational energy (Q_G) associated with the exclusion of S into the outer core are also computed as part of the heat budget.

Sulfur: No matter the value of our other variables, [S] ranging from 1–2.5 wt% resulted in inner core nucleation at higher temperatures, causing the core to solidify completely early in its history. As a result, these sulfur abundances are not compatible with the lunar dynamo history. Sulfur abundances from ~3–6 wt% results in the inner core nucleating around the time that the BMO-hosted dynamo ceases, leading to a relatively weak, core-hosted dynamo that is consistent with paleomagnetic [3] and seismic [4] data. Abundances of sulfur above 6 wt% result in a significant delay in inner core nucleation, resulting in the impossible scenario of a core-hosted dynamo occurring at present day.

These results reveal the critical effect of sulfur content on the liquidus and the growth of an inner core. As the abundance of sulfur in the bulk core increases, its liquidus decreases, resulting in a delay in inner core nucleation, core convection, and thus, a dynamo. Once the inner core nucleates and grows with respect to time, the outer core is progressively enriched in sulfur, leading to density differences between the inner and outer core that facilitates a dynamo [6].

CMB heat flow, thermal conductivity, and potassium: The duration of the field and the intensity of the field generally increases with decreasing thermal conductivity values, as expected from basic principles. Increasing the total heat flow also increases the duration and strength of the core-hosted dynamo, unless rapid cooling leads to complete solidification of the core. In contrast, adding more potassium to the core contributes thermal energy to the dynamo but suppresses growth of the inner core, which can decrease the predicted strength and intensity overall. Compared to the abundance of sulfur in the bulk core, our simulations reveal that small variations in parameters such as [K], Q_C, and k_c are degenerate and play an overall negligible role in the timing of inner core crystallization and the dynamo.

Nominal model: Results of the nominal core-hosted dynamo model are presented in Figure 1. Here we assumed [S] = 5 wt%, [K] = 25 ppm, $Q_C = 10^9$ W at present day, and k_c = 40 W/m/K. Our nominal model produces a core-hosted dynamo that begins at the cessation of the BMO-hosted dynamo [2] or 2.9 Ga from present day and ends at ~1 Ga from present day when the lunar dynamo likely ceased [3]. Fig. 1A shows the evolution of core temperatures throughout the simulation. The average temperature spikes due to radiogenic heating in the BMO and begins solidifying when temperatures fall back to ~1700 K. Inner core nucleation (Fig. 1C) begins at 3 Ga and marks the time at which sulfur enrichment begins in the outer core (Fig. 1D), latent heat and gravitational energy are released (Fig. 1B), and the core-hosted dynamo begins (Fig. 1F). The surface field intensity reaches a peak of 0.45 µT at 3.11 Ga, and is ~1 order of magnitude lower than the surface field intensity of 4.1 µT produced from the BMO-hosted dynamo [2].

Conclusions: The thermal evolution of the lunar core was modeled to understand the sensitivity of the model output to parameters such as [S], [K], Q_C, and k_c. Simulations reveal the time at which the inner core begins to nucleate is not too sensitive to values of [K], Q_C, and k_c but rather mostly to the abundance of sulfur. We found the range of [S] values that facilitate a dynamo. Simulations with [S] ~ 3–6 wt%, also favored by seismology, result in a dynamo and our nominal model reveals that a value of 5 wt% best explains a transition between a BMO dynamo to a later thermo-compositional core dynamo driven by inner core crystallization.

Our model for the coupled evolution of a basal magma ocean and the core places strong constraints on the abundance of sulfur in the core. These constraints can further translate into predictions about the density of the outer core and the radius of the inner core that can be verified with future missions such as the Lunar Geophysical Network, which aims to understand the evolution of the lunar interior from the crust to its core.

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References: [1] Evans et al. (2018) JGR, 45, 98-107. [2] Scheinberg et al. (2018) EPSL, 492, 144-151. [3] Mighani et al. (2020) Sci. Adv. 2020; 6:eaax0883. [4] Weber et al. (2011) Sci. Mag., 331. [5] Williams et al. (2014) JGR Planets, 119, 1546–1578. [6] Laneuville et al. (2014) EPSL, 401, 251–260.

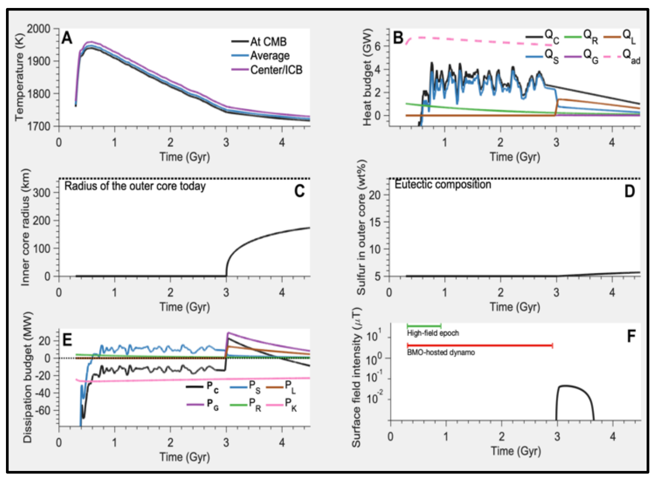

Figure 1 | Nominal model output. Simulations begin at 4.2 billion years before the present day. (A) Temperature at the core-mantle boundary (CMB), center/inner core boundary (ICB), and the average temperature of the core. (B) Heat budget in GW: latent heat, Q_L, radiogenic heating, Q_R, gravitational energy, Q_G, adiabat of the core, Q_{ad}, heat flow across the core, Q_C, and secular cooling, Q_S. (C) Inner core radius with respect to time. (D) Sulfur abundance in the outer core. (E) The dissipation budget in MW. (F) BMO-hosted dynamo compared against a core-hosted dynamo and paleomagnetic intensity during the high-field epoch. The BMO-hosted dynamo has a duration of 2.6 Ga and a surface field intensity of 4.1 µT obtained using the mixing length scaling theory from Scheinberg et al., 2018. The high-field epoch has a paleointensity of ~35 µT that persisted ~4.2–3.6 Gyr from present day [2].