The Case Against an Early Lunar Dynamo Powered by Core Convection

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Abstract Paleomagnetic analyses of lunar samples indicate that the Moon had a dynamo-generated magnetic field with ~50 μT surface field intensities between 3.85 and 3.56 Ga followed by a period of much lower (≤ ~5 μT) intensities that persisted beyond 2.5 Ga. However, we determine herein that there is insufficient energy associated with core convection—the process commonly recognized to generate long-lived magnetic fields in planetary bodies—to sustain a lunar dynamo for the duration and intensities indicated. We find that a lunar surface field of ≤1.9 μT could have persisted until 200 Ma, but the ~50 μT paleointensities recorded by lunar samples between 3.85 and 3.56 Ga could not have been sustained by a convective dynamo for more than 28 Myr. Thus, for a continuously operating, convective dynamo to be consistent with the early lunar paleomagnetic record, either an exotic mechanism or unknown energy source must be primarily responsible for the ancient lunar magnetic field.

1. Introduction

Remanent magnetization of the lunar crust and samples indicates the past existence of an ancient, internally generated magnetic field on the Moon induced by the systematic churning of molten metal within its core (i.e., core dynamo) (e.g., Cournède et al., 2012; Garrick-Bethell et al., 2009, 2017; Halekas et al., 2001; Hart et al., 1995; Hood, 2011; Hood et al., 2001, 2014; Shea et al., 2012; Suavet et al., 2013; Tsunakawa et al., 2015; Weiss & Tikoo, 2014). Multiple mechanisms have been proposed to generate the sustained motion in the lunar core required to produce a magnetic field; however, no one model or scenario has been able to reproduce both the paleointensity and minimum longevity suggested by modern high-fidelity paleomagnetic analyses of lunar samples (e.g., Dwyer et al., 2011; Evans et al., 2014; Konrad & Spohn, 1997; Laneuville et al., 2013; Le Bars et al., 2011; Scheinberg et al., 2015; Stegman et al., 2003; Zhang et al., 2013).

A suite of recently analyzed lunar samples have paleomagnetic records of thermoremanent magnetization (TRM) that could have only been acquired in the presence of an ancient and high-intensity surface magnetic field of ~40–100 μT (see Weiss & Tikoo, 2014 for review). A majority of the high-intensity paleomagnetic records are found to have been acquired between 3.85 and 3.56 Ga, although the earliest evidence of remanent magnetization detected within the sample suite requires a dynamo to have been initiated no later than ~4.25 Ga (Cournède et al., 2012; Garrick-Bethell et al., 2009, 2017; Shea et al., 2012; Suavet et al., 2013). Paleomagnetic signatures recorded by younger samples indicate that lunar surface fields decreased in intensity to less than ~10 μT by 3.2 Ga (Buz et al., 2015; Tikoo et al., 2014). This significantly reduced surface field represents a very rapid decline of the lunar core dynamo. However, a recent study demonstrated that the lunar dynamo persisted in a weakened (~5 μT) state until at least 2.5 Ga (Tikoo et al., 2017). Apollo-era paleointensity studies imply that the core dynamo may have persisted until ~200 Ma (see Fuller & Cisowski, 1987 for review), although the fidelity of many of these studies has been called into question (e.g., Tikoo et al., 2012). Hence, the timing for the termination of the lunar dynamo remains unclear.

Of the multiple processes that have been proposed to generate the sustained motion in a core necessary to induce a dynamo, thermochemical convection is the process most commonly recognized to operate within planetary cores (e.g., Christensen et al., 2009; Roberts & Glatzmaier, 2000). Several models of lunar interior evolution have been successful in reproducing longevities for a convective core dynamo consistent with the early lunar paleomagnetic record (Evans et al., 2014; Laneuville et al., 2013; Scheinberg et al., 2015; Zhang et al., 2013). However, these models typically yield magnetic field surface intensities that are a factor of 100 below those required by lunar samples and rely on thermochemical mantle evolution models that are...
strongly and inexorably dependent on poorly constrained parameters for the lunar mantle (e.g., density, temperature, and viscosity). As a result, such models provide limited insight into the overall capabilities of a lunar core dynamo in sustaining surface field intensities consistent with the paleomagnetic record.

Accordingly, for this study, we disregard constraints imposed by assumed properties of the mantle, and instead, we focus on constraining the maximum available energy within the lunar core that could theoretically sustain a convective core dynamo. For such a dynamo, the intensity of the magnetic field is ultimately limited by the energy sources driving core convection (e.g., Roberts & Glatzmaier, 2000; Labrosse & Macouin, 2003). Herein, we examine if these energy sources are sufficient to sustain a dynamo for the period and intensity indicated by the lunar paleomagnetic record.

2. Core Thermodynamics

A core dynamo has the potential to sustain a magnetic field over billion-year timescales but requires that both of the following criteria be met: (1) magnetic induction must dominate relative to magnetic diffusion, and (2) sufficient excess power must be available beyond that required for convection. In this work, we assume that the former requirement is met and exclusively focus on the maximum power (or energy) that would be available to sustain a convective core dynamo.

The energy that drives convection within a planetary core is commonly considered to be primarily derived from compositional differentiation, secular cooling, inner core crystallization, and radioactive decay (e.g., Labrosse, 2003). Below, we determined the maximum contributions from each of the aforementioned energy sources. Each energy source was independently maximized, at times permitting contradictory assumptions to be invoked with respect to the state of the core. Maximizing each energy source independently simplifies our calculations and increases the robustness of our results. Parameters and values used in the calculations below are provided in Table A1.

2.1. Compositional Differentiation

We consider a lunar core, primarily composed of iron, that may be alloyed with a lighter element, such as sulfur or carbon. For a liquid iron-alloy core, upon cooling, gravitational energy is released as an inner iron core crystallizes extending to progressively larger radii while the outer core is increasingly enriched in the lighter element. The release of gravitational energy due to the progressive enrichment of the lighter element in the outer core will continue until the eutectic composition is reached. In this scenario, the energy $E_G$ released from a core that transitions from an initial compositionally uniform state with an average density $\rho$ to a two-layer core in its lowest gravitational potential energy configuration, is represented by the relation

$$E_G(\rho_1, \rho_2) = \frac{16}{15} \pi^2 G R_c^5 \left[ \frac{p_1^2 - p^2}{2} \rho_1 (p - p_1) + \frac{3}{2} (\rho_1 - \rho_2) \left( \frac{p - p_1}{\rho_2 - \rho_1} \right)^2 \right],$$

(1)

where $G$ is the gravitational constant, $R_c$ is the outer core radius, $\rho_1$ is the outer core density, and $\rho_2$ is the inner core density (see equations 2–4 in Breuer & Moore, 2007).

Both sulfur and carbon have been suggested as the predominant light element within the lunar core (Steenstra et al., 2017; Weber et al., 2011). Given the lower density of iron-sulfur alloys compared to that of iron-carbon (Fei et al., 1995, 2000, 1997; Terasaki et al., 2010), equation (1) is maximized when sulfur is considered as the light element. For the subset of lunar core models that allow for up to 6 wt % of sulfur in the outer core (Weber et al., 2011) and are consistent with mean density and solid moment values for the Moon (Williams et al., 2014), radius ranges of 0–280 km and 200–380 km are found to be permissible for the solid inner and fluid outer core, respectively. Densities of 8,000 kg m$^{-3}$ and 5,100 kg m$^{-3}$ are inferred for the solid iron inner core ($\rho_2$) and Fe-FeS composition within the outer core ($\rho_1$), respectively (Weber et al., 2011; Williams et al., 2014). For the permissible range of core radii, up to $4 \times 10^{24}$ J of energy can be derived from compositional differentiation of the core.

2.2. Thermal Energy (Secular Cooling)

The thermal energy $E_T$ associated with secular cooling of the lunar core can be represented by the equation

$$E_T = \frac{4}{3} \pi G R_c^3 C_p (T_i - T_f),$$

(2)
where \( \rho \) is the core density and \( C_p \) is the specific heat of the core. \( T_i \) is the initial core temperature defined as

\[
T_i = T_0 + \frac{E_G(\rho_{\text{avg}}/\rho_{\text{Fe}})}{C_p\rho_{\text{Fe}}V_C},
\]

(3)

where \( \rho_{\text{Fe}} \) is the density of iron in the core, \( \rho_{\text{avg}} \) is the average density of the Moon, \( V_C \) is the volume of the core, and \( T_0 \) is the temperature of the material within the core prior to differentiation. The second term in equation (3) reflects an increase in the initial core temperature if the energy of lunar compositional differentiation were stored fully within the core.

The total available energy associated with secular cooling of the core was further maximized through the following assumptions:

1. the core has a radius of 380 km;
2. \( T_f \) in equation (2) is defined to be \( \sim 1,200 \) K, the eutectic melting temperature at 5 GPa;
3. the core is composed of pure iron; and
4. \( T_0 \) can be estimated to be 1,800 K, the volumetrically averaged temperature of a Moon initially heated by accretional energy (e.g., Pritchard & Stevenson, 2000).

Applying the above assumptions to equations (2) and (3), we found that the maximum energy that may be derived via secular cooling from the assumed initial thermal state of the core, \( E_T \), is \( 1.9 \times 10^{27} \) J.

### 2.3. Latent Energy (Inner Core Crystallization)

As the core cools below its liquidus and an inner iron core crystallizes, latent energy is released. The latent energy \( E_L \) is represented by the equation

\[
E_L = \frac{4}{3} \pi \rho R_{ic}^3 L,
\]

(4)

where \( L \) is the latent heat of fusion and \( R_{ic} \) is the radius of the solid inner core at present. The latent energy \( E_L \) is at a maximum for the greatest possible value of \( R_{ic} \). Using \( R_{ic} = 280 \) km, we determined that the maximum energy that may be derived from inner core crystallization, \( E_L \), is \( 2.2 \times 10^{26} \) J.

### 2.4. Radiogenic Heat

As the fraction of radiogenic heat in the Moon that is contributed to the core is not well known, radioactivity is generally neglected as an energy source for the lunar core. However, given that previous convective core dynamo models have been significantly underpowered with regard to the inferred lunar magnetic field duration and intensities, we examine the possible energy that could be generated by radioactive decay in the Moon.

Heat-producing elements could have been sequestered into the lunar core as has been suggested for Earth’s core (Buffett, 2003; Wohlers & Wood, 2015), although it is unknown if this could constitute a substantial fraction of the thermal budget for the core. Alternatively, a dense layer enriched in radioactive heat-producing elements (\( U, Th, K \)) just above the core-mantle boundary (CMB) has been proposed to explain the ancient paleomagnetic signatures preserved by lunar samples (e.g., Stegman et al., 2003). This scenario has been suggested to result from the sinking of ilmenite-rich cumulates into the deep mantle, which could have conceivably entrained heat-producing elements in the form of KREEP (material with an enhanced concentration of K, rare earth elements, P, and other incompatible elements). Notionally, the higher thermal conductivity of iron relative to that of the mantle, the efficient heat transfer in the liquid outer core, and the high density of the enriched layer is expected to lead to preferential heating of the lunar core. The heat imparted to the core would remain sequestered until the heat-producing layer is dispersed away from the CMB, at which time loss of this heat from the core could power a dynamo.

In either case, the expected total radioactive heat budget of the Moon provides a maximum limit to the radiogenic energy that could have been used to power the dynamo. The dominant sources of radioactive energy within planetary interiors at the time of the lunar dynamo result from the decay of radioactive isotopes of \( U, Th, \) and \( K \). The energy derived from the decay of these isotopes \( E_R \) can be represented as a function of time \( t_f \).
in years before present, the fraction of radioactive energy that contributes to the lunar core energy \( f_c \), and the total abundance of uranium in the bulk Moon (TBMU), such that

\[
E_R(f_c, t_f) = f_c \text{TBMU} \int_{t_i}^{t_f} \left( H_i e^{s\cdot\lambda t} + \frac{[Th]}{U} H_{Th} e^{\cdot\lambda \cdot t} + \frac{[K]}{U} H_K e^{\cdot\lambda \cdot t} \right) dt,
\]

where \( H \) and \( \lambda \) represent the heat generation rate and radioactive decay constant corresponding to the subscripted element, \( R_p \) is the mean radius of the Moon, and bracketed elements denote mass abundance. Using values from Table A1, equation (5) can be simplified to

\[
E_R(f_c, 3.56 \text{ Ga}) \approx 1.2 \times 10^{13} \left[ \text{J kg}^{-1} \right] f_c \text{TBMU},
\]

for the period prior to 3.56 Ga, commensurate with the end of the high-intensity magnetic field era.

As the fraction of the radioactive decay energy that is deposited into the core is not reliably constrained, we consider the extreme and unlikely end-member scenario of a Moon that has its total radioactive heat budget deposited into the core (i.e., \( f_c = 1 \)). In this scenario, \( 1.7 \times 10^{28} \text{ J} \) of energy from radioactive decay would be available prior to the end of the high-intensity magnetic field era at 3.56 Ga.

3. Magnetic Field Scaling

Based on observations of celestial bodies combined with fundamental electromagnetic and kinematic relations, general scaling relationships have been developed to relate the vigor of core thermochemical convection, characterized by the core heat flux, to the induced magnetic field intensity (Christensen et al., 2009; Christensen & Aubert, 2006; Roberts & Glatzmaier, 2000). In this work, we use the available energy flux to magnetic field strength scaling of Christensen et al. (2009) to determine the magnetic field surface intensity that can be produced for a given core heat flux. This scaling law relationship can be represented as

\[
B_s = f_{\text{dip}} \left( \frac{R_c}{R_p} \right)^3 \sqrt{2\mu_c f_{\text{ohm}} f_c F (P_{\text{cmb}} F)}
\]

where \( B_s \) is the mean surface intensity for the dipolar component of the magnetic field, \( \mu_c \) is the magnetic permeability of free space, \( f_{\text{ohm}} \) is the ratio of ohmic to total dissipation, \( c \) is a constant of proportionality, \( f_{\text{dip}} \) is the fraction of the magnetic field that is dipolar, and \( P_{\text{cmb}} \) is the heat flux across the CMB. \( F \) is an efficiency factor that characterizes the radially varying properties of the core. We used \( F = 0.05 \), the maximum value determined for the lunar core (see Appendix B).

Equation (7) provides good agreement \((B_s \pm 0.78B_s \text{ at the } 99.7\% \text{ confidence level})\) with geodynamo models and with the convection-driven dynamos of Earth and Jupiter (Christensen et al., 2009). Despite dynamo scaling relationships indicating that \( f_{\text{dip}} \approx 0.14 \) (Christensen et al., 2009), we generously assume \( f_{\text{dip}} = 1 \), thereby providing a maximum value of lunar magnetic field surface intensities for a given core heat flux \( P_{\text{cmb}} \) that are well above the 99.7% confidence interval established for equation (7). Additionally, at \( f_{\text{dip}} = 1 \), equation (7) requires less energy to produce a given surface field intensity than can be obtained either by scaling from the Earth’s magnetic field alone (see Dwyer et al., 2011) or alternative force balance relations invoked by Scheinberg et al. (2015) at a nominal \( f_{\text{dip}} \) value. Equation (7) may be simplified to

\[
B_s \approx 2.2 \times 10^{-5} f_{\text{dip}} \left( \frac{E_{\text{cmb}}(t)}{A_c \Delta t} \right)^{\frac{1}{2}}
\]

where \( A_c \) is the core surface area and \( \Delta t \) is the length of time that the dynamo is active. The maximum available core energy \( E_{\text{cmb}}(t) \) available by a given time \( t \) is defined as

\[
E_{\text{cmb}}(t) = E_G + E_T + E_L + E_R(f_c, t) - E_C(t).
\]

\( E_C(t) \) represents the heat carried conductively along the core adiabat and therefore unavailable energy to drive the dynamo. Previous estimates of the lunar core adiabat (Evans et al., 2014; Konrad & Spohn, 1997; Stegman et al., 2003) for the period encompassing the high magnetic field era between 3.85 and 3.56 Ga yield a maximum value for \( E_C(t) \) of \( \sim 10^{29} \) J for a fully liquid core. However, as the core cools and the solid inner core grows in radius, the energy required to maintain the core adiabat decreases. As the contribution of \( E_C(t) \)
in equation (9) will only serve to decrease the estimate of the total energy available to sustain core convection, we maximize the equation by assuming that $E_C(t)$ is negligible.

By treating the magnetic field surface intensity and the energy transferred across the CMB as prescribed parameters in equation (8), the maximum surface magnetic field duration $\Delta t_c$ for a given surface intensity $B_s$ and energy $E_{cmb}(t)$ may be determined. The equations defined in the current and previous sections allow for the surface intensity of an internally generated magnetic field to be directly related to the energy required of a convective core dynamo.

### 4. Magnetic Field Results and Implications for the Lunar Core Dynamo

Here we consider two classes of scenarios that are presently permitted by the lunar paleomagnetic record. First, we consider scenarios that yield an early, high-intensity magnetic field on the Moon between 3.85 and 3.56 Ga. Based on the mean paleointensities (78 $\mu$T) less the standard error (27 $\mu$T) recorded by paleomagnetic signatures preserved within this era (Cournède et al., 2012; Shea et al., 2012; Suavet et al., 2013), we require a minimum surface intensity of ~50 $\mu$T. Second, we consider those scenarios that yield a long-lived, low-intensity magnetic field that may have persisted until 200 Ma. Such a magnetic field is expected to have a nominal intensity of ~5 $\mu$T or less after 3.56 Ga (Buz et al., 2015; Tikoo et al., 2014, 2017). Figure 1 and Table 1 summarize the maximum magnetic field surface intensities generated for a suite of lunar convective dynamo cases with varying durations and contributions of radioactive energy.

![Figure 1](image-url)

**Figure 1.** Magnetic field surface intensity (\(\mu\)T) versus time before present (Ga) for lunar convective dynamo. (a) Stacked horizontal bars are shown for a series of maximum surface intensities $B_s$ that can be sustained for a lunar core during the time period indicated on the horizontal axis and at the fraction of the total lunar radioactive energy $f_c$ indicated. The relative proportion of the energy derived from radioactivity (blue), gravitational differentiation and latent heat (black), and secular cooling (orange) are shown as a function of bar width with respect to the combined width of the bars at a prescribed surface intensity. For the high-intensity magnetic field era between 3.85 and 3.56 Ga, maximum intensities are shown for 50, 23, and 11 $\mu$T corresponding to $f_c$ values of 12, 1, and 0, respectively. Values for $f_c$ of 12 and 1 are considered to be implausible. Also shown is a maximum surface field intensity of 4.4 $\mu$T between 4.55 and 0.2 Ga for $f_c$ is 0. Surface paleointensity measurements (as summarized by Weiss & Tikoo, 2014 are shown in gray).

### Table 1

<table>
<thead>
<tr>
<th>Energy contribution</th>
<th>Energy ($10^{28}$ J)</th>
<th>Max. duration of 50 $\mu$T field</th>
<th>Max. duration of 10 $\mu$T field</th>
<th>Max. surface intensity for ancient field(^a)</th>
<th>Max. surface intensity for lifetime field(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T + E_G + E_L$</td>
<td>0.2</td>
<td>3.0 Myr</td>
<td>380 Myr</td>
<td>7.3 $\mu$T</td>
<td>4.4 $\mu$T</td>
</tr>
<tr>
<td>$E_R(t_0, t) + E_T + E_G + E_L$</td>
<td>2.0$^c$ – 6.0$^d$</td>
<td>28.0 Myr(^e)</td>
<td>&gt;4500 Myr(^d)</td>
<td>15.2 $\mu$T(^c)</td>
<td>13.5 $\mu$T(^d)</td>
</tr>
</tbody>
</table>

\(^a\)For an ancient magnetic field active between 4.55 and 3.56 Ga. \(^b\)For a lifetime magnetic field active between 4.55 and 0.20 Ga. \(^c\)Value determined with radioactive energy contribution of $E_R(1, 3.56$ Ga). \(^d\)Value determined with radioactive energy contribution of $E_R(1, 0.20$ Ga).
Scenarios consistent with the generation of a high-intensity magnetic field between 3.85 and 3.56 Ga could conceivably be generated either by the operation of a core dynamo that was exclusively and continuously active between 3.85 and 3.56 Ga, or alternatively, a core dynamo that was active shortly after lunar formation (~4.55 Ga) until 3.56 Ga, for a total duration of ~1 Gyr. For the former case, Figure 1 shows the maximum surface field intensities and relative proportion of energy derived from core differentiation and crystallization, radioactivity, and secular cooling of three distinct scenarios in which 12, 1, and 0 times the total lunar radioactive heat budget contributes to core convection. In these three scenarios, the core retains all energy acquired or produced prior to 3.85 Ga, allowing the energy to be fully expended between 3.85 and 3.56 Ga. As illustrated by Figure 1, without the energy contribution of radioactive decay ($f_C = 0$), a surface field of no more than 11 $\mu$T can be generated by a convective dynamo operating between 3.85 and 3.56 Ga. In fact, the nonradioactive energy sources identified in section 2 can only sustain a 50 $\mu$T surface field for 3 Myr of the 300 Myr period indicated by the lunar paleorecord (see Table 1). Even with the total energy produced by radioactive decay in the Moon prior to 3.56 Ga (i.e., $f_C = 1$ in equation (7)) contributing to core convection as 90% of the total energy, the generated magnetic field is limited to a surface intensity of 23 $\mu$T between 3.85 and 3.56 Ga. Moreover, as illustrated in Figure 1, to reproduce the lunar paleointensity record between 3.85 and 3.56 Ga, the core would need additional energy equivalent to 12 times the total energy produced by radioactive decay in the Moon prior to 3.56 Ga, approximately $-2 \times 10^{29}$ J. In the unlikely case that this additional energy were of radioactive origin, the energy released from radioactive decay prior to 3.85 Ga would have been stored as thermal energy in the core, resulting in an implausibly high core temperature in excess of 100,000 K at 3.85 Ga.

If instead the dynamo started at 4.55 Ga and lasted until 3.56 Ga, a 50 $\mu$T surface field would require additional energy for the core equivalent to 40 times the total energy produced by radioactive decay within the Moon. Based on current estimates of the heat-producing elements in Earth’s core and the bulk Moon (Buffett, 2003; Taylor & Wieczorek, 2014; Wohlers & Wood, 2015), it is doubtful that the lunar core or Moon has the extremely high abundances of heat-producing elements that would be required to generate a 50 $\mu$T surface field for 300 Myr or more. Furthermore, the nonradioactive energy sources (thermal, latent, gravitational) available to power core convection could provide no more than $-2.1 \times 10^{27}$ J of energy, only 1% of the total energy ($2.1 \times 10^{29}$ J) needed to sustain a dynamo-generated 50 $\mu$T surface field for 300 Myr.

However, we find that a long-lived, low-intensity magnetic field could persist for most of lunar history (4.55 to 0.2 Ga) at a surface intensity of 4.4 $\mu$T without the contribution of radioactive energy to core convection. In this case, as shown by Figure 1, nearly 90% of the energy would be derived from secular cooling. With the contribution of the total lunar radioactive heat budget to core convection, a surface field of no more than 13.5 $\mu$T could be sustained between 4.55 and 0.2 Ga. These results suggest that a convective core dynamo could explain the low paleointensities ($\leq 5 \mu$T) recorded after 3.2 Ga, although the generous assumptions used to determine these field intensities likely result in an overestimation. For example, we previously assumed that the magnetic field is exclusively dipolar (i.e., $f_{\text{dip}} = 1$ in equation (8)), despite dynamo scaling relationships indicating that $f_{\text{dip}} \geq 0.14$ (Christensen et al., 2009). Using $f_{\text{dip}} = 0.14$ would correspond to a reduction of these surface intensities to 1.9 $\mu$T and 0.62 $\mu$T for total available core energy values including and excluding radioactive decay, respectively. Additionally, the energy $E_{C}(t)$ needed to maintain the core adiabat in equation (9) (Evans et al., 2014; Konrad & Spohn, 1997; Laneuville et al., 2013; Scheinberg et al., 2015; Stegman et al., 2003), although negligible with respect to the total energy required for the high-intensity magnetic field era, becomes progressively larger for longer time intervals of dynamo activity. Thus, our calculations increasingly overestimate the total available energy to sustain a core dynamo at longer time intervals of dynamo activity. Accordingly, a long-lived, lunar convective core dynamo that exceeded an average magnetic field surface intensity of $\sim 2 \mu$T remains possible, but is unlikely.

### 4.1. Other Energy Sources or Mechanisms

The possibility exists that an alternative mechanism is responsible for the paleomagnetic signatures recorded during the high-intensity magnetic field era. Several alternative mechanisms (e.g., mechanical stirring of the core due to mantle precession or impacts) have been proposed to explain the duration and intensity of the lunar core dynamo (Dwyer et al., 2011; Le Bars et al., 2011), but these mechanisms have also been unable to reproduce magnetic fields consistent with the high-intensity magnetic field era. For example, differential...
motion between a liquid outer core and mantle due to precession has been suggested as a potential source of energy that could be supplied through continuous mechanical stirring of the liquid core, thereby resulting in a dynamo (Dwyer et al., 2011); however, current energy scaling relationships (which may not be fully applicable as noted by Dwyer et al., 2011) indicate that the energy generated by this mechanism is a factor of 10 less than the total energy needed to sustain a 50 μT surface field for ~300 Myr.

An exotic mechanism or unknown energy source that contributed to a core dynamo remains possible. However, such a mechanism or source must have actively generated energy between 3.85 and 3.56 Ga, or alternatively, stored the energy generated in the core. However, the latter is unlikely, as storage of the necessary energy thermally would require an implausibly high core temperature in excess of 130,000 K at 3.85 Ga.

### 4.2. An Intermittent Dynamo

A convective dynamo that was intermittently active (less than 28 Myr in total, extended across a ~300 Myr period) during the high-intensity magnetic field era would be consistent with the total available energy of the core. Presently, there is insufficient evidence to permit a reliable evaluation of a convective core dynamo that was only active for less than 10% of the ~300 Myr period between 3.85 and 3.56 Ga. An intermittent dynamo during this period would imply the existence of a large population of 3.85–3.56 Ga lunar samples bearing null paleointensities that cannot be accounted for by poor magnetic recording properties (Tikoo et al., 2012) or postformational shock demagnetization effects (Gattacceca et al., 2010). Such samples have not yet been identified by modern, high-fidelity paleomagnetic studies. However, if such a population of reliable paleomagnetic records of low or negligible paleointensities are found to have been preserved during this era, further consideration of an intermittently active dynamo may be justified.

### 4.3. Lunar Mantle Implications

The generation of the ancient, high-intensity magnetic field by a convective dynamo would require a core heat flux of ~10 W m\(^{-2}\) for at least 300 Myr. This large heat flux is significantly higher (factor of 300) than the core heat flux predicted by lunar interior evolution models (Evans et al., 2014; Konrad & Spohn, 1997; Laneuville et al., 2013; Scheinberg et al., 2015; Stegman et al., 2003) and would have likely required vigorous mantle convection or large-scale melting to sustain such a large heat flux for an extended period of time.

### 5. Summary

A lunar core dynamo has been suggested as the only viable explanation for the paleomagnetic signatures recorded by several lunar samples (e.g., Weiss & Tikoo, 2014). In evaluating the most commonly recognized natural mechanism capable of producing a dynamo within a planetary body, that of core thermochemical convection, we find that the energy sources commonly attributed to core convection can sustain a dynamo from 4.5 to 0.2 Ga with an average magnetic field surface intensity of at most 13.5 μT, with a more likely maximum value of around 1.9 μT. These magnitudes are compatible with the observed values of ≤5 μT. Conversely, we find that the lunar core has insufficient energy to sustain the surface field suggested by the high-intensity (~50 μT) paleomagnetic signatures recorded by lunar samples between 3.85 and 3.56 Ga. Our results indicate that conventional energy sources (thermal, latent, and gravitational) for driving a core dynamo by thermochemical convection provide less than 1% of the total energy necessary to produce the high-intensity paleomagnetic signatures. Furthermore, we find that the energy deficit cannot reasonably be furnished by radioactivity or a superheated core, as either implausibly high lunar core temperatures in excess of 100,000 K would be required at the start of the high-intensity magnetic field era (3.85 Ga) or implausibly high abundances of heat-producing elements, at least 12 times that expected to be in the total bulk Moon, would need to have been sequestered in or above the lunar core.

An active convective dynamo on the early Moon, at the high surface field intensities indicated by the lunar paleorecord, would also require a core heat flux of ~10 W m\(^{-2}\), a factor of 300 greater than those previously predicted by lunar interior evolution models between 3.85 and 3.56 Ga (Evans et al., 2014; Konrad & Spohn, 1997; Laneuville et al., 2013; Scheinberg et al., 2015; Stegman et al., 2003). Undoubtedly, such a large transfer of heat into the lower mantle would have resulted in either large-scale melting or vigorous convection within the lunar mantle and may have had an enduring effect on the magmatic history of the early Moon. The inability of interior evolution models to reproduce a surface magnetic field consistent with the lunar paleomagnetic record could have previously been attributed to poorly constrained properties related to...
the thermochemical state of the early Moon. However, our results conclusively demonstrate that the lunar core does not possess sufficient energy to sustain a convective core dynamo capable of generating a 50-μT surface field for ~300 Myr. Additionally, the nonconvective mechanisms that have been proposed to date are also insufficiently powered to generate the required high-intensity magnetic field for ~300 Myr (Dwyer et al., 2011; Le Bars et al., 2011). Based on the present paleomagnetic record for the Moon, our results suggest that one of the following must be true: (1) paleointensities on the early Moon are significantly overestimated; (2) the scaling laws for internally generated magnetic fields are not applicable for the lunar core; or (3) an exotic mechanism or unknown energy source that was active between 3.85 and 3.56 Ga is primarily responsible for the generation of the high-intensity paleomagnetic signatures. The answer to the conundrum of both the ancient, high-intensity magnetic field and the later, low-intensity magnetic field may entail a combination of dynamo mechanisms such as convection and mechanical stirring of the core operating during different periods in lunar history. Additional high-fidelity paleomagnetic analyses of lunar samples may provide greater insight into the possibility of an intermittent dynamo. Ultimately, the resolution to this discrepancy may be at the intersection of improved models of interior geodynamics, paleomagnetic analyses, and core dynamo models.

Appendix A: Parameter Values and Descriptions

The descriptions and values for the parameters used for this work are listed in Table A1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>fS</td>
<td>Core sulfur mass fraction</td>
<td>0–24%</td>
</tr>
<tr>
<td>αc</td>
<td>Core thermal expansivity</td>
<td>9 × 10⁻⁵ K⁻¹</td>
</tr>
<tr>
<td>ρFe,FeS</td>
<td>Density of eutectic Fe-FeS composition</td>
<td>5,100 kg m⁻³</td>
</tr>
<tr>
<td>ρFe</td>
<td>Density of iron</td>
<td>8,000 kg m⁻³</td>
</tr>
<tr>
<td>ρavg</td>
<td>Density of the Moon</td>
<td>3,346 kg m⁻³</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational constant</td>
<td>6.67 × 10⁻¹¹ m³ kg⁻¹ s⁻²</td>
</tr>
<tr>
<td>T₀</td>
<td>Initial, average temperature of Moon</td>
<td>1,800 K</td>
</tr>
<tr>
<td>R₉C</td>
<td>Inner core radius</td>
<td>0–280 km</td>
</tr>
<tr>
<td>L</td>
<td>Iron latent heat of fusion</td>
<td>300 kJ kg⁻¹</td>
</tr>
<tr>
<td>ᴞp,Fe</td>
<td>Iron heat capacity</td>
<td>850 J kg⁻¹ K⁻¹</td>
</tr>
<tr>
<td>R₀D</td>
<td>Mean radius of Moon</td>
<td>1,737 km</td>
</tr>
<tr>
<td>R₀C</td>
<td>Outer core radius</td>
<td>200–380 km</td>
</tr>
<tr>
<td>P₀</td>
<td>Pressure at center of core</td>
<td>5 GPa</td>
</tr>
<tr>
<td>λK</td>
<td>Decay constant for potassium</td>
<td>5.5 × 10⁻¹⁰ yr⁻¹</td>
</tr>
<tr>
<td>λTh</td>
<td>Decay constant for thorium</td>
<td>5.0 × 10⁻¹¹ yr⁻¹</td>
</tr>
<tr>
<td>λU</td>
<td>Decay constant for uranium</td>
<td>1.6 × 10⁻¹⁰ yr⁻¹</td>
</tr>
<tr>
<td>ᴬK</td>
<td>Heat generation rate for natural potassium</td>
<td>3.5 × 10⁻⁹ W kg⁻¹</td>
</tr>
<tr>
<td>ᵴTh</td>
<td>Heat generation rate for thorium</td>
<td>2.6 × 10⁻⁹ W kg⁻¹</td>
</tr>
<tr>
<td>ᵴU</td>
<td>Heat generation rate for natural uranium</td>
<td>9.5 × 10⁻⁹ W kg⁻¹</td>
</tr>
<tr>
<td>TBMU</td>
<td>Total abundance of uranium in the bulk Moon</td>
<td>1.5 × 10¹⁷ kg</td>
</tr>
<tr>
<td>[Th]/[U]</td>
<td>Ratio of thorium to uranium</td>
<td>3.7</td>
</tr>
<tr>
<td>[K]/[U]</td>
<td>Ratio of potassium to uranium</td>
<td>2,500</td>
</tr>
<tr>
<td>F</td>
<td>Efficiency factor</td>
<td>0.05</td>
</tr>
<tr>
<td>fM</td>
<td>Ratio of dipolar to total magnetic field strength</td>
<td>0.14–1</td>
</tr>
<tr>
<td>fOhm</td>
<td>Ratio of ohmic to total dissipation</td>
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</tr>
<tr>
<td>c</td>
<td>Constant of proportionality</td>
<td>0.63</td>
</tr>
<tr>
<td>µ₀</td>
<td>Magnetic permeability of free space</td>
<td>1.26 × 10⁻⁶ H m⁻¹</td>
</tr>
</tbody>
</table>

*Weber et al. (2011). †Scheinberg et al. (2015). ‡Williams et al. (2014). §Calculated from the volumetric average of the radial, postaccretion temperature profile determined by Pritchard and Stevenson (2000) for a Moon that accreted between 1 and 10 years. †Braginsky and Roberts (1995). ‡Heat generation rates resummarized by Lowrie (2005) for natural potassium (0.01167%²³⁵K), thorium (²³²Th), and uranium (99.28%²³⁵U and 0.71%²³⁵U). †Based on a uranium abundance of 20 ppb for the bulk Moon (Taylor, 1979; Taylor & Wieczorek, 2014). ‡Warren and Wasson (1979). ‡Calculations for value are detailed in Appendix B. ‡Christensen et al. (2009). †fM = 1 considered by Dwyer et al. (2011).
Appendix B: Determination of the Efficiency Factor for the Lunar Core

The efficiency factor $F$ described in the main text and used in equation (7) is defined as

$$F^2 \approx \frac{1}{V} \int_0^{R_c} \left( \frac{q_c(r)}{q_o} \right) \frac{L(r)}{H(T)(r)} \frac{\rho(r)}{\rho_c} 4\pi r^2 \text{ dr},$$

(B1)

where $V$ is the volume of the fluid core, $q_c(r)$ is the heat flux as a function of radius $r$ where $r \leq R_c$, $q_o$ is the reference heat flux, defined here as the CMB heat flux, $L(r)$ is the height of convective cells within the fluid outer core, $\rho(r)$ is the density as a function of radius, and $H(T)(r) = g(r) - 1/c_p/c_v$ (Christensen et al., 2009). As noted by Dwyer et al. (2011), the magnetic field strength depends on the total power and not the spatial distribution over which it is deposited; therefore, those authors assumed that the core properties are constant and approximated $F$ as

$$F \approx \frac{4\pi G m_c R_c^2}{3c_p \rho_c},$$

(B2)

where $c_v$ is the thermal expansivity for the core. Substituting values appropriate for the Moon (Table A1), we obtain a value for $F$ of ~0.03 in equation (B2). Alternatively, if it is assumed that (1) gravity varies as a function of core radius ($g(r) = g_c r/R_c$) referenced to the gravitational acceleration at the surface of the core $g_c$, (2) the maximum height of convective cells within the core corresponds to the height of the outer core ($L(r) = R_c - R_o$), and (3) the heat flux $q$ within the core varies such that there is a total constancy of heat flux with radius ($q = 4\pi r^2 q(r)$), $F$ can be approximated as

$$F \approx c_t \frac{4\pi G m_c R_c^2}{3c_p \rho_c},$$

(B3)

where $c_t$ is

$$c_t = \left( \frac{9}{7} \right) \left( 1 \right) \left( \frac{R_c}{R_o} \right) \left( \frac{R_o}{R_c} \right) \left( \frac{1}{1} \right) \left( \frac{1}{R} \right) \left( \frac{1}{R} \right) \left( \frac{1}{R} \right),$$

(B4)

For all values of $R_c$ where $0 \leq R_c \leq R_o$, $c_t$ is less than ~1.46. Using 1.46 as the value of $c_t$ in equation (B3), we determined a maximum value of $F$ for the lunar core of 0.05.

Acknowledgments

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References


