There are several lines of evidence that a core dynamo once operated for the Moon. Orbital magnetic anomalies indicate a model in which the core magnetic field in large areas of the lunar crust [1]. In addition, paleomagnetic analyses of Apollo samples point towards a strong magnetic field with surface intensities of 0.1 and 0.1 G (a field generating between 4.2–5.3 billion years ago [2–5]. Furthermore, the paleomagnetic lines are observed to decrease by 8 G between 3.56 and 3.3 billion years ago [6].

Cooling of crustal rocks in the presence of a steady magnetic field generated by a core dynamo is the only mechanism consistent with all late lunar paleomagnetic studies [3–8]. A model of the lunar dynamo must be able to not only generate the observed longevity and paleofield strength at the surface, but also reproduce the timing of its rapid decline. The small size of the core and of the Moon itself is problematic for canonical convective dynamo models to reproduce.

Alternative to convection, precessional energy was also readily available to drive the lunar dynamo earlier in the orbital evolution of the Earth-Moon system [9]. In this study, we solve the full magnetohydrodynamics (MHD) equations for a dynamo driven by differential precession of the core and mantle.

Rotational States of the Core and Mantle

The lunar spin axis is currently inclined 6.7° from the orbit normal, and precessed at a period of 18.6 years (1965) [10]. In the past, the obliquity M of the lunar spin may have been as high as 7° when the Moon first transitioned to its present Cassini state at an orbital distance of 54R \(_E\) from Earth [11].

Although the mantle precesses at frequencies depending on its obliquity, the core’s precession was decoupled from mantle motion during the evolution of the lunar orbit. In the case of the Moon, the core is thought to be aligned with the ecliptic and primed at a constant tilt about the orbit normal, as suggested by lunar ranging experiments [12].

The evolution of the obliquity as a function of a semi-major axis of the lunar orbit can be fit to a polynomial for a > 2.424, [9]"

\[ \alpha(\psi) = 0.1074\alpha^3 - 0.0323\alpha^2 - 0.0086\alpha + 0.611 \times 10^{-6} \times 2.7016\times 10^{-6} - 1.7208\times 10^{-6} - 2.328\times 10^{-6} - 1.405\times 10^{-6} - 6.995\times 10^{-6} - 6.620\times 10^{-6} = 10.7428 \]

where \(\alpha = 0.2949R_\oplus, 46.38\%

As the Moon’s semi-major axis increased further, the mantle obliquity eventually decreased to present-day values of 6.7°. At some point during this decrease in the semi-major axis, the core dynamo would also decrease below some critical value. Thus, this mechanical-dynamo model has the potential of reproducing both the longevity and decline of paleofield intensities. The evolution of the rotational states of the lunar core and mantle throughout its orbital evolution are summarized in Figure 1.

Model Outputs

We solve for the magnetic field \(B\) and velocity field \(\mathbf{v}\) of the following system of non-dimensional MHD equations in a precessing spherical shell with angular velocity \(\Omega = \Omega_\odot\sin \theta\). Here, \(\theta\) is the perturbation to the rotation rate of the reference frame from the mean rotation rate \(\Omega_\odot\).

\[
\begin{align*}
\nabla \cdot \mathbf{v} &= 0 \\
\n\nabla \cdot \mathbf{B} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B}) - \nu \nabla^2 \mathbf{B} - \frac{\partial}{\partial t} \rho
\end{align*}
\]

(2)

(3)

(4)

This non-dimensional form is controlled by the magnetic Reynolds number \(R_m\), the Ekman number \(E\), and the Poincare number \(Po\). The variable \(t\) is the non-dimensional precessional frequency or reference frame. Values for the control parameters are given in Table 1. Free-slip boundaries were employed at the CMB. At the CMF, the flow field is forced towards the velocity of the differentially precessing mantle.

Table 1. Control parameters for the dynamo models, \(\gamma\) and \(\chi\), are the ratio of the inner and outer core respectively, \(\gamma\) is the kinematic viscosity. \(\Omega_\odot\) is the mean rotation rate, and \(\nu_\odot\) and \(\alpha_\odot\) are the precession rates of the mantle and the core respectively. \(\gamma\) denotes ranges due to uncertainty of current observations, rather than a range of values applicable to the Moon throughout its orbital history.

Critical Mantle Oblivities for Dynamo Action

In our mechanically driven dynamo model, the forcing is parameterized to scale with \(R_m\). It is too computationally expensive to use a linear \(R_m\) in dynamo simulations. Thus, in order to infer properties of the lunar dynamo, we have carried out simulations over a range of magentic Raynold numbers for different obliques. We find that a preecessionally driven core in the lunar parameter regime is supercritical to dynamo action when the mantle obliquity is \(< 15°\) and subcritical when the mantle obliquity is \(> 15°\).

A summary of the parameter space explored in terms of \(R_m\) and \(\psi\) is plotted in Figure 2.

Surface Field Strength Scaling

We have also derived scaling laws for the surface field intensity as a function of \(R_m\). We find that the surface intensity is stronger for lower \(R_m\) values. We find that the surface field intensity is higher at higher obliques. Figure 4 demonstrates that the scaling laws we found predict lunar surface field intensities in the range of \(1\) – \(10\)G.

Summary/Conclusions

(1) A mechanically-driven lunar core is capable of dynamo action.

(2) Our model of this type of lunar dynamo produces surface magnetic field strengths in the range of \(1\) – \(10\)G after the Cassini transition and before 3.3G.

(3) The precessionally driven dynamo naturally dies as the mantle obliquity falls below \(10°\), consistent with the rapid decline of surface intensities in the paleomagnetic record.