THE LUNAR CORE DYNAMO ENERGY DILEMMA. Alexander J. Evans[1], Sonia M. Tikoo[2], Jeffrey C. Andrews-Hanna[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA, alex@lpl.arizona.edu; [2]Department of Earth and Planetary Sciences, Rutgers University, Piscataway Township, NJ, USA.

Introduction: Remanent magnetization of both the lunar crust and returned lunar samples indicate that an ancient, internally generated magnetic field existed on the early Moon [1–3]. Modern paleointensity studies have revealed a thermoremanent magnetization (TRM) in several Apollo samples that could have only been acquired in the presence of a high-intensity lunar magnetic field of ~40–100 µT that operated between ~4.25 and 3.56 Ga [1].

Multiple mechanisms (convective and mechanical) have been proposed to generate the sustained motion in the lunar core required to produce such a magnetic field [4–6], however, no one model or scenario has been able to reproduce both the paleointensity and minimum longevity suggested by the modern high-fidelity analyses of lunar samples [4–11]. 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 [12]. Several models of lunar interior evolution have been successful in reproducing longevities for a convective core dynamo consistent with the early lunar paleomagnetic record [8–11], however, these models typically yield magnetic field surface intensities that are a factor of 100 below those required by ~4.25-3.56-Ga 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 the lunar core dynamo in sustaining surface field intensities consistent with the paleomagnetic record.

Therefore, in this analysis, we disregard constraints imposed by the lunar mantle and constrain the maximum available energy within the lunar core that could theoretically sustain a convective core dynamo. For such a dynamo, the magnetic field surface intensity is constrained by the energy that drives thermochemical convection in the core [e.g., 12].

Minimum Required Core Energy: Similar to other studies [8–10], we use the available energy flux to magnetic field strength scaling of [13] to determine the magnetic field surface intensity that can be produced for a given core heat flux. To determine the minimum required energy needed to drive a dynamo powered by core convection, we assume that the magnetic field is exclusively dipolar and that the total energy of the core is available to power the dynamo. In this instance, as shown by [14], the magnetic field strength scaling of [13] can be reduced to $B_s \cong 2.2\times10^{-5} {P_{cmb}}^{\frac{1}{3}}$ for a lunar core with a radius R_c of 380 km, where B_s is the magnetic field surface intensity and P_{cmb} is the core heat flux. From this equation, it can be shown that a continuously powered lunar dynamo at a 40–µT surface intensity requires a core heat flux of at least 6 W m^{-2}, equivalent to a total energy of ~2.5×10^{29} J for the 700-Myr period between 4.26 and 3.56 Ga.

Energy Sources for Core Convection: For a convective core dynamo, the energy that drives convection is primarily sustained by compositional differentiation, secular cooling, and inner core crystallization. For the early Moon, radioactive decay and impact-derived energy may also power core convection. Below, we examined the maximum energy contributions associated with each of the aforementioned energy sources. Each energy source was independently maximized with respect to the possible states of the lunar core [15]. Independently maximizing each energy source simplifies our calculations and faciliates analysis of end-member scenarios.

Gravitational and Latent Energy. As the liquid iron-alloy core cools below its liquidus and a solid iron core crystallizes, both gravitational energy and latent heat is released.

During inner core crystallization, the outer core is increasingly enriched in the lighter (alloy) element and 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 released from a core that transitions from an initial compositionally uniform state with an average density $\bar{\rho}$ to a two-layer core in its lowest gravitational potential energy configuration, can be computed by a straightforward relation provided by eqs. 2–4 in [16]. For the permissible range of core radii and densities, the maximum gravitational energy that can be released is 4×10^{24} J.

The latent energy E_L released by inner core crystallization is represented by the relation $E_L = \frac{4}{3}\pi\rho_2 R_{ic}^3 L$, where E_L is maximized by assuming the inner core radius R_{ic} is 280 km, ρ_2 is the density of iron, and L is the latent heat of fusion for iron. Accordingly, we determined the maximum value of E_L to be 2.2×10^{26} J.

Thermal Energy. The thermal energy E_T associated with secular cooling of the lunar core is represented by the relation $E_T = \frac{4}{3}\pi\bar{\rho}R_c^3 C_p(T_i - T_f)$, where C_p is the specific heat of the core. T_i and T_f are the initial and melting temperatures of the lunar core, respectively. E_T can be maximized by assuming that the melting temperature T_f is ~1200 K, the eutectic melting temperature for an Fe-FeS core at ~5 GPa, and the maximum initial temperature of the lunar core, T_i, is 2400 K. T_i is approximated from the combination of the volumetric average of a Moon initially heated by accretional energy (1800 K) and the core temperature increase from the energy of lunar compositional differention (600 K), if the energy were fully stored within the core. Ultimately, we find that the maximum energy from secular cooling of the core, E_T, is 1.9×10^{27} J.

Radiogenic Heat. Radiogenic heat is not commonly considered as a major energy source to power core convection, but it has been suggested that a dense layer enriched in radioactive heat-producing elements (*U, Th, K*) just above the core-mantle boundary could insulate and heat the core while simultaneously delaying the onset of a core dynamo until ~4 Ga [7]. Alternatively, it is conceivable that heat-producing elements could have been sequestered into the lunar core as has been suggested for Earth's core [17]. In either case, the fraction of radiogenic heat that powered the lunar dynamo is ultiamtely limited by the total radiogenic heat of the Moon, E_R. By the end of the high-intensity magnetic field epoch at ~3.56 Ga, we find that the maximum value for E_R is 1.9×10^{28} J. This value is determined using nominal values for the uranium abundance in the bulk Moon of 20 ppb as well as Th/U and K/U ratios of 3.7 and 2500, respectively [e.g., 10,18].

Impact Energy. It may be possible that the dynamo was, in part, powered by energy deposited by basin-forming impacts. For simplicity, we generously assume that the total energy of these impacts could be efficiently used by the core dynamo and that each impactor that formed the total inventory of 74 lunar basins recognized by [19] deposited the same $\sim 4 \times 10^{26}$ J of energy into the Moon as the impactor that formed the largest lunar basin, that of South Pole–Aitken [20]. Ultimately, we find that these 74 basins could provide an energy contribution of no more than $\sim 3 \times 10^{28}$ J.

Comparison of Required Core Energy to Known Energy Sources: Figure 1 summarizes the contribution of the energy sources discussed in the previous section to a convective core dynamo capable of sustaining a 40–μT surface intensity for the 700-Myr period between 4.26 and 3.56 Ga. Our results show that the traditional energy sources commonly considered to power a core dynamo (i.e., gravitational, thermal, latent) provide less than 1% of the total energy needed to sustain an ancient lunar dynamo for 700 Myr at the minimum 40–μT surface intensity inferred from the lunar paleomagnetic record. Furthermore, even after invoking several generous assumptions, we also find that non-traditional energy sources (i.e., radioactive, impact) generate insufficient power to sustain a convective lunar dynamo.

Summary: Our results demonstrate that the lunar core is unlikely to possess sufficient energy to sustain a convective core dynamo capable of generating a 40-μT surface field for ~700 Myr. 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 strong magnetic dynamo inferred from samples was only intermittently active (3) the scaling laws for internally generated magnetic fields are not applicable for the lunar core; or, (4) an exotic mechanism or unknown energy source that was active between ~4.26 and 3.56 Ga is primarily responsible for the generation of the high-intensity paleomagnetic signatures.

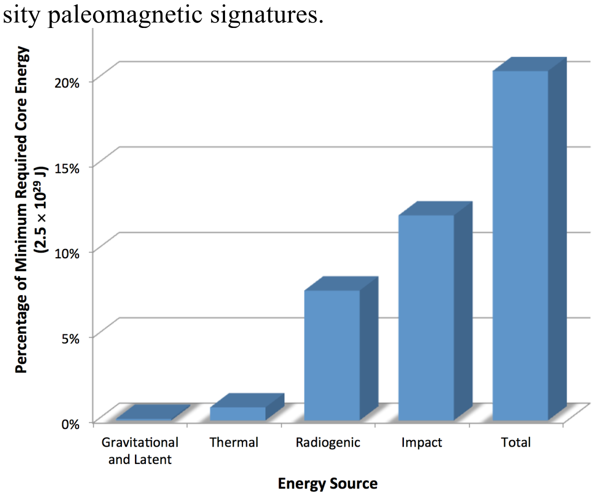

Figure 1. The contributions of various energy sources are shown as a percentage of the total minimum energy needed to sustain a 40–μT surface intensity on the Moon for the 700-Myr period between 4.26 and 3.56 Ga. Energy sources shown are gravitational (0.002%), latent (0.09%), thermal (0.76%), radiogenic (7.6%), and impact (12%).

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