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Persistence and origin of the lunar core dynamo

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The lifetime of the ancient lunar core dynamo has implications for its power source and the mechanism of field generation. Here, we report analyses of two 3.56-Gy-old mare basalts demonstrating that they were magnetized in a stable and surprisingly intense dynamo magnetic field of at least ∼13 μT. These data extend the known lifetime of the lunar dynamo by ∼160 My and indicate that the field was likely continuously active until well after the final large basin-forming impact. This likely excludes impact-driven changes in rotation rate as the source of the dynamo at this time in lunar history. Rather, our results require a persistent power source like precession of the lunar mantle or a compositional convection dynamo.

The existence of a global planetary magnetic field provides evidence of an advecting liquid core. Although the Moon does not have a global field today, lunar crustal magnetism and paleomagnetism in returned samples provide evidence of an ancient lunar dynamo (1, 2). Laser ranging experiments (3) and reanalysis of Apollo-era seismic data (4, 5) indicate that the Moon currently has a small (∼330 km) partially molten metallic core. Recent paleomagnetic studies of slowly cooled, unshocked samples demonstrate that the Moon had a core dynamo at 4.2 Ga (6) and 3.7 Ga (7). However, the subsequent history of the lunar dynamo is largely unknown.

Determining the lifetime of the lunar dynamo would constrain the nature of its power source and the mechanism of magnetic field generation. Models of core thermal convection have found that a lunar dynamo can only unambiguously persist for as late as 4.1 Ga, well before the youngest current evidence for the magnetic field at 3.7 Ga (7). Although a compositional convection dynamo driven by the crystallization of the core is also possible, the lifetime of such a dynamo is currently unclear. This has motivated alternative models that use precession (8, 9) and/or basin-forming impacts (10) to power the dynamo mechanically via differential motion between the liquid core and rocky mantle. Precession appears to be capable of powering a dynamo until as late as ∼1.8–2.7 Ga (9). By comparison, a dynamo driven by impact-induced unlocking from synchronous rotation could likely be active only when basin-forming impacts occurred, before or during the Early Imbrian epoch (∼3.57 Ga). Therefore, these two mechanisms could potentially be distinguished using measurements of the lunar magnetic field after this time.

Some Apollo-era paleomagnetic studies argued that the termination of the lunar dynamo occurred before the eruption of the Apollo 11 high-K basalts at ∼3.6 Ga (11), whereas others suggested that the dynamo persisted but slowly decayed until at least ∼3.2 Ga (12). Two Apollo 11 samples, mare basalts 10017 and 10049, provided contrasting results that were central to this debate. Analyses of 10017 (13–16) identified one of the most stable natural remanent magnetization (NRM) records identified in any lunar sample. However, the presence of Johnson Space Center (JSC) saw marks on some subsamples and what was perceived to be a wide range of paleointensities (∼40–90 μT) led these investigators to exclude 10017 as a constraint on the lunar dynamo. Instead, these authors relied on their analyses of 10049, whose subsamples were found to carry a unidirectional magnetization (17) with a seemingly weak paleointensity (4–10 μT). However, our reanalysis of their data with modern multicomponent methods yields paleointensities up to ∼30 μT (SI Appendix).

A recent paleomagnetic study found that lunar samples with ages of 3.3 Ga and in the range 3.7–3.94 Ga may have recorded a field of several tens of microteslas (18). In this study, only one sample (12002, which has an age of 3.3 Ga) was younger than Apollo high-K basalts. However, the nature of its paleomagnetic record is currently ambiguous: Its NRM does not trend toward the origin during alternating field (AF) demagnetization, its remanent magnetization derivative (REM) paleointensity (19) varies by nearly an order of magnitude throughout the demagnetization, the sample was measured while encased in a container whose moment was similar to the demagnetized sample, and no mutually oriented subsamples were measured.

Samples

Mare basalts 10017 and 10049 are fine-grained, high-K ilmenite basalts of petrological group A (20, 21). Their major phases are pyroxene (50.6 vol % and 51.3%, respectively), plagioclase (23.6 vol % and 24.5%, respectively), and ilmenite (15.1 vol % and 14.1%, respectively), and minor mesostasis includes high-K glass (21) (SI Appendix). These basalts erupted at ∼3.56 Ga and form the present surface of most of the southwest portion of Mare Tranquillitatis. The collected rock samples are thought to have been excavated by the impact that formed West Crater ∼100 Ma (21), ∼0.5 km from the Apollo 11 landing site.

We observed similar mineral assemblages and compositions as those previously described for these samples (21). Our electron microprobe analyses of metal in 10017,62 and 10049,40 found that it has a composition of nearly pure metallic iron (Fe1−xNi, with x < 0.02) and is typically intergrown with troilite (SI Appendix). Because the high-temperature taenite phase (γ-Fe) with this bulk composition transforms fully to kamacite at 912 °C, which is above Curie temperature of 780 °C (22), the kamacite in these rocks should have acquired a pure theromremanent magnetization (TRM) during primary cooling rather than the thermochemical remanent magnetization that forms when x > 0.03 (23). Rock magnetic experiments (SI Appendix) indicate that the kamacite grain size is in the multidomain range for both 10017 and 10049.


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To constrain the samples’ cooling rates below 1,100 °C, we measured the width of the largest plagioclase lath perpendicular to the (010) faces following the method used by Grove and Beaty (20) (SI Appendix, Section 9). Our measured values of 550 μm and 120 μm indicate cooling rates of ~0.03 °C·h⁻¹ and ~0.43 °C·h⁻¹ for 10017 and 10049, respectively, which correspond to cooling times from the Curie point to ambient lunar surface temperatures of ~10⁴ d and ~10³ d, respectively. Because these samples are antiphasic, these are likely minimum estimates of the cooling timescale (20). These time scales are much longer than the expected 1-d maximum lifetime of fields generated by basin-forming impacts (24). Therefore, any primary magnetization in these samples is likely a record of a temporarily stable field like that expected for a core dynamo. Furthermore, we observed no petrographic evidence for shock (peak pressure <5 GPa), such as plagioclase fracturing, mechanical twinning, or alteration to maskelynite (SI Appendix). Mare basalts 10017 and 10049 are therefore ideal samples for testing the lunar dynamo hypothesis late in lunar history.

NRM

We carried out AF demagnetization up to 85–290 mT on eight mutually oriented subsamples of 10017,378 and on three mutually oriented subsamples of 10049,102 (all samples without JSC saw cut faces). Because 10017 and 10049 were collected as regolith cut faces. Because these samples are contaminated by viscous remanent magnetization (VRM) acquired during their 40-yr exposure to the geomagnetic field since return to Earth, and how much of this VRM subsequently decayed during storage in our shielded room before our NRM measurements, we conducted VRM acquisition and decay experiments (SI Appendix). For 10017, we found that the residual VRM would be 9.4 × 10⁻¹¹.

To determine whether the NRM of 10017 and 10049 were demagnetized by AF demagnetization up to 85 mT on eight mutually oriented subsamples of 10017,378 and on three mutually oriented subsamples of 10049,102; and 10049,102-2 during AF demagnetization. Solid (●) open (○) circles represent end points of magnetization projected onto the Y-Z (X-Z) planes for 10017 and onto the Y-Z (X-Z) planes for 10049. Peak fields for selected AF steps are labeled in microteslas. Red arrows denote HC component directions determined from principal component analyses. Subsample 10017,378-3 (A); subsample 10017,378-8 (B); subsample 10049,102-1 (C); and subsample 10049,102-2 (D).
Am², equivalent to only 2.4% of the observed initial NRM. For 10049, we found that the residual VRM would be 9.3 × 10⁻¹³ Am², equivalent to only 2.7% of the initial NRM. Therefore, neither the LC nor HC components of 10017 and 10049 are likely to be VRM-acquired in the Earth’s magnetic field.

Although our petrographic observations exclude shocks with pressures >5 GPa, even shocks with lower peak pressures could produce magnetization if a field were present. To investigate this possibility, we conducted pressure remanent magnetization (PRM) acquisition experiments (SI Appendix) for subsamples 378-3 and 102-1 following the method used by Gattacceca (27). Like previous studies of lunar rocks (27), we found that PRM was acquired dominantly by LC grains (<~30–40 mT) with even the 2.0-GPa PRM significantly softer than the NRM (SI Appendix). This suggests that neither the LC nor HC components are likely shock remanent magnetizations (SRM). We found that a 1-mT field and a 2-mT field would have been necessary to produce the LC and HC components of 378-3, respectively. Similarly, a 0.1-mT field and a 0.3-mT field would have been necessary to produce the LC and HC components of 102-1, respectively. Such fields are well above theoretical estimates of maximum dynamo fields for the Moon and at the upper end of predicted impact-generated fields (e.g., refs. 28, 29). Therefore, these field values provide further evidence against an SRM origin for either NRM component.

We conducted AF demagnetization of laboratory-induced magnetizations and compared them with that of the NRM. The HC component in each rock demagnetizes like an ARM [an analog of TRM (30)] and unlike either a PRM or an IRM (SI Appendix).

Table 1. Summary of LC and HC components for subsamples from 10017,378 and 10049,102 obtained with principal component analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>Component</th>
<th>AF range, mT</th>
<th>Type</th>
<th>Dec., Inc., °</th>
<th>MAD, °</th>
<th>DANG, °</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>10017,378-1</td>
<td>LC</td>
<td>NRM-10</td>
<td>L</td>
<td>52.0, −30.9</td>
<td>2.3</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>310.6, −44.0</td>
<td>4.1/4.8</td>
<td>3.5</td>
<td>90</td>
</tr>
<tr>
<td>10017,378-2</td>
<td>LC</td>
<td>NRM-9</td>
<td>L</td>
<td>322.0, 43.5</td>
<td>23.3</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td></td>
<td>310.0, −35.6</td>
<td>2.8/3.6</td>
<td>1.3</td>
<td>102</td>
</tr>
<tr>
<td>10017,378-3</td>
<td>LC</td>
<td>NRM-10</td>
<td>L</td>
<td>271.3, 25.4</td>
<td>7.9</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>312.6, −30.1</td>
<td>4.8/5.7</td>
<td>3.0</td>
<td>101</td>
</tr>
<tr>
<td>10017,378-6</td>
<td>LC</td>
<td>NRM-20</td>
<td>L</td>
<td>232.6, 25.6</td>
<td>7.8</td>
<td></td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>303.6, −34.0</td>
<td>7.0/12.3</td>
<td>1.9</td>
<td>70</td>
</tr>
<tr>
<td>10017,378-7</td>
<td>LC</td>
<td>NRM-10</td>
<td>L</td>
<td>186.8, 16.0</td>
<td>3.0</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>308.7, −35.4</td>
<td>3.9/5.7</td>
<td>2.3</td>
<td>90</td>
</tr>
<tr>
<td>10017,378-8</td>
<td>LC</td>
<td>NRM-13</td>
<td>L</td>
<td>213.1, 26.7</td>
<td>5.2</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>297.1, −28.8</td>
<td>10.0/14.0</td>
<td>5.8</td>
<td>95</td>
</tr>
<tr>
<td>10017,378-10</td>
<td>LC</td>
<td>NRM-20</td>
<td>L</td>
<td>219.2, −24.1</td>
<td>7.3</td>
<td></td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>271.7, −51.4</td>
<td>3.8/4.9</td>
<td>2.5*</td>
<td>128</td>
</tr>
<tr>
<td>10017,378-11</td>
<td>LC</td>
<td>NRM-15</td>
<td>L</td>
<td>243.3, −58.6</td>
<td>8.2</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>313.5, −40.1</td>
<td>3.0/4.2</td>
<td>4.1*</td>
<td>137</td>
</tr>
<tr>
<td>10049,102-1</td>
<td>LC</td>
<td>NRM-10.5</td>
<td>L</td>
<td>353.1, −53.3</td>
<td>5.7</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>332.5, −77.9</td>
<td>10.6/13.7</td>
<td>4.7</td>
<td>89</td>
</tr>
<tr>
<td>10049,102-2</td>
<td>LC</td>
<td>NRM-11.5</td>
<td>L</td>
<td>175.2, −51.2</td>
<td>12.6</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>294.2, −80.2</td>
<td>5.2/6.0</td>
<td>2.9</td>
<td>96</td>
</tr>
<tr>
<td>10049,102-3</td>
<td>LC</td>
<td>NRM-4</td>
<td>L</td>
<td>268.6, −11.1</td>
<td>23.8</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td></td>
<td>AL</td>
<td>339.7, −79.1</td>
<td>6.6/9.1</td>
<td>7.6</td>
<td>20</td>
</tr>
</tbody>
</table>

Notes: The first column gives the subsample name and component name; the second column gives the magnetization component; the third column gives the range of AF steps used for the fit; the fourth column gives the fit type (AL, line anchored to the origin; C, circle fit forced through the origin, poles reported; L, line); the fifth column gives the declination (Dec.) and inclination (Inc.) of the fit direction (for line fits) or great circle pole (for circle fits); the sixth column gives the MAD of the component forced through the origin/not forced through the origin; the seventh column gives the DANG; and the eighth column gives the number of AF steps used in the fit (N). The last three columns give paleointensities: ARM paleointensity (in microteslas) = (NRM lost)/(ARM lost/5° × [bias field (in microteslas)]) × anisotropy correction factor; IRM paleointensity (in microteslas) = (NRM lost)/(IRM lost) × x anisotropy correction factor. We used f = 1.34 and a = 3,000. Uncertainties on each paleointensity value are formal 95% confidence intervals on the slope fit using the Student t test (31) and do not include the factor of ±3° uncertainty associated with the unknown ratios of ARM and IRM to TRM.

*DANG calculated using first point of fit.

Fig. 2. Equal area stereographic projection of NRM component fits. Circles denote HC directions (primary magnetization) for each subsample, and squares denote LC directions (overprint). The stars are the Fisher mean HC direction from principal component analyses, with surrounding dashed ellipses indicating 95% formal confidence intervals on mean directions (not accounting for additional ~3°–5° mutual orientation uncertainty). (A) Sample 10017,378. Black and gray symbols correspond to samples measured at the Massachusetts Institute of Technology and University of California, Santa Cruz, respectively. The dashed great circle denotes a circle fit forced through the origin for the HC data of subsample 10. (B) Sample 10049,102.
Therefore, the HC components of 10017 and 10049 are likely TRMs acquired during cooling in a stable field on the Moon.

**Paleointensity**

The HC components of 10017, 378 yielded anisotropy-corrected paleointensities ranging between 47 and 84 μT from the ARM method and between 43 and 95 μT from the IRM method; 10049, 102 yielded anisotropy-corrected HC component paleointensities ranging between 49.3 and 86.3 μT from the ARM method and between 59.1 and 95.2 μT from the IRM method (Table 1 and SI Appendix). The range of variability between subsamples is expected, given the uncertainty in the calibration factors for these methods. Furthermore, the similarity between the ARM and IRM values gives confidence that each method is producing relatively accurate results. Given that each individual paleointensity is uncertain by a factor of 3–5, the multispecimen mean values should be significantly less uncertain than this factor. The average values for the ARM method are 67 ± 15 μT for 10017 and 65 ± 14 μT for 10049 [uncertainties are formal 95% confidence intervals on the slope fit using the Student t test (31) and do not include the factor of ~3–5 uncertainty associated with the unknown ratios of ARM and IRM to TRM]. The average values for the IRM method are 71 ± 21 μT for 10017 and 77 ± 18 μT for 10049 (uncertainties on mean values are observed 1 SD from multiple samples). These paleointensities are indistinguishable within the uncertainty and give a mean value for all experiments on both samples of 69 ± 16 μT, which corresponds to a very conservative minimum paleofield of ~13 μT. These values are also within error of the paleointensity inferred at 3.7 Ga from mare basalt 10020 (7) and consistent with values recently obtained for other samples with crystallization ages from 3.7 to 3.94 Ga (18) (although the age and origin of the magnetization in the latter samples are not well constrained). These paleointensities are higher than previous estimates for 10049, likely due to lack of complete NRM demagnetization in these earlier studies (SI Appendix).

**Thermochronology**

The 3.56-Ga crystallization ages of 10017 and 10049 place an upper limit on the time at which they acquired their magnetization. It is possible that the magnetization of these rocks could have been acquired or reset during thermal excursions following their formation. Although the lack of shock features in these rocks precludes direct shock heating, they could have experienced temperature excursions from burial in a hot ejecta blanket or nearby volcanic activity. To assess this possibility, we conducted 40Ar/39Ar and 39Ar/38Ar thermochronometry on two whole-rock subsamples of 10017 and 10049 (Fig. 3 and SI Appendix).
Our analyses confirm that like other Apollo group A basalts (32), 10049 has a weighted average \(^{40}\text{Ar}/^{39}\text{Ar}\) plateau age of 3.556 \(\pm\) 8 Ma [uncertainty is 1 SD; uncertainty in the decay constant and age of the fluence monitor is excluded (33)]. However, 10017’s \(^{40}\text{Ar}/^{39}\text{Ar}\) plateau age of 3.037 \(\pm\) 7 Ma is \(-600\) Ma younger than its crystallization age (34). Our thermochronological calculations suggest that 10017 may have been heated to several hundred °C at \(-3.05\) Ga. Although this event may have partially remagnetized or demagnetized low blocking temperature grains in this rock (depending on whether a field was present at this time), many of these grains would have subsequently been demagnetized during zero-field residence on the lunar surface over the intervening 3 Ga and during residence in our laboratory’s shielded room. As has been inferred for many other Apollo 11 basalts (7, 35), both 10017 and 10049 also apparently experienced modest gas loss due to solar heating over the last 304.7 \(\pm\) 2.0 Ma and 17.5 \(\pm\) 0.1 Ma, respectively. In particular, numerical models of simultaneous production and diffusion of both radiogenic \(^{38}\text{Ar}\) and cosmogenic \(^{39}\text{Ar}\) indicate that sample 10049 only experienced temperatures in excess of the ambient crustal conditions because it was exposed near the lunar surface.

**Implications for the Power Source of the Lunar Dynamo**

Large impacts have the potential to unlock the Moon from synchronous rotation (36), such that the resulting differential motion between the librating mantle and core could generate a dynamo lasting for up to 10\(^{12}\) y (10). It is estimated that this can only occur for impactors that are larger than that required to produce a crater with a diameter of \(-300\) km (assuming an Earth-Moon distance of 25 Earth radii) (36). The youngest such basin is Orientale, which formed at 3.73 Ga and marks the end of the Early Imbrian epoch (37, 38). Because this event occurred \(-160\) Ma before the Late Imbrian eruption of 10017 and 10049, this likely excludes unlocking from synchronous rotation as a field source at 3.6 Ga.

Smaller impacts that are insufficient to unlock the Moon from synchronous rotation could still generate a dynamo mechanism by inducing longitudinal free librations (10). However, it is estimated that this was only possible while the Earth-Moon separation was \(-40\) Earth radii. Orbital history models constrained by geological evidence for the past 0.6 Ga (39, 40) suggest that the smallest Earth-Moon separation was \(-37\)–\(-44\) Earth radii at 3.6 Ga, whereas uniformly scaled models give a range of \(-47\)–\(-51\) Earth radii (41). Therefore, the conditions for the existence of a libration dynamo might have been met during the eruption of the high-K basalts. Assuming this is the case, it is estimated that for the smallest Earth-Moon separation (37 Earth radii), an impact would have to produce a libration amplitude of at least 70° to trigger a libration dynamo (10). Using equations 1 and 6 in ref. 42, we determined the minimum impactor diameter (assuming a spherical bolide with uniform density of \(-3,500\) kg m\(^{-3}\) and a lunar crustal density of \(-2,691\) kg m\(^{-3}\) (43)) required to induce a libration dynamo as a function of impact location colatitude \(\theta\), impact trajectory inclination relative to the lunar spin axis \(\theta_i\), impact trajectory declination relative to the impact location \(\phi_i\), and velocity \(V\) (angles are defined in Fig. 4, *Inset*). Using the crater-scaling equation 5.6 in ref. 44, we calculated the corresponding crater size \(D_{\text{min}}\). Using the impact velocity probability distribution \(p(V)\) of Le Feuvre and Wieczorek (37), the probability distribution of impact geocentric colatitude \(p(\theta)\) calculated from the relative cratering rate variations with latitude of Le Feuvre and Wieczorek (45); assuming a uniform distribution for impact declinations \(\phi_i\); and ignoring the curvature of impact trajectories and acceleration due to the gravity of the Moon (which would tend to make trajectories more vertical and larger craters, and therefore reduce the effect on librations for a given crater size), we computed the probability

\[
P_{\text{LD}}(D) = \int \int \int \int \delta(\theta, \theta_i, \phi_i, V) \cdot p(\theta) \cdot p(\theta_i) \cdot p(\phi_i) \cdot p(V) \cdot d\theta \cdot d\theta_i \cdot d\phi_i \cdot dV,
\]

\[
\delta(\theta, \theta_i, \phi_i, V) = \begin{cases} 1 & \text{if } D_{\text{min}}(\theta, \theta_i, \phi_i, V) \leq D \\ 0 & \text{if } D_{\text{min}}(\theta, \theta_i, \phi_i, V) > D \end{cases}
\]

where \(\delta\) selects impact parameters that produce craters larger than the threshold value \(D_{\text{min}}\). Impacts with incidence angles \(\alpha > 80°\) [where \(\alpha = \arccos(RV/|R|F)\); angle and vector definitions are provided in Fig. 4, *Inset*] are expected to produce elliptical craters (46). Because no such crater is known to have formed in the Late Imbrian era, we excluded these trajectories. We find that only craters with a diameter \(-230\) km have a probability to induce a libration dynamo >10% (Fig. 4). All the craters with a diameter \(-230\) km identified in a recent Lunar Reconnaissance Orbiter survey* (47) are presented in *SI Appendix, Table S1*. The largest crater identified in the Late Imbrian era is Humboldt (38, 47); its diameter is \(-207\) km, which corresponds to a probability of \(-6\%\) to induce a libration dynamo. The youngest impacts that had

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a significant (>25%) probability to trigger a libration dynamo are the Early Ibirnian basins Schrodinger and Orientale (47) .

The Late Ibirnian 3.56-Ga crystallization age of the high-K basalts means that they are very likely too young to have been magnetized by an impact-driven dynamo. Furthermore, attributing the paleomagnetic records of 76535 at 4.2 Ga (6), 10020 at 3.7 Ga (7), and 10017 and 10049 at 3.6 Ga to an impact-driven dynamo would require the presence of transient impact-driven dynamos. The fact that the 10017 and 10049 paleointensities are so similar to one another, as well as those of the 3.72-Ga basalt 10020 (7), argues strongly in favor of a stable lunar dynamo at least between 3.72 and 3.56 Ga. This lifetime is inconsistent with existing models of core convection, which have been unable to power a dynamo unambiguously after 4.1 Ga by thermal convection alone (48). Rather, these results support the possibility of a longer-lived power source for the lunar dynamo, such as precession (9) or theromochanical convection due to core crystallization, although impact-induced core dynamos could have operated earlier in lunar history.

Nevertheless, the high paleointensities of 10017 and 10049 [and 10020 (7)] still present a major challenge, given that all current lunar dynamo models are only thought to be capable of producing surface fields <15 μT (9). It currently remains unclear when the dynamo finally decayed.

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