EVIDENCE FOR A LONG-LIVED LUNAR DYNAMO FROM MAGNETIZATION IN APOLLO SAMPLES AND THE LUNAR CRUST.

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Overview: Natural remanent magnetization (NRM) in the lunar crust is generally agreed to provide evidence for an ancient dynamo. Furthermore, lunar NRM has been widely interpreted to indicate that fields > 1 μT persisted on the Moon from at least 4.249 ± 0.012 until 1.47 ± 0.45 Ga ago [1-3], although the intensity likely fluctuated by >10× during this time [4]. However, a recent study argued that stable NRM identified in essentially all lunar samples is the product of fields generated by impact plasmas and therefore that the dynamo had dissipated prior to 4.25 Ga [5]. Here we present new high-fidelity paleomagnetic and geochronometry analyses of Apollo glassy regolith breccia 10018 providing evidence for a strong (1.24 ± 0.2 μT) and temporally stable (> 10 min) field on the Moon at ~1.5 Ga. We also show that crustal magnetic anomalies in impact basins require temporally stable (> tens of ka) fields on the Moon after 4.2 Ga. In the context of numerous previous studies, this provides overwhelming evidence for a lunar dynamo field lasting beyond 4.2 Ga ago and likely until at least 1.5 Ga ago.

Apollo sample magnetism: NRM in Apollo samples has three main proposed origins: (1) contamination of samples during or after return to Earth, (2) fields generated by impacts, and (3) a lunar dynamo.

1. Artificial contamination. Short term exposure to strong artificial fields and long-term exposure to Earth's field following sampling partially remagnetized some lunar samples. This can be readily mitigated by studying samples not allocated to previous investigators, acquiring subsamples > ~2 mm from any saw-cut faces (e.g., [6]), the use of alternating field (AF) (~20-50 mT) and thermal demagnetization (~300°C) [2] in a controlled oxygen fugacity atmosphere [7], and targeting samples dominated by grains in the single vortex and smaller size range.

The importance of studying pristine samples is exemplified by NRM in the impact glass 64455,24, which was interpreted as evidence for impact-generated fields 2 Ma ago [5] but instead might be sample contamination [8]. As another example, thermal demagnetization in air, even with rapid (several min) heating and cooling times [5], can oxidize metal and troilite grains [7, 9, 10] that would produce inaccurate paleointensity estimates.

2. Impact-generated fields. It has been theoretically proposed that impacts could transiently produce strong (tens of μT) fields by amplification of the interplanetary magnetic field (IMF) [11] or of a dynamo field [12], or field generation by charge separation in the impact cloud [13]. However, there has been no unambiguous evidence for impact-field produced NRM in any planetary materials. Furthermore, recent magnetohydrodynamic modeling has shown that the IMF-amplification mechanism cannot produce paleointensities above 0.1 μT [14]. Impact amplification of a dynamo field is currently being investigated [12].

In any case, a key difference between core dynamo and putative impact fields is their duration: the former can last billions of years or longer while the latter are predicted to last <1 day for IMF-amplification by basin forming impacts [11] and ~40 s and 0.2 s for charge separation during formation of 30-km and 200-m radius craters [13]. Therefore, stable impact-field-produced NRM could only be acquired by samples that are shocked and/or cooled faster than these timescales. By comparison, measured mare basalts (3.56-3.9 Ga) have *e*-folding cooling times from the 780°C kamacite Curie temperature of 10^2 to 10^3 days [15] and the glassy regolith breccia 15498 (1.47±0.45 Ga) has a cooling time from the 780°C to 620°C of ~10 min and longer at lower temperatures [2, 16]. All of these samples formed after the youngest basin-forming impact and have cooling rates >10-100× slower than charge separation

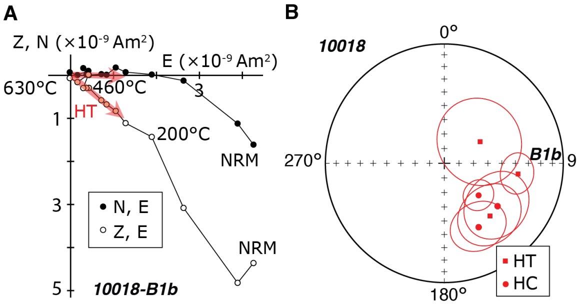

Fig. 1: Paleomagnetism of glassy regolith breccia 10018. The sample has a stable high temperature (HT), high coercivity (HC) unidirectional component formed in a 1.24 ± 0.2 μT field (A) Orthographic projection showing endpoints of NRM during controlled oxygen fugacity thermal demagnetization of subsample B1b. Partial thermoremanent magnetization checks (not shown) are consistent with no major thermochemical alteration to >630°C. (B) Equal area stereonet showing directions of unidirectional HC (34-100 mT) and HT (320-610°C) NRM components.

impact fields predicted for nearby crater-forming events (e.g., Dune and Aristillus craters, which might have excavated 15498). All of these samples show no petrographic evidence of shock (<5 GPa), such that any significant shock remanent magnetization should have removed by AF demagnetization (<50 mT; [17]).

3. Dynamo. For stable NRM in pristine lunar samples that are unshocked, slowly cooled, and shown not to have post-sampling magnetic contamination, the remaining explanation is a lunar dynamo. As an example, we present a new paleomagnetic study of glassy regolith breccia 10018. The glassy matrix of 10018 should have acquired a thermoremanent NRM following assembly, which our laser probe trapped $^{40}Ar/^{36}Ar$ measurements indicate occurred at 1.542 ± 0.019 Ga. Our hysteresis data indicate a dominant single vortex and smaller size. Our controlled oxygen fugacity double-heating experiments using checks for thermochemical alteration indicate an NRM stable to >630°C that formed in a field of 1.24 ± 0.2 μT, in agreement with AF-based estimates (1.73 ± 0.42 μT). Given 10018's dimensions, we estimate the conductive cooling timescale following thermal equilibration of clasts and matrix to be >10 min. Along with 15498 [2], 10018 is now the second known sample to provide strong evidence for a dynamo after 2 Ga.

Crustal magnetism: The lunar crust is pervasively magnetized with fields at 30 km altitude ranging from 0.1 to 27 nT. Although the strength is just 0.2 to 1 nT at this altitude over large surface regions, these fields are intrinsic to the Moon and not measurement noise since maps from independent magnetometry and electron reflectometry techniques are broadly compatible [18].

Most crustal anomalies formed by a dynamo. Unlike for some Apollo samples, the NRM of the crust cannot be artificial contamination. Likewise, the sources of most crustal anomalies cooled so slowly from 780°C to 0°C (~1 ka for Reiner Gamma [19], ~tens of ka for a 1 km-thick impact melt sheet [20], and >100 Ma for the 100 km-deep crust and upper mantle [21]) that they cannot have been magnetized by impact fields. This leaves a lunar dynamo as the only remaining explanation for most large-scale lunar anomalies.

Paleofield lifetime. About half of the 12 Nectarian-aged impact basins have magnetic anomalies located within their peak rings, which is where hydrocode simulations predict the existence of a thick impact melt sheet [22]. The partial melt at these locations should have extended to > 120 km depth beneath the pre-impact surface [23]. Thermal evolution studies indicate that the 780°C Curie isotherm was ~140 km below the pre-impact surface for the cold farside and shallower near the prominent nearside mare [20]. This indicates that any pre-existing subsurface NRM within the peak rings would have been entirely thermally erased following the impact.

Therefore, the magnetic anomalies within the peak rings of the Nectarian-aged basins must postdate basin formation, estimated to be no earlier than 4.2 Ga and as young as 3.85 Ga ago [24]. The most plausible explanation for these anomalies is the slow cooling of the impact melt sheet in a dynamo. Moreover, a dynamo origin for the even younger anomalies cannot be excluded (e.g., the ~3.3-3.9 Ga old [25] Reiner Gamma anomaly). The absence of anomalies at spacecraft altitudes above some impact basins could be due to (a) a dynamo that is episodic, fluctuating in intensity and/or reversing more rapidly than the melt sheet cooling timescale, and/or (b) low quantities of metallic Fe in the impact melt sheet, which could reflect the composition of the impactor and/or the pre-impact crust.

Summary. The NRMs of Apollo samples indicate a lunar dynamo field of ~1-5 μT persisted until ~1.5 Ga, while NRM within Nectarian basins indicates that a dynamo existed until after 4.2 Ga. Because theory [26] suggests the dynamo intensity may have been fluctuating in intensity, low paleointensities inferred from weakly magnetized samples [4, 5, 27] do not require the long-term absence of a dynamo. The dynamo's long lifetime supports a power source like core crystallization or mantle precession [1].

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