NEXT-GENERATION LUNAR MAGNETISM BY ARTEMIS. S. M. Tikoo[1], B. P. Weiss[2], I. Garrick-Bethell[3,4], J. L. Kirschvink[5], L. L. Hood[6], D. Blewett[7], O. Aharonson[8], and J. Head[9], [1]Department of Geophysics, Stanford University, Stanford, CA (smtikoo@stanford.edu), [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, [3]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA, [4]School of Space Research, Kyung Hee University, Yongin-si, South Korea, [5]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, [6]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, [7]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [8]Department of Earth and Planetary Sciences, Weizmann Institute of Science, Israel, [9]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI.

Introduction: Recent studies of Apollo samples and crustal magnetism have demonstrated that the Moon produced a dynamo magnetic field (with intensities seeming to rival that of the modern Earth) between at least 4.25 and 1.9 billion years ago (Ga) [1,2]. However, despite these advances in our understanding of the Moon's magnetism, the detailed paleointensity history, field geometry, and dynamo generation mechanism(s) remain uncertain. The crewed Artemis missions, which will land near the Moon's southern pole, present an unprecedented opportunity to collect new samples and make surface field measurements that will collectively transform our understanding of these questions. Below, we outline strategies for Artemis to achieve those goals.

1. Paleomagnetic sampling: Terrain around the lunar southern pole is primarily pre-Nectarian (>4 Ga). Therefore, the Artemis landing sites would permit paleointensity studies that capture the earliest history of the lunar dynamo—a time period that was very sparsely sampled during the Apollo missions (**Fig. 1**). The south polar region contains numerous younger craters that vary in age, including the ~20 km diameter Shackleton crater, so it is possible to collect materials representing a wide range of ages [3]. Developing a detailed paleointensity history will help discriminate between proposed dynamo generation mechanisms (e.g., convective vs. mechanical) [1].

Nearly all Apollo samples were collected from the regolith without primary orientation information. While unoriented samples allow for paleointensity analyses, they cannot be used to obtain absolute magnetization directions and paleopole locations which are critical for constraining the overall geometry of the global magnetic field. Studies of crustal magnetic anomalies using Lunar Prospector and Kaguya orbital data have found magnetic paleopoles near the poles as well as other latitudes [4]. It is unclear whether the inferred paleopole distribution is due to a non-axial dipole field, true polar wander, or uncertainties associated with magnetic inversion techniques. Conducting paleomagnetic studies on absolutely oriented bedrock or in-place impact melt sheets would circumvent uncertainties associated with inversion techniques and enable precise radiometric ages.

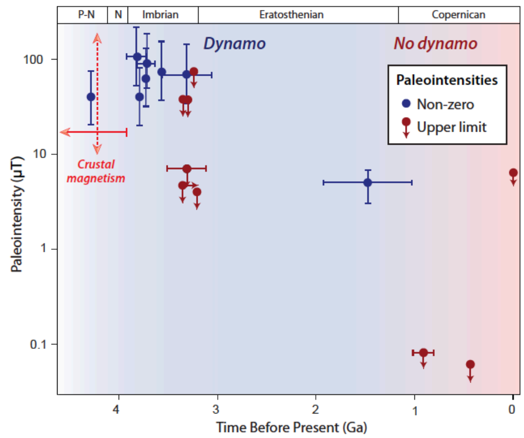

Figure 1. Modern lunar paleointensity measurements. Blue points represent actual paleointensity values and uncertainties (vertical error bars). Dark red points and associated downward arrows represent upper limit constraints on surface field values. Age uncertainties are shown using horizontal error bars. Also shown in light red is the timing of dynamo activity as indicated from orbital measurements of crustal magnetic anomalies. Modified from [2].

Sample collection. Lunar rocks vary greatly in terms of their magnetic recording fidelities. Therefore, samples should be collected from a range of rock types, including lunar igneous rocks, impact breccias, melt rocks, and soils. Because exposure to high pressures associated with meteoroid impacts can remagnetize rocks [5], astronauts should be trained to identify shock features within rocks and should focus on collecting unshocked samples on the Moon.

As mentioned above, collection of oriented samples would enable the most comprehensive paleomagnetic studies possible. It may be possible to acquire orientable bedrock or impact melt rock samples from crater rims or walls, where material has been excavated and not subsequently buried by substantial regolith. Some Apollo samples could have their orientations reconstructed via detailed surface photography that documented sunlight angles where and when each sample was collected [6]. However, near the south pole it is likely that substantial regions within craters will be in permanent shadow, which would preclude reorientation by sunlight angle. Therefore, paleomagnetic samples should be collected from sunlit areas (or have their absolute orientations be determined via some other approach that does not rely on the Sun). To ensure proper documentation of geologic context and surface orientation, all samples should be photographed from multiple angles (including background features) prior to collection.

Another way to collect in-place bedrock or impact melt samples would be to conduct drilling to acquire continuous cores. While it may be difficult to reconstruct azimuthal orientation from such cores, simply knowing the paleo-horizontal plane of cored materials would permit determining the paleoinclination of the recorded field. Such coring may also facilitate study of numerous oriented paleomagnetic samples per site, increasing statistical robustness of results [7].

2. Surface magnetometer measurements: There are numerous crustal magnetic anomalies present in the vicinity of the lunar south pole that would be interesting to investigate (**Fig. 2**) [8]. Regardless of whether these features can be reached, a continuous series of surface magnetic field measurements acquired over the course of a traverse would provide crucial information regarding the intensity and spatial heterogeneity of crustal fields. This information would, in turn, elucidate the origins of lunar magnetic sources and determine whether they are magmatic or impact-related in origin.

Some Apollo missions conducted surface magnetic field measurements using tripod-mounted, portable fluxgate magnetometers. The tripod mounting and the need to maintain a ~15 m distance from spacesuits and other landing equipment (which emit magnetic fields) permitted few measurements to be obtained at each landing site [9]. Future missions could achieve a large number of continuously acquired magnetic field measurements, similar to those obtained during a 1.5 km traverse by Lunokhod-2 [10], by mounting a fluxgate magnetometer at the end of boom extending from a rover. An alternative possibility that is less sensitive to contaminating fields involves using a magnetic field gradiometer to make measurements. Absolute magnetometer orientations could be reconstructed from video recordings or rover navigation data. An additional stationary magnetometer should be placed in the same region to monitor the general time-dependence of the magnetic field, which would constrain the lunar interior temperature profile, the size of the lunar core, and conceivably even be used to prospect for water [7].

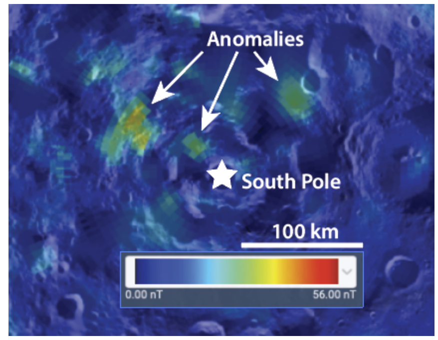

Figure 2. Kaguya and Lunar Prospector magnetic anomaly map for the total field intensity at the surface [8].

3. Sample handling and curation: During sample handling and transportation both on the Moon and on Earth, it is possible for samples to be magnetically contaminated from exposure to strong fields. Below, we outline ways to mitigate magnetic contamination during Artemis studies.

Lunar and spacecraft operations: To avoid contamination from spacesuit electronics, astronauts should be provided with nonmagnetic hammers, scoops, and tongs with long handles to collect samples from the surface or from boulders. Once collected, samples should ideally be placed in a nonmagnetic container and stored in a magnetically shielded environment during their transportation to Earth to mitigate exposure to spacecraft magnetic fields. It may also be useful to include a magnetic witness plate in the sample storage container to record exposure to magnetic fields during transit.

Curation and handling: Samples (or portions of them) should be stored on Earth in a magnetically shielded environment (<~200 nT ambient field). This would prevent samples from acquiring magnetization from long-term exposure to the Earth's field while also allowing prior magnetic contamination to viscously decay. Both astronauts and curatorial staff should be trained in basic magnetic contamination protocols and be provided with nonmagnetic tools for sample handling.

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