LUNAR MAGNETISM STUDIES BY CREWED MISSIONS TO THE MOON. I. Garrick-Bethell[1] and B. P. Weiss[1], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, e-mail: iang@mit.edu.

Introduction: The Moon offers a tremendous opportunity to further our understanding of magnetic fields observed on solar system bodies. The origins of these fields have far ranging implications for topics such as early atmospheric loss rates on Mars and the thermal state of Mercury's interior. Future missions to the Moon have the potential to fill in the details where Apollo left off and conclusively determine the origin of lunar magnetism. We recommend that future missions: 1) obtain oriented drill cores from undisturbed mare basalt flows and possibly crustal bedrock, 2) obtain samples of impact melt sheets and other impactites in craters, 3) continuously collect measurements of the local magnetic field during all traverses, and 4) protect samples from external magnetic fields after collection. We briefly comment on programmatic issues associated with these objectives.

1. Oriented mare basalt flows. Oriented samples of undisturbed basalt flows offer the best opportunity to test if and when a dipolar lunar core dynamo was operating on the Moon, as suggested by previous studies [1]. Sampling bedrock may be done either at exposures on the flanks of rilles, as achieved with some success on Apollo 15, on the flanks of craters, or by drilling through regolith into bedrock. If outcrop samples are collected, special care must be taken to document the position and context of the outcrop. During the Apollo 15 mission, two samples were collected as oriented pieces of bedrock from Hadley Rille. However, in part because of uncertainty in the photographs and context of the samples, it is difficult to truly determine if the sample is bedrock. Excavation of debris surrounding an outcrop, such as the one in Fig. 1, and documentation of surrounding outcrops, can help establish if an outcrop has been disturbed from its initial position. Multiple oriented samples should be collected from multiple flow units to build the required statistics. Mission durations longer than Apollo missions can ensure that samples are collected with sufficient abundance and documented in sufficient detail.

If mare samples are collected by drilling, one problem is that unless many tens of meters of drill depth can be achieved, it may be unclear if the core is from a large, displaced boulder, or from true bedrock. The collection of oriented bedrock and/or deep drill cores will undoubtedly overlap with other science objectives and this synergy should be exploited. The difference for magnetism is that nonmagnetic drill materials should be used, as is the standard procedure on Earth.

Unfortunately, the current NASA plan for a base at the lunar poles does not place astronauts close to known mare basalts.

2. Samples of melt sheets and crater materials. Impact craters several kilometers in diameter may have melt sheets near the tops and bottoms of their breccia lenses [2]. These melt sheets may record the ambient magnetic field minutes to days after crater formation, and their rapid cooling times will likely crystallize ideal magnetic recorders. Because of these properties and the fact that craters have formed throughout lunar history, melt sheets are perfect for studying lunar magnetism across all epochs. In addition, a melt sheet can provide abundant samples from an unequivocal single source, providing the statistics and confidence that lunar paleomagnetism has so far lacked. Fortunately, kilometer sized craters are prevalent all over the Moon, so that even a polar base could have access to melt sheets. The trick will be to find melt sheets that are intact and accessible by drills or excavation.

Samples in the vicinity of a crater. Impact melt glasses, shocked bedrock, and heated breccia debris from impacts are all materials of interest for studying the relationship between magnetic fields and impact craters. Currently, we are studying similar materials from Lonar Crater (1.8 km diameter), the only terrestrial impact crater in basalt, as an analog for impact magnetization processes [3]. Impact melt glasses and coarse fine materials (2-4 mm fragments) near the rims of lunar craters can easily be collected in great abundance and provide useful magnetization information [4]. The age of the magnetic field would be provided by any clustering of ages in such materials. Bedrock from the crater walls, ideally basalt, can be tested for shock demagnetization, and these samples can be compared with samples from the exterior of the crater, or even from a central peak if the crater is large enough. We note that some of the above samples are easier to collect than a sample of an interior melt sheet, but the melt sheet is of greater importance.

3. Surface magnetometer. A portable flux gate magnetometer (the "LPM") was carried on the Apollo 14 and 16 missions [5, 6]. However, because the devices were tripod mounted and had to be deployed sufficiently far from the spacesuits' magnetic fields, only two measurements were taken on Apollo 14, and only five were taken on Apollo 16. For future missions to any location on the Moon, a flux gate magnetometer could be mounted on a rover to permit con-

tinuous measurements as the astronauts move over the surface. The LPM required a standoff distance of ~15 m to avoid interference from the rover, which suggests that a 15 m boom extending from the back of a rover could be used to mount the flux gates. Alternatively, a magnetic field gradiometer could be mounted closer to the rover, without as much concern for contaminating fields. The absolute orientation of the magnetometers can be reconstructed based on video, and/or navigation data from the rover. This is not as precise as making each measurement with a tripod, but the added value of continuous measurements outweighs the uncertainty in orientation. Either method should ensure that lunar dust does not contaminate the sensors.

Finally, a separate station should be established in the general vicinity of the EVAs to measure the time dependence of the field due to changes in the Moon's position relative to the Earth. These time-dependent changes are then used to calculate the intrinsic magnetic field of local materials [5, 6].

4. Sample curation. Samples collected during the Apollo missions were not protected from magnetic fields on the spacecraft and they have been continuously stored without shielding from Earth's geomagnetic field. This has resulted in some samples being remagnetized by fields more than 100 times stronger than the ambient surface fields in which they had been sitting for billions of years [6]. However, for a modest investment compared to the cost of returning the samples, the sample storage containers on the Moon and Earth can be wrapped in a layer of μ-metal, shielding them from external magnetic fields.

Programmatic considerations: Some of the above activities are uniquely suited for humans. Drilling tens to hundreds of meters at multiple locations is likely best performed by humans. Excavating, sampling, and documenting bedrock on the steep slopes of rilles or crater walls is also well suited for humans. Other measurements, such as sampling coarse fines, or roving with a magnetometer, can be performed almost equally well by robots. Robotic scouts may also be useful for identifying bedrock or loose layered rocks (Fig. 2) that may later be sampled and studied in detail by humans.

Several of our proposals, such as sampling of bedrock and collection of impactites, are compatible with other lunar science objectives. Therefore, it may seem possible that some basic magnetism science could be accomplished without specifically collecting these materials for paleomagnetism. However, it is imperative that minimum paleomagnetism sampling requirements be specified and built into the mission design at an early time. Otherwise, without the necessary sample statistics and context, the origin of lunar magnetism will continue to be inconclusive. We also note that two of our ideas that are unique to the field of lunar magnetism are the surface field measurements and the special packaging of samples. These two are, however, perhaps the lowest cost items.

The Apollo results provided many surprises about magnetism on the Moon and have raised important questions that are applicable to other bodies in the solar system. Future human missions on the Moon have the potential to answer these questions with the same certainty that we have about the origin of Earth's magnetic field.

References: [1] M. Fuller and S. M. Cisowski (1987), *Geomagnetism 2*, 309-455. [2] H. J. Melosh, *Impact Cratering: A Geologic Process* (1987), Oxford U. Press, 245 pp. [3] B. P. Weiss, I. Garrick-Bethell, S. Pedersen, et al. (2007) *LPS XXXVIII*, submitted. [4] I. Garrick-Bethell and B. P. Weiss (2007), *LPS XXXVIII*, submitted. [5] Apollo 14 Preliminary Science Report, NASA SP-272 (1971). [6] Apollo 16 Preliminary Science Report, NASA SP-315 (1972). [7] Apollo 15 Preliminary Science Report, NASA SP-289 (1972).

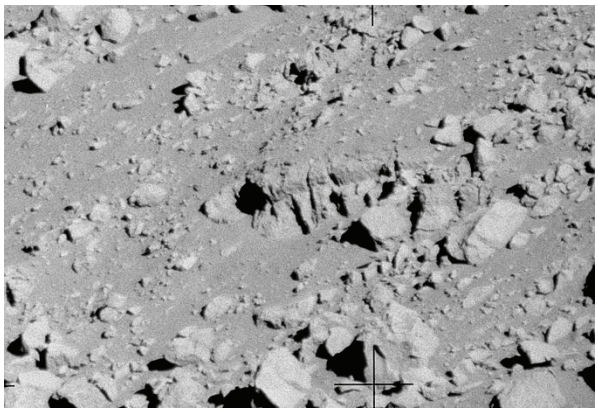

Figure 1: 18 m long layered outcrop at Hadley Rille (photo AS15-84-11257, slightly stretched for clarity) [7].

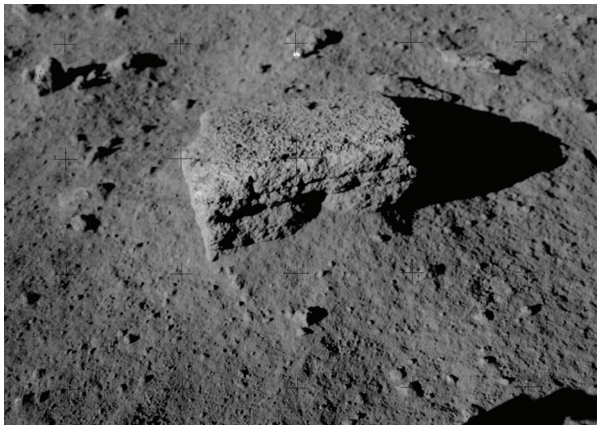

Figure 2: Close up of a layered rock at Hadley Rille (photo AS15-82-11131, slightly stretched for clarity).