UNDERSTANDING LUNAR MAGNETISM: PRESENT STATUS AND FUTURE WORK USING SURFACE MAGNETOMETERS. Nicola C. Richmond[1,2] and Lon L. Hood[1]; [1]Lunar and Planetary Lab, University of Arizona, 1629 E. University Blvd., Tucson, Arizona 85721; lon@lpl.arizona.edu; [2]Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, Arizona 85719; nic@lpl.arizona.edu.

Introduction: Measurements during the Apollo manned lunar landing missions (including surface and low-altitude orbital magnetometer measurements) revealed an unexpected magnetization of large portions of the lunar crust (e.g., [1,2,3]). In this paper, we summarize first the present status of our understanding of the observed magnetization and then discuss how future surface measurements can help to resolve remaining fundamental issues.

Present Status: Early analyses of returned sample data showed that (a) reduced metallic iron particles produced during meteoroid impacts are the main ferromagnetic carriers in the available samples; (b) these carriers are especially common in impact-produced materials such as breccias and are relatively rare in igneous materials such as mare basalt. Paleointensity estimates for returned samples indicate that fields with amplitudes exceeding 10 μT (i.e., comparable in intensity to the Earth's field) existed at the lunar surface during at least some periods prior to about 3.6 Gyr ago [4,5].

Surface magnetometer data at four Apollo landing sites showed that the strongest surface fields (> 300 nT) were measured near the Apollo 16 landing site [6], a region now known to be dominated geologically by impact basin ejecta materials. Low-altitude orbital measurements with magnetometers on the 1999 Lunar Prospector spacecraft and the Apollo 15 and 16 subsatellites showed that anomalies on the lunar near side correlate often with impact basin ejecta materials including the Fra Mauro Formation, the Cayley Formation, and the Descartes mountains [7,8,9,10]. The global distribution of orbital anomalies is characterized by relatively weak fields over young nearside basins (e.g., Imbrium) but much stronger fields in regions antipodal to these same basins [11,12, 8]. Correlative studies of magnetic fields vs. surface geology in these antipodal regions indicate that the fields correlate best with unusual ``grooved and mounded'' or ``hilly and lineated'' terrain [13], interpreted by lunar geologists to be a consequence of the associated basin-forming impact.

Finally, correlative studies have also shown that the strongest individual anomalies often occur coincident with unusual albedo markings of the Reiner Gamma class [14,15]. For example, the strongest single anomaly on the near side correlates with a high-albedo region of the Descartes mountains located about 50 km from the Apollo 16 landing site [10]. The second strongest anomaly correlates with the Reiner Gamma albedo marking. Other similar albedo markings are found on the far side in regions antipodal to young lunar basins where strong concentrations of crustal anomalies are also found.

Key Issues: From a planetary science perspective, the single most important unresolved issue relating to lunar magnetism is the origin of the magnetic field(s) that were responsible for producing the observed crustal magnetization. Possibilities include a former core dynamo (e.g., [4,5]) and transient fields generated as a consequence of large-scale, hypervelocity impacts on the Moon (e.g., [16,17]). A former core dynamo imposes basic constraints on the early evolution and thermal history of the Moon. On the other hand, if lunar crustal magnetization is caused mainly by impact-generated transient fields, then important implications follow for the origin and nature of crustal paleomagnetism on other airless silicate bodies in the solar system (e.g., Mercury, asteroids).

Two approaches toward resolving this issue are (a) a determination of directions of magnetization for major crustal anomaly sources around the Moon, especially those associated with impact basins; and (b) a better determination of the sources of lunar crustal magnetic anomalies, including obtaining ground truth evidence at locations of strong anomalies. For example, if basin ejecta are truly the main sources of orbital anomalies, then such sources would have formed relatively quickly (times < 1 day) so that transient fields could have contributed importantly to the magnetization. On the other hand, if large crustal blocks or subsurface igneous intrusions (e.g., dike swarms) are found to be significant anomaly sources, then their long formation times would imply a steady magnetizing field, i.e., a core dynamo.

An additional unresolved issue is the origin of uusual albedo markings that correlate with strong individual lunar magnetic anomalies. Unlike most high-albedo markings on the Moon, the Reiner Gamma-type markings do not appear to be associated with a fresh young crater. One hypothesis for the origin of the albedo markings is surface scouring by relatively recent (< 1 Myr) cometary coma impacts or meteoroid swarm impacts [18,19]. The associated magnetic anomaly sources are then suggested to be surficial materials heated and exposed to transient magnetic fields during the coma or meteoroid swarm impacts. This hypothesis predicts strong magnetization intensities in a near-surface layer. Another hypothesis for their existence supposes that the solar wind ion bombardment plays a role in the darkening with time (``optical maturation'') of freshly exposed lunar surface materials such as secondary crater ejecta [20, 15, 10]. This hypothesis is based on calculations indicating that the strongest lunar magnetic anomalies are able to stand off the solar wind producing regions on the surface that are shielded from the solar wind ion bombardment (e.g., [21]).

Future Work Using Surface Magnetometer Data: The Apollo surface magnetometer data were obtained at locations that were not ideal for testing hypotheses about the origin of the lunar crustal magnetizing field or the origin of the Reiner Gamma-type albedo markings. In the future, a number of geophysical stations equipped with magnetometers should be deployed at surface sites of known strong anomalies. This would be beneficial in several ways. First, direct measurements of the surface field intensity and direction combined with low orbital measurements would allow much more reliable modeling of the vertical thicknesses of major anomaly sources and their bulk directions of magnetization. Repetitions at different sites around the Moon would then constrain the large-scale structure, if any, of the magnetizing field. The inferred source thicknesses would assist in determining whether sources are deep-seated in the crust or are relatively shallow (< 1-2 km), as expected for basin ejecta deposits. It should also be possible to test whether a very shallow (10's of meters) layer could be the anomaly source as expected according to the cometary coma or meteoroid swarm hypothesis for the origin of the albedo markings. In addition, surface magnetometer measurements combined with solar wind spectrometer measurements at the same station would directly test the solar wind deflection model for the origin of the albedo markings.

Possible sites for early deployment of surface magnetometers (and solar wind spectrometers) on the near side include the Descartes mountains and Reiner Gamma. The Descartes mountains site has the advantage that the proposed source materials of the anomaly are exposed at the surface. Surface magnetometer measurements together with existing orbital measurements would allow detailed modeling of the depth of the source, which would test the plausibility of a Descartes mountains source. Simultaneous measurements at the same station using a solar wind detector would also directly test the solar wind deflection model for the origin of the unusual albedo markings. The Reiner Gamma site contrasts with the Descartes mountains site in that the source materials of the anomaly are unclear. If basin ejecta materials are the sources, then they must be buried beneath the visible veneer of mare basalt flows. If a very thin surficial layer is the source (predicted by the recent impact model), then very high magnetizations are implied. Surface magnetometer data would strongly assist in distinguishing between these two possibilities.

Concluding Remarks: Future deployment of surface magnetometers (with at least several located at sites of strong crustal anomalies identified from orbit) would impose significant new constraints on both the nature of lunar magnetizing fields and the identities of major anomaly sources. The addition of a solar wind particle detector at the same sites would also allow more direct tests of the origin of unusual albedo markings that correlate with the strongest individual anomalies. In principle, these new constraints can be obtained without simultaneous orbital magnetometer data. This is because of the existence of several low-altitude orbital magnetometer data sets (although coverage is not complete) and the planned acquisition of new orbital data in the near future (e.g., the Japanese Kaguya mission).

References: [1] Fuller, M. (1974) *Rev. Geophys. Space Phys., 12,* 23-70. [2] Fuller, M. & S. Cisowski (1987) In: *Geomagnetism,* J. Jacobs, ed., Academic Press, Orlando, vol. 2, 307-456. [3] Hood, L. L. (1995) *Earth, Moon & Planets., 67,* 131-142. [4] Cisowski, S. M. et al. (1983) *J. Geophys. Res. Suppl, 88*, A691-A704. [5] Garrick-Bethel, I., & B. P. Weiss (2007) Lunar Planet. Sci. XXXVIII, Abstract #2405. [6] Dyal, P. et al. (1974) *Rev. Geophys. Space Phys., 12*, 568-591. [7] Hood, L. L. (1980) *Proc. Lunar Planet. Sci. Conf. 11th,* LPI, Houston, 1879-1896. [8] Hood, L. L. et al. (2001) *J. Geophys. Res., 106*, 27825-27839. [9] Halekas, J. S. et al. (2001) *J. Geophys. Res., 106*, 27841-27852. [10] Richmond, N. C. et al. (2003) Geophys. Res. Lett., 30, doi:10.1029/2003GL016938. [11] Lin, R. P. et al. (1988) *Icarus, 74*, 529-541. [12] Mitchell, D. et al. (2008) *Icarus*, in press. [13] Richmond, N. C. et al. (2005) *J. Geophys. Res., 110*, doi:10.1029/2005JE002405. [14] Hood, L. L. et al. (1979) *Phys. Earth Planet. Int., 20*, 291-311. [15] Hood, L. L. & C. Williams (1989) *Proc. Lunar Planet. Sci. Conf. 19th*, LPI, Houston, pp. 99-113. [16] Crawford, D. & P. Schultz (1999) *Int. J. Impact Eng., 23*, 169-180. [17] Hood, L. L. & N. Artemieva (2008) *Icarus*, in press. [18] Schultz, P. & L. Srnka (1980) *Nature, 284*, 22-26. [19] Starhukina, L. V. & Y. Shkuratov (2004) *Icarus, 167*, 136-147. [20] Hood, L. & G. Schubert (1980) *Science, 208*, 49-51. [21] Harnett, E., & R. Winglee (2000) *J. Geophys. Res., 105*, 24997-25007.