CHRONOLOGY OF LUNAR MAGNETISM REVISITED. P. Surdas Mohit[1], Kristin P. Lawrence[1], Hideharu Uno[2], and Catherine L. Johnson[2]. [1]Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, La Jolla, CA, 92093 (pmohit@ucsd.edu), [2]Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada.

Introduction: Paleomagnetic experiments on the Apollo samples were initially interpreted to indicate the existence of a strong magnetic field (~ 100 μT) on the Moon between 3.9-3.6 Ga [1]. However, a recent study – including a re-evaluation of published data and new measurements of Apollo samples – has concluded that the magnetizations measured do not represent primary thermoremanent magnetization (TRM) acquired by cooling in the presence of an ambient field [2]. The new Thellier-Thellier paleointensity results suggest a complex, multi-component magnetization history, possibly involving shock remanent magnetization (SRM). As a result, the field strength at the time of formation [2] cannot be inferred.

The coincident release of global magnetic field models based on the Lunar Prospector (LP) Magnetmeter [3,4] and Electron Reflectometer (ER) [5] data provides a unique opportunity to revisit the constraints provided by satellite data. In particular, we will evaluate the models proposed for producing the lunar magnetic anomalies with the goal of determining which are required in order to explain the data and what chronological constraints can be imposed.

Previous Interpretations: In this study, we consider six datasets and interpretations thereof: 1) measurements of the Apollo samples, 2) magnetic field data acquired by the Apollo 15 and 16 subsatellite magnetometers, 3) Apollo 15 and 16 subsatellite ER data, 4) surface magnetic field measurements made at the Apollo 12, 14, 15, 16 landing sites, 5) LP magnetic field data, and 6) LP ER data. While the magnetometer directly measures the magnetic field at spacecraft altitude, the ER measurements (of electron pitch angles) are used to infer the surface field amplitude.

The magnetic measurements made by the Apollo missions revealed some key characteristics of the lunar magnetic field. 1) The magnetic field is of crustal origin, with small spatial scale variations across the lunar surface. 2) The strongest anomalies occur antipodal to the largest lunar basins: namely, Orientale, Crisium, Serenitatis, and Imbrium. This has also been confirmed by LP data. 3) Mare regions exhibit weaker anomalies than highland regions, with no correlation between field strength and the locations of impact craters in the maria [6]. LP data also show that the mare-filled Oceanus Procellarum is nearly devoid of strong magnetic anomalies, which occur only near the edges; however, strong anomalies are associated with certain mare-filled basins, including Moscoviense and Crisium. 4) Analysis of the magnetic measurements taken around the Apollo 16 landing site – where strong (> 300 nT) fields were detected– using experimental results on the magnetic properties of lunar samples, proposed that ejecta deposits consisting of intermediate metamorphic grade breccias are the primary sources of magnetic anomalies on the Moon [7]. Subsequent studies using LP data have supported the idea that magnetized ejecta deposits are significant sources of magnetic anomalies on the nearside [8,9].

Two principal families of models have been put forward in order to explain the observations. 1) A lunar dynamo with surface magnetic field strength was comparable to that of Earth operated during a 3.9 – 3.6 Ga "magnetic epoch" early in lunar history [1]. Models for thermochemical mantle convection in the moon can predict a dynamo from 3.9 – 3.6 Ga [10], but under a quite restricted set of conditions. In light of [2], we now consider other possibilities, such as a dynamo powered by core cooling that operated earlier in lunar history, or a later or long-lived dynamo powered by solidification of a multiphase core. 2) Some or all of the observed magnetization was produced by transient impact-generated fields or amplification of an existing field (internal, interplanetary or geomagnetic) by impact processes. The expansion of a hot, impact-generated plasma cloud generates strong magnetic fields [11]. It has been proposed that convergence of the cloud and compression of a pre-existing magnetic field at the antipode can produce strong magnetization there [e.g., 12]. The magnetic field generated inside the cloud may also have magnetized material in or near the crater [11], so we will also consider the possibility of non-antipodal magnetization.

Data Analysis: We will start with the simplest model, in which all magnetization was effected by an internally-generated field that shut off early in lunar history – similar to the model currently favored for Mars. Large basins that formed after the shut-off, having demagnetized the crust, would be devoid of significant anomalies [13,14,15]. Under this scenario, conservatively, we can say that at least Orientale, Hertzsprung, and Humorum have demagnetization signatu res, defined here as including a basin interior completely devoid of significant anomalies while the surroundings show significant anomalies (see Fig. 1). Imbrium and Serenitatis show ambiguous signatures and may well have been magnetically modified by the intense magmatic activity during the Imbrian period. The oldest demagnetized basins are Humorum and Hertzsprung. Both basins formed late in the Nectarian period; their relative age is N-4 according to the system of [15]. As they fall between Nectaris and Imbrium in age, they must have formed between 3.9-4.1 Ga and 3.85 Ga. Crisium falls in the same relative age range and encloses fields of up to 20 nT; as long as Hertzsprung (and possibly Humorum) formed after Crisium, as suggested by [16], one can conclude that if a dynamo once operated on the Moon, it must have ended prior to the formation of this basin.

If so, when did the magnetic epoch begin? As pointed out by Halekas *et al.* [15], several lunar basins show magnetic highs in the ER-based magnetic field map. Conservatively, Moscoviense (N-6), Crisium (N-4) and possibly Nectaris (N-4) show distinct central anomalies. These authors cite TRM of impact melt by a putative core dynamo and SRM of the central uplift as possible causes; as these basins contain substantial mare fill, another possibility is that mare basalts or associated intrusives were magnetized some time after basin formation. Modeling of the sources of the anomalies may provide evidence for one or another of these hypotheses. However, the SRM scenario appears to be unlikely, since younger basins (e.g. Hertzsprung and Orientale) do not show central anomalies. If the result of melt sheet TRM, they should date from the formation of the basins, which would suggest that the dynamo started in the early Nectarian. Thus, one scenario that is consistent with all observations involves the operation of a dynamo for a period similar to that of the Nectarian age. We cannot rule out the possibility of a primordial origin, as certain Pre-Nectarian basins do show evidence of demagnetization [15], but the evidence is ambiguous.

Next, we consider the possibility that the Moon never had an internally-generated field, in which case all fields would be impact-generated. This scenario is more difficult to evaluate as we do not fully understand the complex processes involved in impact magnetization; indeed, it is not even clear that impact-generated fields can produce coherent magnetization [e.g., 17]. However, by stipulating that transient impact-generated fields can produce coherent magnetization, we can show that the satellite data is not fully explained by the "impact only" hypothesis. In this scenario, each basin would demagnetize its surroundings during formation and be subsequently overprinted by succeeding impacts. As the magnetic field generated decreases as the square of distance from the impact point [11], the magnetization generated should peak at some point over the ejecta blanket and decrease steadily until the antipodal amplification region is reached. In fact, many basins do show magnetic field peaks within 2-3 radii of the center [8], as illustrated by Figs. 1 and 2. However, this hypothesis cannot account for the anomalies within Moscoviense, for example, as the closest younger impact basin is Mendeleev, which is almost certainly too small and distant to be responsible for the ~ 80 nT anomaly (see Fig. 2).

References. [1] Cisowski S. M. *et al* (1983), *JGR* 88, A691. [2] Lawrence, K.P. *et al*. (1983), *PEPI.*, sub. [3] Hood *et al.* (2008), *Icarus,* in press. [4] Purucker *et al*. (2008), *Icarus*, sub. [5] Mitchell *et al.* (2008), *Icarus*, acc. [6] Lin, R.P. (1979), *PEPI* 20, 271. [7] Strangway, D.W. *et al.* (1973), *Nature Phys. Sci*. 246, 112. [8] Halekas *et al.* (2001), *JGR* 106, 27, 841. [9] Richmond *et al.* (2003), *GRL* 30, 1395. [10] Stegman *et al*. (2003), *Nature* 421, 143. [11] Crawford, D.A., and P.H. Schultz (1999), *Int. J. Imp. Eng.* 23, 169. [12] Hood and Artemieva (2008), *Icarus*, in press. [13] Hood *et al.* (2003), *GRL* 30, 1281. [14] Mohit, P.S. and J. Arkani-Hamed (2004), *Icarus* 168, 305. [15] Halekas *et al*. (2003), *MAPS* 38, 565. [16] Wilhelms, D.E. (1987), *USGS Prof. Paper* 1348. [17] Carporzen *et al.* (2005), *Nature* 435, 198.

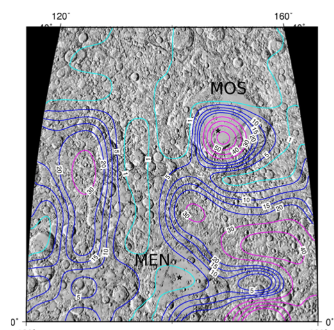

Figure 1. ER-based [5] contour map of the magnetic field around Moscoviense (MOS) and Mendeleev (MEN), with contours at 1 (cyan), 5 (blue), and 10 nT (magenta) intervals.

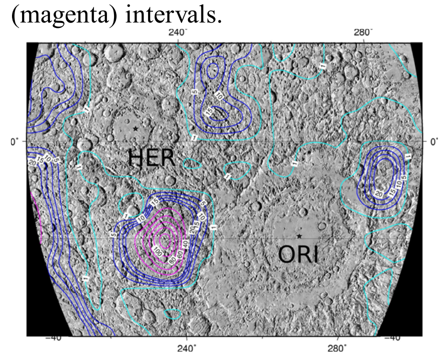

Figure 2. ER-based [5] map of the magnetic field around Orientale (ORI) and Hertzsprung (HER) basins, with contours at 1 (cyan), 5 (blue), and 20 nT (magenta) intervals.