Joint Analysis of Gravity and Magnetic Anomalies on The Moon. Colleen Milbury[1], Gerald Schubert[1,2], Carol Raymond[3] and Suzanne Smrekar[3], [1]UCLA, ESS (colleen.milbury@ucla.edu), [2]UCLA, IGPP, [3]JPL.

Introduction: The Moon and Mars are similar in that they both have remanent crustal magnetic fields, but internal core magnetic fields have not been detected. In general, the distribution of magnetic anomalies on the Moon is somewhat sparse and the intensity is somewhat weak when compared with Mars [1-4]. Lunar crustal magnetism is dominated by individual, isolated anomalies with the exception of the regions that are antipodal to the major impact basins where anomaly clusters are present. The source of the lunar crustal magnetization is uncertain. Proposed sources of the inducing field include the solar wind or the geomagnetic field, transient fields produced by impacts, or a lunar dynamo. It is unclear if the Moon had an internal core dynamo.

In this study we do a least squares inversion of the gravity and magnetic field data, and numerically analyze the correlations of the resultant density and magnetization anomalies. The interpretation of the results are guided by the topography and geology to test the hypothesis that the processes that created or modified the magnetic field anomalies also altered the density structure. For example, a magmatic intrusion that demagnetized the lunar crust would result in a (negative) correlation between gravity and magnetic anomalies. A positive correlation would result if the intrusion instead magnetized the crust. This approach has already been used to study the observed correlations between gravity and magnetic field data along Mars' eastern dichotomy boundary [5-8]. We will analyze the magnetic and gravity anomalies for regions on the Moon where correlations of gravity and magnetic field anomalies are similar to those found on Mars by [7-8] (see Table 1).

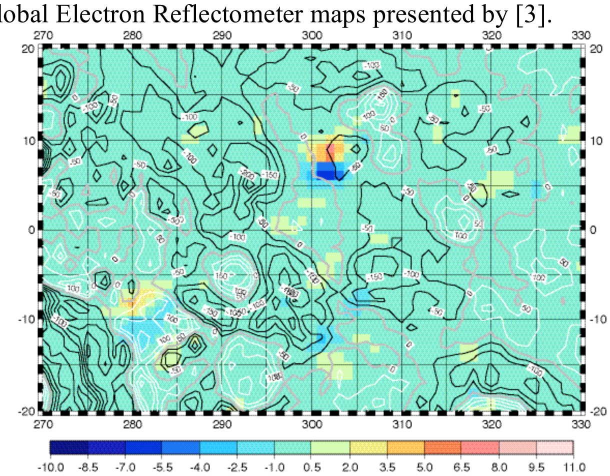
Previous Studies: Lunar magnetic field anomalies have been mapped by the Electron Reflectometer [1,4,8-9] and Magnetometer [2-3, 10-11] instruments on board the Lunar Prospector (LP) spacecraft. Earlier measurements of the lunar magnetic field were made by similar instruments on the Apollo subsatellites [12-13]. These studies find that the principal concentrations of magnetic field anomalies with the strongest magnitudes are on the far side of the Moon antipodal to the Crisium, Serenitatis, Imbrium, and Orientale impact basins. Isolated magnetic anomalies have been mapped at Reiner Gamma [2,14], Rima Sirsalis [2], Descartes [9, 15] and Airy [16]. Richmond and Hood [3] have mapped previously unidentified magnetic anomalies near the Abel, Hartwig and Stöfler craters, the Crisium and Moscoviense basins, and the Snellius and Rheito crater chains.

Lunar Feature	magnetic anomaly		gravity anomaly	
	lat (ºN)	lon (ºE)	lat (ºN)	lon (ºE)
Reiner Gamma	5	300	10	305
Rima Sirsalis	-15	300	-20	290
Hartwig Crater	-10	280	-5	280
Airy Crater	-20	5	-15	5
Descartes Crater	-10	15	-10	15
Stöfler Crater	-40	5	-40	5
Mare Crisium	10	60	15	60
Mare Moscoviense	25	150	25	150
Abel Crater	-35	90	-35	85
Vallis Snellius	broad		broad	
Vallis Rheito	broad		broad	
Orientale Antipode	broad		broad	
Imbrium Antipode	broad		broad	
Serenitatis Antipode	broad		broad	
Crisium Antipode	broad		broad	

Table 1. Approximate locations of lunar radial magnetic field anomalies [27] and gravity anomalies [28] to be studied.

The presence of the large-scale magnetic anomalies antipodal to the major impact basins has been found statistically unlikely to be a coincidence [4]. One explanation for the observed distribution is that the anomalies became magnetized by transient magnetic fields generated by the major basin-forming impacts [17-19]. In this model a basin-forming impact produces a massive, hot, partially ionized cloud of vapor and melt that expands thermally around the Moon. Because of its high electrical conductivity and relatively high energy density, a lunar impact vapor–melt cloud interacts strongly with any ambient plasmas and magnetic fields (arising from the solar wind, geomagnetic field, or an internal dynamo) leading to transient magnetic field amplification. Magnetic field lines are compressed and intensified as the cloud converges on the antipodal region and magnetizes the materials there. Moore et al. [20] showed that impact ejecta could be deposited at the antipode, which may further contribute to the magnetic anomaly. Seismic waves generated by the impact that converge at the antipode may induce shock remanent magnetization [21]. Hood et al. [2] noted that the anomalies associated with the Reiner Gamma Formation and Rima Sirsalis rille are aligned approximately radially from the center of the Imbrium basin and suggest that they are ejecta materials from the impact. The albedo swirls that are observed in association with Reiner Gamma are suggested by many authors to be due to shielding from the solar wind [2, 14, 16, 22-23]. Richmond and Hood [3] noted that identification of source materials is difficult for the previously unmapped Abel crater, and that an albedo feature has not been mapped in this region. This raises questions about the association between magnetization and albedo.

Another hypothesis is that the crust became magnetized during cooling through the Curie temperature in the presence of an internal core dynamo field. It is thought that the dynamo had two distinct activity periods, one driven by initial cooling and one by mantle overturn [24] or core formation [25]. Halekas et al. [9] suggested the existence of a magnetic era by surveying basin magnetization. They note that magnetization associated with small basins manifests as magnetic lows implying shock demagnetization, and that large impact basins have central anomalies implying TRM or shock remanent magnetization. Another line of evidence comes from the Apollo lunar samples [13]. Collinson [26] reviewed these data and considered the dynamo versus the transient impact field generation hypotheses. The study concluded that the most reasonable explanation of lunar crustal magnetization is that the crust was magnetized by cooling in the presence of a dynamo-generated lunar magnetic field. Many of the previously cited papers concluded that the relevance of the transient impact field generation model is established by the observation that the strongest anomalies are antipodal to the major impact basins and the weakest anomalies are within the basins themselves. Impact demagnetization of the basins means that the crust was at one time magnetized by a core dynamo. The effect of impact demagnetization is seen most clearly in the global Electron Reflectometer maps presented by [3].



This Study: We find many regions exhibiting similar correlations, although not all are shown here in the interest of space and are instead summarized in Table 1. Figure 1 shows the magnetic field [27] data with the gravity [28] superimposed on top, for a selected region on the Moon. The magnetic field anomalies may be offset slightly from the gravity anomalies due to differences in inclination and declination of the magnetizing field. The other regions in Table 1 exhibit similar correlations and we intend to investigate all areas.

We will use a least squares inversion of the gravity and magnetic field data described above to carry out the analysis. We will first invert the gravity data to obtain crustal density structure by assuming the anomalies are located in layers of various thicknesses at different depths. We will then use the best fit depth and thickness to invert the magnetic field data for an array of paleopole positions to find the best fit paleopole position. For each region we will consider the geologic and topographic information that is available to guide the interpretation of the results. Additional details are provided in [7-8].

The above analyses will provide insight into the crustal magnetization and density structure and the formation history of the magnetic and gravity anomalies for the studied regions of the Moon. It will provide constraints on the mechanisms that formed the anomalies and estimates of magnetic paleopole positions and timing of dynamo activity. This will improve our knowledge of the interior structure and thermal evolution of the early Moon.

References: [1] Halekas, J. S. et al.(2001), JGR, 106, 27,841–27,852. [2] Hood, L. L. et al. (2001) JGR, 106, 27,825–27,839. [3] Richmond, N.C., Hood, L.L., (2008) JGR, doi:10.1029/2007JE002933. [4] Mitchell, D. L. et al. (2008), Icarus, 194, 401-409. [5] Smrekar, S. E. et al. (2004) JGR, 109. [6] Milbury, C. A. et al. (2005) LPS XXXVI, Abstract #2075. [7] Milbury, C. A. E. et al. (2007a). Planet. and Space Sci., 55, 280-288. [8] Milbury, C. A. et al. (2007b), LPS XXXVIII, Abstract # 2067. [8] Lin, R. P. et al. (1998) Science, 281, 1480–1484. [9] Halekas, J. S. et al. (2003) Meteoritics & Planet. Sci.,38, 565– 578. [10] Richmond, N. C. et al. (2003) GRL, 30(7). [11] Richmond, N. C. et al. (2005) JGR, 110, E05011. [12] Coleman, P. J. et al. (1972) Phys. Earth Planet. Inter., 6, 167– 174. [13] Cisowski, S. M. et al. (1983) JGR, 88, A691–A704. [14] Hood, L. L. (1980), Proc. Lunar Planet. Sci. Conf., 11th, 1879– 1896. [15] Richmond, N.C. and L.L. Hood (2003) LPS XXXIV, Abstract #1721. [16] Hughes, C. G. et al. (2006) LPS XXXVII, Abstract #1230. [17] Hood, L. L., and A. Vickery (1984), Proc. Lunar Planet. Sci. Conf. 15th, Part 1, J. Geophys. Res., 89, suppl., C211– C223. [18] Hood, L. L., and Z. Huang (1991), JGR, 96, 9837–9846. [19] Hood, L. L., and N. A. Artemieva (2008) Icarus 193, 485-502. [20] Moore, H. J. et al. (1974), Geochim. Cosmochim. Acta, 1, Suppl. 1, 71–100. [21] Schultz, P. H., and D. E. Gault (1975) Moon, 12, 159– 177. [22] Hood, L. L., and G. Schubert (1980), Science, 208, 49– 51. [23] Nicholas, J. B. et al. (2007) GRL, 34. [24] Stegman, D. R. et al. (2003) Nature, 421, 143– 146. [25] Russell C. T. et al. (1974) Science, 186, 825-826. [26] Collinson, D. W. (1993) Surv. Geophys. 14, 89–118. [27] Purucker, Michael (2008) Icarus, in press. [28] Konopliv, A. S. et al. (2001) Icarus, 150, 1-18.