LIMITS ON THE LUNAR METALLIC CORE SIZE FROM ORBITAL MAGNETOMETER DATA: FURTHER ANALYSIS OF LUNAR PROSPECTOR DATA.

L. L. Hood[1] and N. C. Richmond[2], [1]Lunar and Planetary Lab, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721, lon@lpl.arizona.edu; [2]Institutional Research, Pima Community College, 4905 E. Broadway, Tucson, AZ 85709.

Introduction: The size and mass of a dense metallic core is a basic constraint on lunar bulk composition and, therefore, on lunar origin models. The core size also has basic implications for our understanding of the origin of lunar crustal magnetization (see, e.g., ref. 1). Currently, the size and even the existence of a lunar metallic core are not well established observationally [2] although geochemical data favor a metallic core [3] and interpretations of lunar laser ranging data suggest a molten core radius of < 345 km [4].

One approach toward constraining the lunar metallic core size involves measurement and interpretation of the lunar induced magnetic dipole moment during passages of the Moon through the geomagnetic tail lobes [5,6]. In this paper, we report efforts to test and improve earlier applications of this technique using Lunar Prospector magnetometer data [6].

Previous Work: Previous inferences of electrical conductivity vs. depth in the Moon using simultaneous Apollo 12 surface and Explorer 35 orbital magnetometer data yielded an upper bound of ~ 435 km on the metallic core radius [7,8]. However, small gain and offset errors between the two magnetometers significantly limited the accuracy of this method at very low frequencies [9].

An alternate method uses only measurements from a single low-altitude orbiting magnetometer, thereby avoiding the intercalibration problem [10,11,5,6]. In this quasi-static method, the conductivity profile of the mantle is not consrained but the radius of a core with conductivity much greater than that of the lower mantle (i.e., > 0.1 mho/m) can be estimated. In principle, the core may be either metallic ($\sigma > 10^3$ mhos/m) or molten silicate ($\sigma \sim$ 1-10 mho/m) to satisfy the high conductivity requirement. However, it is theoretically difficult to maintain a large reservoir of silicate melt in the lunar interior in the presence of subsolidus convection early in lunar history.

The method takes advantage of passages of the Moon through the nearly spatially uniform magnetic field and low-density plasma environment of the geomagnetic tail lobes. To a first approximation, the Moon is suddenly exposed to a uniform field of constant amplitude in a low-density plasma environment. After the decay of induced currents in the mantle and neglecting effects of magnetic susceptibility in the crust and upper mantle, any remaining induced dipole moment has an amplitude that ideally depends only on the radius of a highly electrically conducting core. The induced dipole moment is negative, i.e., it is oriented opposite to the applied field.

In a previous study [6], 21 orbits of LP magnetometer data were selected from a single tail lobe pass in April 1998 during which the tail lobe field was relatively steady and oriented toward the Sun with an amplitude that varied between approximately 12 and 16 nT (1 nT = 10^{-5} G). The final estimated induced moment amplitude was $-2.4 \pm 1.6 \times 10^{22}$ G-cm^3/G of applied field. The corresponding maximum core radius (neglecting metallic iron in the mantle and crust) was 340 ± 90 km. For comparison, Russell et al. [5] analyzed 21 orbits of data from 7 months of Apollo 15 and 16 subsatellite magnetometer data. Induced moments for each orbit were estimated using a Fourier analysis technique. Averaging together all individual orbit estimates yielded a final estimate of $-4.23 \pm 0.64 \times 10^{22}$ G-cm^3/G of applied field. Neglecting magnetic susceptibility effects, the corresponding core radius was 439 ± 22 km.

While the error bars of the Apollo subsatellite core radius estimate [5] and the LP core radius estimate [6] do overlap, the mean of the latter estimate is ~ 100 km less than the former estimate. It is therefore important to complete the LP analysis and re-examine the Apollo subsatellite data using a consistent analytic technique to more accurately estimate the actual core radius.

Improved LP Induced Moment Estimates: The analysis of [6] considered only one lunation of LP data. We have recently determined all available intervals of LP data during which induced moment measurements are possible. Altogether, 9 geometrically suitable magnetotail passes occurred during the 19-month mssion containing a total of 412 orbits of data. However, data toward the end of the mission become increasingly complicated by magnetospheric disturbances as solar maximum conditions were approached. Here, we report a preliminary analysis of data from relatively quiet LP tail lobe passes occurring in April and May of 1998. The April pass is the same as that considered by [6] while the May pass has not previously been analyzed. After editing to accept only those orbits and major orbit segments characterized by the smallest possible rms deviations, only three such orbit segments remained for each of the two tail lobe passes. For the April 1998 pass, two of the three x-component orbit segments have rms deviations less than 0.3 nT while for the May 1998 pass, all three have rms deviations under 0.32. Thus, while the number of orbits is reduced, the quality of the data is improved.

Averaging together the three available orbit segments for each tail lobe pass and smoothing the data using a 51-point running mean algorithm, one obtains the mean x-component field perturbations shown in Figure 1 (solid line). For comparison, the long dashed lines show theoretical field perturbations expected for an induced moment of -3.2×10^{22} G-cm^3/G (equivalent core radius: 400 km) after all mantle currents have decayed and neglecting finite susceptibility effects. Although significant short-wavelength field fluctuations remain in the data, both mean field time series show relatively high values between 0.5 and 1 hours local orbit time and reduced values between 1 and 1.3 hours, which is consistent with expectations for a negative induced moment.

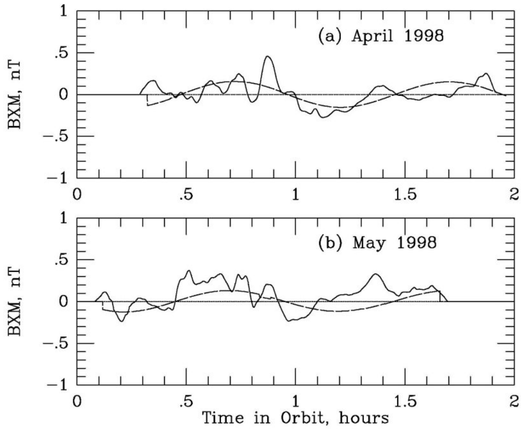

Figure 1

Plotted in Figure 2 is the variance between the smoothed x-component measurements of Figure 1 for April and May of 1998 and theoretical curves for a range of negative induced moments (and corresponding highly conducting core radii) for each tail lobe pass. While the variances are generally larger for the May data than for the April data, both analyses yield a distinct minimum variance for core radii between 350 and 400 km. Specifically, the April 1998 data yield a minimum variance of 0.0141 nT^2 for a core radius of 370 km while the May 1998 data yield a minimum variance of 0.0250 nT^2 for a 390 km core. The LP data therefore demonstrate a repeatable negative induced moment of the Moon in the geomagnetic tail lobes, a result that is consistent with earlier analyses of Apollo subsatellite data [5].

Concluding Remarks: Analysis of selected data from two tail lobe passes occurring in April and May 1998 yields evidence for a highly electrically conducting core ($\sigma > 0.1$ mhos/m) with a radius of roughly 370-390 km. However, this upper limit on the metallic core radius neglects any positive induced moment resulting from the presence of metallic iron in the crust and upper mantle. If we take Fe$_m$ ~ 0.1 wt% for the entire crust and upper mantle (probably an upper limit), the combined ferromagnetic and paramagnetic positive moment [12] is ~ 0.4×10^{22} G-cm^3/G. This requires increasing the core radius bound by ~ 50 km to 420-440 km.

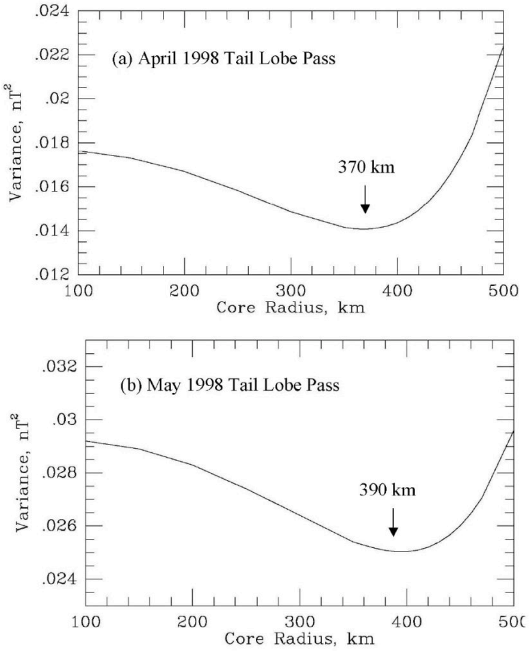

Figure 2

References: [1] Hood L. L. and Artemieva N. (2008) *Icarus, 193,* 485-502. [2] Hood L. L. and Zuber M. (2000) In: *Origin of the Earth and Moon,* K. Righter and R. Canup, eds., Univ. of Arizona Press, Tucson, pp. 397-412. [3] Day J. M. D., Pearson D. G. and Taylor L. A. (2007) *Science, 315,* 217-219. [4] Williams J. G., Boggs D. H., and Ratcliff J. T. (2006) LPSC37, LPI, Abstract #1229. [5] Russell C. T., Goldstein B. E. and Coleman P.J., Jr., *Proc. Lunar Planet. Sci. Conf. 12th*, LPI, 831-836. [6] Hood L. L., Mitchell D. L., Lin R. P., Acuña M. H., and Binder A. B. (1999) *Geophys. Res. Lett., 26,* 2327-2330. [7] Hood L. L., Herbert F., and Sonett C. P. (1982) *JGR, 87,* 5311-5326. [8] Hobbs B. A., Hood L. L., Herbert F., and Sonett C. P. (1983) *Proc. LPSC 14th, JGR, 88, supplement,* p. B97-B102. [9] Daily W. D. and Dyal P. (1979) *JGR, 84,* 3313-3326. [10] Goldstein B. E. and Russell C. T., *Proc. LPSC 6th, Geochim. Cosmochim. Acta, Suppl. 6,* LPI, 2999-3012. [11] Goldstein B. E., Phillips R. J., and Russell C. T. (1976) *Geophys. Res. Lett., 3,* 289-292. [12] Rochette P. (2000) *Geophys. Res. Lett., 27,* 1077-1078.