LUNAR INTERIOR RESULTS AND POSSIBILITIES. J. G. Williams, D. H. Boggs, and J. T. Ratcliff, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 (e-mail James.G.Williams@jpl.nasa.gov)).

Introduction: Variations in rotation and orientation of the Moon are sensitive to solid-body tidal dissipation, dissipation due to relative motion at the fluid-core/solid-mantle boundary, and tidal Love number k_2 [1,2]. There is weaker sensitivity to flattening of the core-mantle boundary (CMB) [2-6] and fluid core moment of inertia [1]. Accurate Lunar Laser Ranging (LLR) measurements of the distance from observatories on the Earth to four retroreflector arrays on the Moon are sensitive to lunar rotation and orientation variations and tidal displacements. Past solutions using the LLR data have given results for dissipation due to solid-body tides and fluid core [1] plus Love number [1-7]. Detection of CMB flattening has improved with time [3,5,6] and now is significant. This strengthens the case for a fluid lunar core. For the future, ways are considered to detect a solid inner core.

LLR Solutions: Reviews of Lunar Laser Ranging (LLR) are given in [2,8]. Three decades of Lunar Laser Ranging data, 1970-2005, are analyzed using a weighted least-squares approach. This year we add the first ranges from Apache Point Observatory, New Mexico and Matera, Italy to the extensive set of data from McDonald Observatory, Observatoire de la Côte d'Azur (OCA), and Haleakala Observatory. The lunar solution parameters include dissipation at the fluid-core/solid-mantle boundary, tidal dissipation, dissipation-related coefficients for rotation and orientation terms, potential Love number k_2, and displacement Love numbers h_2 and l_2. To approximate the influence of core-mantle boundary (CMB) flattening, early solutions used a constant term in the tilt of the equator to the ecliptic. Replacing this approximation, a torque for CMB flattening is introduced into the model for numerical integration of lunar rotation. This year we include the oblateness torque model in the numerically integrated partial derivatives as well, allowing high quality solution parameters for CMB flattening, core moment of inertia, and core spin vector. Solutions use combinations of solution parameters and constraints.

Core Oblateness: Detection of the oblateness of the fluid-core/solid-mantle boundary (CMB) is evidence for the existence of a liquid core which is independent of the dissipation results. In the first approximation, CMB oblateness should influence the tilt of the lunar equator to the ecliptic plane [2]. The integration model implicitly includes the tilt and other effects of CMB oblateness. The equator tilt is also influenced by moment-of-inertia differences, gravity harmonics, and Love number k_2, solution parameters that are expected to be affected by CMB oblateness. The current detection of CMB oblateness is three times its uncertainty. The oblateness parameter anticorrelates with k_2 so that larger CMB oblateness corresponds to smaller k_2.

Torque from CMB oblateness depends on the fluid core moment of inertia and the CMB flattening. The former is uncertain and there is no information about the latter apart from these LLR solutions. For a uniform iron core with a 340 km radius, with ratio of the fluid core to solid mantle moments C_f/C_m fixed at $6x10^{-4}$, the flattening solution is $f=5x10^{-4}$. The corresponding retrograde free core nutation period is 150 yr; a similar period was inferred in [9,10]. The fluid core moment and flattening parameter are not separable in the solutions with useful significance and it is the product $f\ C_f/C_m=(3\pm1)x10^{-7}$ which is well determined. The derived oblateness varies inversely with fluid core moment so a smaller fluid core corresponds to a larger oblateness value and smaller free core nutation period. Core moment uncertainty causes major uncertainty in these quantities. For comparison, the lunar "dynamical flattening", from LLR-determined moment of inertia differences, is $(2C-A-B)/2C = 5.18x10^{-4}$ and the surface geometrical flattening based on altimetry is $1.3x10^{-3}$ [11]. The CMB oblateness, like the whole Moon values, is not close to the equilibrium figure for the current tides and spin.

Love Number Determination: Sensitivity to the potential Love number k_2 comes from rotation and orientation while h_2 and l_2 are determined through the tidal displacement of the retroreflectors. An LLR solution solving for k_2 and h_2, but fixing l_2 at a model value of 0.0106, gives $k_2 = 0.0205\pm0.0025$ and $h_2 = 0.041\pm0.009$. Compared to early spherical core results [1,2], the LLR value for k_2 has decreased due to consideration of core oblateness. The value has also decreased compared to our earlier approximate treatment of oblateness. There is an orbiting spacecraft result for the lunar Love number of $k_2 = 0.026\pm0.003$ determined from tidal variation of the gravity field [12].

Model Love numbers: Model Love number calculations, using seismic P- and S-wave speeds deduced from Apollo seismometry, have been explored here and in [4,7]. The seismic speeds have to be extrapolated from the sampled mantle regions into the deeper zone above the core. One model, with a 340 km radius liquid iron core, gives $k_2 = 0.0226$, $h_2 = 0.0395$, and $l_2 = 0.0106$. The Nakamura three mantle layer model [13], with the third layer extrapolated down to a 340 km core, gives $k_2 = 0.0218$, $h_2 = 0.0381$, and $l_2 = 0.0105$. A smaller core decreases the model k_2 and h_2 values, but has little effect on l_2; absence of a core reduces k_2 and h_2 by about 5%. Any partial melt above the core would increase k_2 and h_2. The Apollo seismic uncertainties contribute several percent uncertainty to the three model Love numbers. LLR k_2 and h_2 determinations are compatible with conventional model values with extrapolated seismic speeds and a small core. The spacecraft k_2 value is larger than simple model values, but consistent with the uncertainty.

Dissipation from Fluid Core and Tides: Theory and LLR solutions for lunar dissipation have been presented in [1]. The interpretation of the dissipation results invoked both strong tidal dissipation and interaction at a fluid-core/solid-mantle boundary (CMB). New solutions use combinations of tide and core parameters and rotation coefficients. Of the five independent dissipation terms in the rotation which were considered, four are well above the noise and one is marginal. Compared to the solutions in [1], the solution parameters have changed by amounts comparable to their uncertainties.

An analysis of the dissipation coefficients is similar to that in [1]. The fluid core component is found to be somewhat stronger and the monthly tidal Q is found to be 29±4. The core fraction is f_c=0.40 for the principal term and the frequency power law exponent is -0.07. For k_2 = 0.0205, the power-law expression for tidal Q as a function of tidal period is 29(Period/27.212d)$^{0.07}$ so the Q increases from 29 at a month to 35 at one year. The decrease in Qs compared to [1] is largely due to the decrease in k_2 which resulted from including CMB oblateness. Based on Yoder's turbulent boundary layer theory [14], a fluid iron core would have a radius of about 345 km, but any topography on the CMB or the presence of an inner core would tend to decrease the inferred radius.

Inner Core Possibilities: A solid inner core might exist inside the fluid core. Gravitational interactions between an inner core and the mantle could reveal its presence in the future. An inner core might be rotating independently or it might lock to the mantle rotation through gravitational interactions.

The theoretical precession dynamics for locked rotation has been investigated. Inner core precession torques arise from its gravitational field through interactions with both the Earth and the mantle and through inner-core/fluid-core boundary oblateness. Like the mantle, the equator of the inner core would be tilted with respect to the ecliptic plane and precessing along that plane with an 18.6 yr period. This is a forced retrograde precession. The tilt may be more or less than the mantle's 1.54˚ tilt and could even have reversed sign. The attraction between a triaxial inner core field and the interior gravitational harmonics of the mantle has unknown strength but may be strong enough to cause a shorter inner core resonance (free precession) period than the mantle's 81 yr. This resonance period determines which mantle orientation terms are more strongly perturbed by the inner core and hence which terms are potentially observable by LLR. Nearly all important parameters are unknown.

An inner core might also be detected from its gravitational field. Tilted by a different amount than the mantle, inner core second-degree harmonics would cause time varying C_{21} and S_{21} harmonics viewed in a coordinate frame fixed with respect to the mantle. The period would be 27.212 days. For a small mantle-inner core tilt angle difference ΔI, the C_{21} amplitude depends on inner core $(J_2+2C_{22}) \sin(\Delta I)$, while the S_{21} amplitude is proportional to $(J_2-2C_{22}) \sin(\Delta I)$. A conventional tidal term at 27.212 d for C_{21} would require a good determination of k_2, but the S_{21} tidal term is small. A search for variable C_{21} and S_{21} harmonics should be a goal of future orbiting satellites.

An inner core would complicate interpretation of LLR rotation and orientation: there would be two surfaces for solid-mantle/fluid-core/inner-core dissipation and an inner core which does not share the fluid rotation will have its own flattening interaction.

Summary: Adding new lunar ranges gives solutions for lunar parameters with improved uncertainties. Dissipation parameters continue to indicate a fluid core and strong tidal dissipation. The potential and displacement Love numbers are consistent with models which include a core. The computation of the effect of the oblateness of the fluid-core/solid-mantle boundary has been made more sophisticated and the corresponding determination is significant. This is a second line of evidence for a fluid lunar core. Direct detection of the fluid core moment and detection of a solid inner core are future possibilities. Additional ranges with current accuracy and future data with improved accuracy should improve the determination of these lunar science results. A wider network of lunar retroreflectors would also strengthen the results.

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