LUNAR TIDES, FLUID CORE AND CORE/MANTLE BOUNDARY. 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) [2-3] 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 plus Love number [1-4]. Detection of CMB flattening is now significant and the fluid core moment of inertia is weakly detected. Both strengthen the case for a fluid lunar core. Future ways are considered to detect a solid inner core.

LLR Solutions: Reviews of Lunar Laser Ranging (LLR) are given in [2,5]. Lunar ranges over 1970-2007 are analyzed using a weighted least-squares approach. Here we include 19 months of ranges from Apache Point Observatory, New Mexico with the extensive set of data from McDonald Observatory, Observatoire de la Côte d'Azur (OCA), and Haleakala Observatory. Lunar solution parameters include dissipation at the fluid-core/solid-mantle boundary (CMB), tidal dissipation, dissipation-related coefficients for rotation and orientation terms, potential Love number k_2, and displacement Love numbers h_2 and l_2. A solution can combine 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 influences the tilt of the lunar equator to the ecliptic plane [2]. For high quality solution parameters for CMB flattening, core moment of inertia and core spin vector, a torque for CMB flattening is introduced into the numerical integration model for lunar rotation and partial derivatives. 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.

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 350 km radius, with ratio of the fluid core to solid mantle moments C_f/C_m fixed at 7×10^{-4}, the flattening solutions give 4×10^{-4} to 5×10^{-4}, depending on the k_2 solution value. The oblateness parameter f anticorrelates with k_2 so that larger CMB oblateness corresponds to smaller k_2. Corresponding retrograde free core nutation periods are 190 to 150 yr; similar periods were inferred in [6,7]. 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. There is weak sensitivity to core moment in the LLR data and a solution gives $C_f/C_m = (9\pm5)\times10^{-4}$ with $f = 3.5\times10^{-4}$. While the fluid core moment and flattening parameters are not well separated in solutions, the product $f\,C_f/C_m=(3\pm1)\times10^{-7}$ is better determined. The computed equilibrium value for the CMB flattening is 2.2×10^{-5}. For comparison, the flattening of the lunar gravity field is $1.5J_2 = 3.05\times10^{-4}$ [9], with a computed equilibrium value of 1.4×10^{-5}, and the surface geometrical flattening based on altimetry is 1.3×10^{-3} [8], with an equilibrium value of 2.3×10^{-5}. The CMB oblateness, like the whole Moon values, is not close to the equilibrium figure for the current tides and spin.

Love Number Determination: LLR sensitivity to the potential Love number k_2 comes from rotation and orientation while h_2 and l_2 are determined from tidal displacement of the retroreflectors. Solving for k_2 and h_2, but fixing l_2 at a model value of 0.0105, gives $k_2 = 0.0195\pm0.0025$ and $h_2 = 0.043\pm0.008$. A second solution, with the ratio of h_2/k_2 constrained to a model value of 1.75, gives $k_2 = 0.0206\pm0.0022$ and $h_2 = 0.0360\pm0.0038$. Compared to early spherical core results [1,2], the LLR value for k_2 has decreased due to consideration of core oblateness. An orbiting spacecraft result for the lunar Love number is $k_2 = 0.026\pm0.003$, determined from tidal variation of the gravity field [9].

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]. The seismic speeds have to be extrapolated from the sampled mantle regions into the deeper zone above the core. One model, with a 350 km radius liquid iron core, gives $k_2 = 0.0227$, $h_2 = 0.0397$, and $l_2 = 0.0106$. The Nakamura three mantle layer model [10], with the third layer extrapolated down to a 350 km core, gives $k_2 = 0.0219$, $h_2 = 0.0384$, and $l_2 = 0.0105$. A smaller core decreases the model k_2 and h_2 values, but has less 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.

Dissipation from Fluid Core and Tides: Theory and LLR solutions for lunar dissipation have been presented in [1]. Interpretation of the dissipation results invokes 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 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 for $k_2 = 0.0206$. The principal term core fraction is f_c=0.415 and the frequency power law exponent is -0.09. The power-law expression for the tidal Q dependence on tidal period is $29(\text{Period}/27.212\text{d})^{0.09}$ 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 as a result of including CMB oblateness. Based on Yoder's turbulent boundary layer theory [11], a fluid iron core would have a radius of about 350 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 and longitude dynamics for locked rotation have been investigated. Inner core 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 shorter inner core free precession and longitude resonance periods than the mantle's 81 yr and 3 yr periods, respectively. These resonance periods determine which mantle orientation and rotation terms are more strongly perturbed by the inner core and hence which terms are potentially observable by LLR. Inner core effects are likely subtle and depend on a number of currently unknown parameters including inner and outer core moments, inner core gravity coefficients, and mantle internal gravity coefficients.

An inner core might also be detected from its gravitational field [12]. 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. 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 results: there would be two surfaces for solid-mantle/fluid-core/inner-core dissipation, an inner core which does not share the fluid rotation will have its own flattening interaction, and the result for CMB flattening (which influences k_2) may be modified since it is based on a weak torque.

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 detection of the oblateness of the fluid-core/solid-mantle boundary is significant, and direct detection of the fluid core moment is weak but significant. Both are additional evidence for a fluid lunar core. The potential and displacement Love numbers are consistent with models. Detection of a solid inner core is a future possibility. Additional ranges should improve the determination of these lunar science results. A wider network of lunar retroreflectors would also strengthen the results.

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