LUNAR CORE AND TIDES. 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) [2,3,4] 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 [1-5]. Detection of CMB flattening, which in the past has been marginal but improving [3,4,5], now seems significant. Direct detection of the core moment has not yet been achieved.

LLR Solutions: Reviews of Lunar Laser Ranging (LLR) are given in [2,6]. Three decades of Lunar Laser Ranging data, 1970-2003, are analyzed using a weighted least-squares approach. 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, a correction to the constant term in the tilt of the equator to the ecliptic which is meant to approximate the influence of core-mantle boundary flattening, and displacement Love numbers h_2 and l_2. Solutions with combinations of solution parameters and constraints are considered.

Love Number Determinations: 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 0.011, gives k_2 = 0.0227±0.0025 and h_2 = 0.039±0.010. Compared to the results of [1-5] the LLR value for k_2 has decreased due to consideration of core oblateness. There is an orbiting spacecraft determination of the lunar Love number of k_2 = 0.026±0.003 determined from tidal variation of the gravity field [7].

Model Love number calculations, using seismic P- and S-wave speeds deduced from Apollo seismometry, were explored in [4]. The seismic speeds have to be extrapolated into the deeper regions above the core. Models with a liquid or solid Fe core with a size ~20% of the whole Moon give k_2 around 0.022 to 0.023, h_2 about 0.039, and l_2 0.011. A smaller core decreases the model k_2 and any partial melt above the core increases it. So the LLR k_2 value is in the upper range of simple models (extrapolated seismic speeds and a 20% core, but little or no partial melt) and the spacecraft value is larger, but there is consistency within the observational uncertainties.

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 considered independent dissipation terms in the rotation, 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 core component is found to be somewhat stronger and the monthly tidal Q is found to be 33±4. The core fraction is f_c=0.41 for the principal term and the frequency power law exponent is -0.05. For k_2 = 0.0227 the power-law expression for tidal Q as a function of tidal period is $33(\text{Period}/27.212\text{d})^{0.05}$ so the Q increases from 33 at a month to 38 at one year. The decrease in Qs compared to [1] is largely due to the decrease in k_2. Based on Yoder's turbulent boundary layer theory [8] 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.

Core Oblateness: The detection of the oblateness of the fluid-core/solid-mantle boundary (CMB) would be independent evidence for the existence of a liquid core. In the first approximation CMB oblateness should influence the tilt of the lunar equator to the ecliptic plane [2]; the LLR solutions include an analytical parameter to alter this tilt. This tilt is also influenced by moment-of-inertia differences, gravity harmonics, and Love number k_2, which are also solution parameters. The solution value is twice its uncertainty. These results are stronger than past solutions [3-5] which were close to the noise. The tilt parameter anticorrelates with k_2 so that larger CMB oblateness corresponds to smaller k_2.

The tilt correction depends on the fluid core moment 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 radius of about 345 km, with ratio of the fluid core to solid mantle moments $C_c/C_m = 6\text{x}10^{-4}$, the flattening would be of order $3\text{x}10^{-4}$. The oblateness scales inversely with fluid core moment so smaller fluid cores and inner solid cores would be expected to increase the oblateness value. For comparison the whole Moon "dynamical flattening" based on moment differences is $(2C-A-B)/2C = 5.18\text{x}10^{-4}$ and the surface geometrical flattening is $1.3\text{x}10^{-3}$ [9]. The free core nutation period would be several centuries.

Core Moment of Inertia: An analytical development in [1] presents a rotation term sensitive to the fluid core moment of inertia. This term is potentially important because it would both confirm the presence of a fluid core and it would give a direct measurement of the moment of the fluid core. It was argued that this term would be difficult to detect because it is close in frequency (81 yr beat period) to a free libration term (free precession).

The least-squares solution procedure requires partial derivatives of range with respect to core moment. The partial derivatives of the three lunar rotation components with respect to core moment have been developed using numerical integration. Solutions using these partial derivatives confirm the difficulty of detection.

Inner Core: 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. An inner core would complicate interpretations: 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 affect core moment and flattening interpretations.

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 Love number is consistent with models which include a core. The effect of the oblateness of the fluid core/solid-mantle boundary seems to be significant. Direct detection of the fluid core moment remains elusive. Detection of a solid inner core is a future possibility. Additional ranges with current accuracy and future data with improved accuracy [10] should improve the determination of these lunar science effects.

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