LUNAR SCIENCE FROM LUNAR LASER RANGING. 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, tidal Love number k_2, and moment of inertia differences [1-3]. 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 variations in lunar rotation, orientation and tidal displacements. Past solutions using the LLR data have given results for Love numbers plus dissipation due to solid-body tides and fluid core [1-4]. Detection of the fluid core polar minus equatorial moment of inertia difference due to CMB flattening is weakly significant. This strengthens the case for a fluid lunar core. Future approaches are considered to detect a solid inner core.

LLR Solutions: Reviews of Lunar Laser Ranging (LLR) are in [2,5]. Lunar ranges to five retroreflectors from 1970 to 2012 are analyzed using a weighted least-squares approach. We have 6.5 yr of accurate ranges from Apache Point Observatory, New Mexico along with the extensive set from McDonald Observatory, Observatoire de la Côte d'Azur (OCA), and Haleakala Observatory. Lunar solution parameters include moment of inertia differences, dissipation at the fluid-core/solid-mantle boundary (CMB), tidal dissipation, dissipation-related coefficients for rotation and orientation terms, potential Love number k_2, displacement Love numbers h_2 and l_2, and fluid core flattening. Solution parameters can be combined with constraints.

Solid Moment of Inertia: The lunar solid moment of inertia I_{solid}, crust and mantle plus solid core, can be determined by combining LLR moment of inertia differences with spacecraft determined J_2 or C_{22}. Here, pre-GRAIL spacecraft J_2 from LP150Q [6], SGM100h [7] and SGM100i [8] are combined with LLR moment differences to get $I_{solid}/MR^2 = 0.3930±0.0003$, where M and R are the mass and radius, respectively.

Fluid Core Moment of Inertia: The fluid core moment of inertia is an important lunar geophysical parameter. In the LLR analysis sensitivity comes from two effects: directly from the response of the orientation to a slow motion of the ecliptic plane and indirectly through dissipation at the CMB [1].

Theory and LLR solutions for lunar dissipation are presented in [1]. Interpretation of dissipation results invokes both strong tidal dissipation and interaction at a fluid-core/solid-mantle boundary (CMB). Solutions include combinations of tide and core parameters plus orientation coefficients. Dissipation provided the first LLR evidence for a fluid core [1]. Evidence for CMB dissipation remains strong, with a value 8 times its uncertainty, and the fluid core moment is of order $C_f/C \approx 7x10^{-4}$ [1] using Yoder's turbulent boundary layer expression [9], but there are major uncertainties from unknown fluid/solid boundary roughness and inner core size.

For the direct approach, the core moment and core/mantle boundary flattening are strongly correlated and separating them in the solutions is difficult. Non-linearities impact solutions for core moment.

Extracting the core moment is challenging and the direct approach has not achieved an acceptable result. The main difficulty with using the direct approach comes from separating effects with similar frequencies and very long beat periods [1]. An increasing LLR data span should improve separation. LLR solutions for other parameters below use two fixed fluid core moments of $3x10^{-4}$ and $7x10^{-4}$ to check sensitivity.

Core Oblateness: Detection of the oblateness of the fluid-core/solid-mantle boundary (CMB) is evidence for the existence of a liquid core that is independent of dissipation results. In a first approximation, CMB oblateness influences the tilt of the lunar equator to the ecliptic plane [2]. A torque for CMB flattening is introduced into the numerical integration model for lunar orientation and its partial derivatives [3] to set up solution parameters for CMB flattening, core moment of inertia and core spin vector. Equator tilt is also influenced by lunar moment differences, gravity harmonics and Love number k_2, solution parameters affected by CMB flattening.

Torque from an oblate CMB shape is proportional to the difference between fluid core polar and two equatorial moments, $C_f–(A_f+B_f)/2$, provided that the fluid has uniform density and the inner boundary is spherical. This moment difference depends on the product of the fluid core moment of inertia C_f and the CMB flattening f, $[C_f–(A_f+B_f)/2]/C = f\,C_f/C$. The mean of the LLR solutions with two fixed core moments is $[C_f–(A_f+B_f)/2]/C = (1.8±0.6)x10^{-7}$. This product is better determined than the two factors. While the flattening f is uncertain, the moment difference seems significant and CMB flattening is weakly detected.

The model equilibrium value for the CMB flattening is $2.2x10^{-5}$. To match the $f\,C_f/C$ value, an equilibrium f would require a very large fluid core with a moment of inertia an order-of-magnitude larger than otherwise indicated. So the CMB flattening does not appear to be at equilibrium. The whole Moon degree-2 shape and gravity field are larger than the equilibrium figure for the current tides and spin and the same appears to be true for the CMB flattening.

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 0.0107, gives k_2 = 0.0241±0.0020 for the two-solution average. The tidal deformation affects the lunar orientation in three ways: through the gravity field torque, and through the responding moment of inertia and its derivative with respect to time. The LLR k_2 value is sensitive to the interior model and the choice of solution parameters. Pre-GRAIL spacecraft results for the lunar Love number k_2 are 0.0248±0.003 for LP150Q [6] 0.0240±0.0015 for SGM100h [7] and 0.0255±0.0016 for SGM100i [8], determined from tidal variation of the gravity field.

Model Love Numbers: Love number calculations require a lunar model. Lunar models use seismic P- and S-wave speeds deduced from Apollo seismic measurements. Recent models of Weber et al. [10] and Garcia et al. [11] also use the arrival times of suspected seismic reflections off of the outer fluid core. Outer fluid core radii are 330 km and 380 km, respectively. Model fluid outer core densities are near the Fe-FeS eutectic. Here densities are slightly modified to satisfy the above solid moment of inertia. The Weber et al. model gives k_2 = 0.0234, h_2 = 0.0409, and l_2 = 0.0107, similar to values in their paper. The Garcia et al. model gives k_2 = 0.0223, h_2 = 0.0389, and l_2 = 0.0104. The Weber et al. model has a layer of partially molten material and lower seismic velocities that overlies the outer core, giving larger Love numbers than the Garcia et al. model, which lacks such a deep partially molten layer. The Weber et al. model matches the k_2 determinations better. A larger core or more extensive partial melt would increase the Love numbers.

Dissipation from Tides: Analysis of the dissipation coefficients follows [1]. Tidal Q depends weakly on period; Q increases from ~35 at a month to larger values at longer periods. Despite strong dissipation, Rambaux and Williams [12] find free librations, indicating stimulation on geological time scales.

Lunar Orbit and Physical Librations: A new lunar and planetary ephemeris is under construction. Lunar physical librations are included. This ephemeris is a combination of LLR and planetary data analysis. The new ephemeris is meant to replace DE421 [13,14] for lunar work. We rely on GRAIL results for a Love number k_2 and a low-degree gravity field up to 6x6. Both are strongly improved by GRAIL [15]. Three of the third-degree gravity coefficients are adjusted during the LLR fits: C_{32}, S_{32}, and C_{33}. This gives a better LLR fit, but it probably indicates unmodeled effects. The LLR moment differences $(C–A)/B$ and $(B–A)/C$ are strongly improved.

Inner Core Possibilities: A solid inner core might exist inside the outer fluid core. Gravitational interactions between an inner core and the mantle could reveal its presence in the future.

A solid inner core might be detected by LLR through the physical librations or by orbiting spacecraft from a variable gravitational field [16]. Inner core degree-2 figure would cause time varying C_{21} and S_{21} harmonics viewed in a mantle-fixed frame. The period would be 27.212 days. A search for variable C_{21} and S_{21} harmonics is a GRAIL data analysis goal.

Summary: Adding new lunar ranges gives lunar parameters with improved uncertainties. Dissipation parameters indicate an outer fluid core and strong tidal dissipation. The weak detection of the fluid core polar/equatorial moment difference due to fluid-core/solid-mantle boundary flattening is additional evidence for an outer fluid lunar core. Detection of a solid inner core is a future possibility. Additional ranges should improve the determination of lunar science results. A wider network of lunar retroreflectors would strengthen the results. GRAIL will give Love number k_2, but solid moment requires GRAIL + LLR.

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