LUNAR FLUID CORE MOMENT 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) [2,3,6] 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 variations in lunar rotation and 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 now 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 given in [2,5]. Lunar ranges over 1970-2009 are analyzed using a weighted least-squares approach. Here we include 38 months of accurate 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, displacement Love numbers h_2 and l_2, and fluid core flattening and moment of inertia. A solution can combine solution parameters and constraints.

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 the 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] and evidence for CMB dissipation remains strong. For the ratio of fluid moment to total moment, CMB dissipation gives $C_f/C = 1.0\text{x}10^{-3}$, using Yoder's turbulent boundary layer expression [10]. The moment value in [1] is about 0.7 of the preceding due to a $\sqrt{2}$ difference in the expression connecting dissipation and moment. The upper uncertainty is about 20%, but the lower uncertainty is unbounded due to unknown CMB roughness as an additional source of CMB dissipation.

For the direct approach, the core moment and core/mantle boundary flattening are strongly correlated and separating them in the solutions is difficult. Multiple integrations and solutions show that nonlinearities affect solutions. While separation is very weak, a larger core moment is indicated.

For a uniform liquid iron core without an inner core the CMB dissipation value corresponds to a radius of 375 km while for the Fe-FeS eutectic the radius would be 400 km. Those two cases correspond to fluid cores with 2.1% and 1.9% of the mass, respectively.

While extracting the core moment is challenging, it should improve as the LLR data span increases. The main difficulty with using the direct approach comes from separating effects with similar frequencies and very long beat periods [1]. The increasing LLR data span should improve the separation.

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 [6] to get 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 equatorial moments, C_f–A_f, 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, $(C_f–A_f)/C = f\,C_f/C$. The LLR solution gives $(C_f–A_f)/C = (3.0\pm0.7)\text{x}10^{-7}$. This product is much better determined than the two factors. For the above CMB dissipation value for C_f/C, one gets $f = 3\text{x}10^{-4}$. For a core moment between $6\text{x}10^{-4}$ and $20\text{x}10^{-4}$, flattening ranges from $5\text{x}10^{-4}$ to $1.5\text{x}10^{-4}$. While the flattening f is uncertain, the moment difference is better determined and CMB flattening is detected.

The model equilibrium value for the CMB flattening is $2.2\text{x}10^{-5}$. The above spread of flattening values is an order-of-magnitude larger than the equilibrium value, so the CMB flattening does not seem 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 0.0105, gives k_2 = 0.0209±0.0025 and h_2 = 0.041±0.008. 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. Our model for numerically integrated orientation does not consider deformation of the fluid core shape for the last two effects. Consequently, our derived k_2 value may lie between the mantle and whole Moon values. A somewhat larger whole Moon k_2 would be more compatible with model values and the h_2 determination. Modifications allowing for core tidal deformation are being implemented. Orbiting spacecraft results for the lunar Love number k_2 are 0.026±0.003 [7] and 0.0213±0.0075 [8], determined from tidal variation of the gravity field.

Model Love Numbers: Model Love number calculations, using seismic P- and S-wave speeds deduced from Apollo seismology, are explored here. The seismic speeds were extrapolated from the sampled mantle regions into the deeper zone above the core. A model with a 380 km radius liquid iron core gives a k_2 of 0.0231, h_2 of 0.0405, and l_2 of 0.0107. A larger core increases the model k_2 and h_2 values, but has less effect on l_2. Any partial melt above the core would increase k_2 and h_2. The Apollo seismic uncertainties contribute ~5% uncertainty to the model k_2 and h_2 Love numbers.

Dissipation from Tides: Analysis of the dissipation coefficients is similar to that in [1]. Tidal Q depends weakly on period; Q increases from ~30 at a month to ~33 at one year.

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 rotate independently, but gravitational interactions are expected to lock it to the mantle rotation.

The theoretical precession and longitude dynamics for locked rotation have been investigated. Inner core torques arise from gravitational 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 have reversed sign. The attraction between a triaxial inner core field and the interior gravitational harmonics of the mantle has unknown strength but it would introduce its own inner core free precession and longitude resonances. 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 inward gravity coefficients.

An inner core might also be detected from its gravitational field [9]. Tilted by a different amount than the mantle, inner core degree-2 harmonics 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 should be a goal of future lunar orbiting spacecraft missions.

An inner core would complicate interpretation of LLR rotation and orientation results since there would be two surfaces for interactions.

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 fluid core polar/equatorial moment difference due to the fluid-core/solid-mantle boundary flattening is significant. This is additional evidence for a fluid lunar core. 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 strengthen the results.

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