**A LARGER LUNAR CORE?** 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 and the fluid core moment of inertia are now significant. Both strengthen 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 1970-2008 are analyzed using a weighted least-squares approach. Here we include 32 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 the latest lunar geophysical parameter to emerge from the LLR analysis. Sensitivity comes from determining the effect on orientation of a slow motion of the ecliptic plane [1]. Solutions for the ratio of fluid moment to total moment give $C_f/C = (12\pm4)\times10^{-4}$. For a uniform liquid iron core without an inner core this value would correspond to a radius of 390±30 km while for the Fe-FeS eutectic the radius would be 415 km. Those two cases would correspond to fluid cores with 2.4% and 2.2% of the mass, respectively. With a solid inner core, assuming that the inner core orientation is gravitationally coupled to the mantle so that they precess together, the fluid moment depends on the fluid density and outer and inner radii, $(8/15)\pi\rho_f(R_f^5 - R_{ic}^5)$. So the outer (CMB) radius would be larger if there is a solid inner core.

In the past we have inferred the fluid core moment of inertia and radius from LLR dissipation results [1,3]. Those moments were about half of the new result. When we used Yoder's boundary layer theory for dissipation at the CMB [6] we did not keep a factor of ½ in Yoder's expression for torque. That factor would reconcile the two approaches. The dissipation results tend to give an upper limit for fluid core moment because topography on the CMB surface will increase the dissipative torque. Any inner core would provide a second surface for dissipation so that a smaller CMB radius would account for the torque.

While the new result for core moment is noisy, it should improve as the LLR data span increases. The main difficulty with using this more direct approach comes from separating two effects with similar frequencies and an eight decade beat period [1]. The increasing LLR data span is improving 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 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 orientation and partial derivatives. Equator tilt is also influenced by moment-of-inertia differences, gravity harmonics and Love number $k_2$, solution parameters affected by CMB oblateness.

Torque from an oblate CMB shape depends on the fluid core moment of inertia and the CMB flattening. Both are uncertain and there is no information about the latter apart from these LLR solutions. The solution gives $f=(2.0\pm2.3)\times10^{-4}$. The uncertainty seems to imply a nondetection, but the oblateness parameter f correlates –0.90 with core moment. The derived oblateness varies inversely with fluid core moment, as expected theoretically, so a smaller fluid core corresponds to a larger oblateness value. The product $f\,C_f/C=(3\pm1)\times10^{-7}$ is better determined than f alone. The detection of core flattening and the foregoing product are more secure than the f uncertainty implies.

The model equilibrium value for the CMB flattening is $2.2\times10^{-5}$. From the product $f\,C_f/C$, the fluid core moment of inertia compatible with the equilibrium f would have to be an order-of-magnitude larger than the value found above. Thus, the CMB flattening is not close to equilibrium. The whole Moon degree-2 shape and gravity field are much larger than the equilibrium figure expected from 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 $k_2 = 0.0199 \pm 0.0025$ and $h_2 = 0.042 \pm 0.008$. 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 somewhere between values for the mantle and the whole Moon. 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 $0.026 \pm 0.003$ [7] and $0.0213 \pm 0.0075$ [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 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. A model with a 390 km radius liquid iron core gives $k_2$ of 0.0233, $h_2$ of 0.0408, and $l_2$ of 0.0107. A larger core increases the model $k_2$ and $h_2$ values, but has minor effect on $l_2$. 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.

**Dissipation from Fluid Core and Tides:** Theory and LLR solutions for lunar dissipation were presented in [1]. Interpretation of the dissipation results invokes both strong tidal dissipation and interaction at a fluid-core/solid-mantle boundary (CMB). Solutions use combinations of tide and core parameters plus orientation coefficients. Dissipation provided the first LLR evidence for a fluid core [1] and the core component remains strong.

Analysis of the dissipation coefficients is similar to that in [1]. There is weak dependence of tidal Q on period. The Q increases from ~30 at a month to ~35 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 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 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 internal 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.

An inner core would complicate interpretation of LLR rotation and orientation results: there would be two surfaces for both solid-mantle/fluid-core/inner-core dissipation and flattening 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 oblateness of the fluid-core/solid-mantle boundary and direct detection of the fluid core moment are both significant. Both are 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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