LUNAR FLUID CORE AND SOLID-BODY TIDES.

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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) [2-5] 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 has been improving [3,5] and now seems significant. This strengthens the case for a fluid lunar core.

LLR Solutions: Reviews of Lunar Laser Ranging (LLR) are given in [2,6]. Three decades of Lunar Laser Ranging data, 1970-2004, 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, and displacement Love numbers h_2 and l_2. Previously, a constant term in the tilt of the equator to the ecliptic has been used to approximate the influence of core-mantle boundary (CMB) flattening. To improve upon this approximation, a torque for CMB oblateness has been introduced into the model for numerical integration of lunar rotation. Solutions with combinations of solution parameters and constraints are considered.

Love Number Determination: 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 0.0106, gives $k_2 = 0.0227 \pm 0.0025$ and $h_2 = 0.045 \pm 0.010$. Compared to early spherical core results [1,2] the LLR value for k_2 has decreased due to consideration of core oblateness. There is an orbiting spacecraft result for the lunar Love number of $k_2 = 0.026 \pm 0.003$ determined from tidal variation of the gravity field [7].

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 $l_2 = 0.0106$. A smaller core decreases the model k_2 and h_2 values, but has little 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 a several percent uncertainty to the three model Love numbers. The LLR k_2 determination is in the range of simple model values with extrapolated seismic speeds and a small core. The spacecraft k_2 value is larger than simple model values, but there is consistency within the observational uncertainties.

A study of possible lunar models has been made by Khan et al. [8,9]. In order to determine the variety of permissible interior structures and properties, a large number of models were generated which satisfy, within measurement uncertainties, four lunar quantities: the mean density, the moment of inertia's measure of mass concentration toward the center, elastic response to solid-body tides, and tidal dissipation. Typically, the central regions of the acceptable models have a higher density core which can take several forms such as completely solid, completely fluid, and a solid inner core within a fluid outer core. The latter two possibilities are compatible with the Lunar Laser Ranging results.

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 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 core component is found to be somewhat stronger and the monthly tidal Q is found to be 30±4. The core fraction is $f_c=0.37$ for the principal term and the frequency power law exponent is -0.04. For $k_2 = 0.0227$ the power-law expression for tidal Q as a function of tidal period is $30(\mathrm{Period}/27.212\mathrm{d})^{0.04}$ so the Q increases from 30 at a month to 34 at one year. The decrease in Qs compared to [1] is largely due to the decrease in k_2 which resulted from including CMB oblateness. Based on Yoder's turbulent boundary layer theory [10] a fluid iron core would have a radius of about 340 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 integration model should implicitly include the tilt and other effects of CMB oblateness. The equator tilt is also influenced by moment-of-inertia differences, gravity harmonics, and Love number k_2, which are solution parameters that are expected to be affected by CMB oblateness. The current solution value for CMB oblateness is twice its uncertainty. These results are stronger than early solutions which were close to the noise [3]. The oblateness parameter anticorrelates with k_2 so that larger CMB oblateness corresponds to smaller k_2.

The effect of CMB oblateness 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 340 km, with ratio of the fluid core to solid mantle moments $C_c/C_m = 6x10^{-4}$, the flattening would be of order $3x10^{-4}$. The free core nutation period would be two centuries. The oblateness scales inversely with fluid core moment so smaller fluid cores would be expected to increase the oblateness value and decrease the free core nutation period. For comparison, the whole Moon "dynamical flattening" based on LLR-determined moment of inertia differences is $(2C-A-B)/2C = 5.18x10^{-4}$ and the surface geometrical flattening based on altimetry is $1.3x10^{-3}$ [11].

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 and this remains a future goal.

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 computation of the effect of the oblateness of the fluid-core/solid-mantle boundary has been made more sophisticated and the corresponding solution parameter seems to be significant. This second line of evidence for a fluid lunar core is becoming stronger. Direct detection of the fluid core moment and detection of a solid inner core are future possibilities. Additional ranges with current accuracy and future data with improved accuracy should improve the determination of these lunar science effects. A wider network of lunar retroreflectors would also strengthen the results.

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