

PROPERTIES OF THE LUNAR INTERIOR: PRELIMINARY RESULTS FROM THE GRAIL MISSION.

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Introduction: The Gravity Recovery and Interior Laboratory (GRAIL) mission [1] has provided lunar gravity with unprecedented accuracy and resolution. GRAIL has produced a high-resolution map of the lunar gravity field [2,3] while also determining tidal response. We present the latest gravity field solution and its preliminary implications for the Moon's interior structure, exploring properties such as the mean density, moment of inertia of the solid Moon, and tidal potential Love number k_2 . Lunar structure includes a thin crust, a thick mantle layer, a fluid outer core, and a suspected solid inner core. An accurate Love number mainly improves knowledge of the fluid core and deep mantle. In the future, we will search for evidence of tidal dissipation and a solid inner core using GRAIL data.

GRAIL Data: The GRAIL Primary Mission (PM) lasted from March to May of 2012. The PM was designed to have only one major orbit maneuver, to change the mutual drift rate of the two spacecraft from separating to closing. The two long, low-activity intervals are ideal for determining properties of interest for the lunar interior, including tidal response and low-degree gravity field. The lower-altitude Extended Mission (EM) followed in the fall. Solutions from two independent analysis programs and groups [4,5] at the Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center (GSFC) provide an invaluable internal check and in addition an assessment of the accuracy of recovered parameters.

Gravity Field Solutions: GRAIL's primary three-month tour resulted in a gravitational field of degree and order 420 with equivalent surface resolution (block size) of 13 km [3]. Three additional months of the EM resulted in an aggregate field of degree and order at least 660. Advanced system calibrations have resulted in unprecedented data quality of better than 0.1 $\mu\text{m/s}$

for the inter-spacecraft range-rate primary measurement [2]. The latest gravity field solution shows an error spectrum with several orders of magnitude improvement for all wavelengths when compared with results from previous missions. High correlations with topography exist through higher harmonic degrees than for the Primary Mission field [2].

Mean Density: GRAIL has improved the lunar-orbiting spacecraft estimate of the product of the gravitational constant and lunar mass, GM , but the DE421 value of $4902.80008 \pm 0.00010 \text{ km}^3/\text{s}^2$ from lunar and planetary ephemeris fits [6,7] appears to have smaller uncertainty. The 0.012% uncertainty in G [8] dominates the uncertainty for the lunar mass and mean density. All modern determinations of GM are more accurate than the uncertainty in G and give the same density within the uncertainty. The mean density of the Moon is $3345.6 \pm 0.4 \text{ kg/m}^3$.

Moments of Inertia: The principal moments of inertia of the Moon are $A < B < C$. Expressions for the moments of inertia involve combinations of spacecraft-derived gravity coefficients J_2 and C_{22} with lunar laser ranging determinations of the physical-libration parameters $(B-A)/C$ and $(C-A)/B$. Combinations of gravity coefficients and physical librations are always necessary. Expressions for moments as functions of two or three of the four parameters are required [9,10].

New fits of lunar laser ranges plus integrations of the orbit and physical librations were generated using the GRAIL gravity coefficients and Love number. This step assured compatibility between the strongly improved GRAIL field and the lunar laser physical libration parameters [11]. Moments result from combinations of spacecraft determinations of the degree-2 gravity field [4,5] with lunar laser ranging determinations of moment of inertia expressions $(B-A)/C$ and $(C-A)/B$ [11].

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After accounting for tides and a fluid core, the physical librations are most sensitive to $(B-A)/C_s$ and $(C-A)/B_s$, where the subscript s stands for the solid crust, mantle, and inner core of the Moon without the fluid outer core. The most accurately determined moments are those for the solid Moon, A_s , B_s , and C_s , rather than those for the entire Moon, A , B , and C . The moments of inertia of the fluid outer core remain poorly known [10].

The average moment of inertia of the entire Moon is $I=(A+B+C)/3$. There are multiple ways to compute any of the moments, but only three ways are most independent and warrant evaluation and comparison. The scatter in the solid-Moon moments is a few in the fifth decimal place, an order-of-magnitude improvement over the pre-GRAIL uncertainty.

The moment of inertia of the entire Moon is an order of magnitude more uncertain than that of the solid Moon. For fluid moment fractions I_f/I from 2×10^{-4} to 9×10^{-4} , the entire Moon I/MR^2 is 0.8×10^{-4} to 3.6×10^{-4} larger than I_s/MR^2 .

Love Number Determination: The JPL and GSFC analysis groups have determined Love number k_2 values that so far differ by 1.6%. A pre-GRAIL combination of several spacecraft and lunar laser determinations had a 5% uncertainty. GRAIL has improved the k_2 uncertainty by a factor of three.

The signal from higher-degree Love numbers falls off by two orders of magnitude per degree, so accurate higher-degree Love numbers are not expected from GRAIL. Nevertheless, detection of the third-degree Love number with a 25% uncertainty has been achieved.

Model Love Numbers: Recent models of Weber et al. [12] and Garcia et al. [13] include Love numbers calculated from seismic P- and S-wave speeds deduced from Apollo seismic measurements, along with the arrival times of suspected seismic reflections off the fluid outer core. Outer core radii are 330 km and 380 km, respectively. The model outer core densities are near the Fe-FeS eutectic values. The Weber et al. model gives $k_2 = 0.0232$ and $h_2 = 0.0406$. The Garcia et al. model gives $k_2 = 0.0223$, $h_2 = 0.0394$, and $l_2 = 0.0106$. 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 has larger Love numbers despite the smaller core. A larger core or more extensive partially molten layer increases the model Love numbers. Model values for k_3 are about 0.00946 while model values for k_4 are about 0.00535.

Future Possibilities: The GRAIL analyses continue to advance, and we anticipate improved solutions. The preliminary interior results have used only Primary Mission results, but the Extended Mission data

should help improve the interior parameters. Lunar laser ranging analyses find tidal dissipation with k_2/Q of about 7×10^{-4} [14]. Detection of the monthly tidal dissipation is a future possibility for GRAIL. An inner core would produce a time variation in the gravity field [15]. The size of such a variation is very difficult to predict, but it should be sought. Asymmetries in the Moon's properties would complicate the tidal response [16]. Such variations can also be sought.

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