PRELIMINARY RESULTS ON LUNAR INTERIOR PROPERTIES FROM THE GRAIL MISSION.

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Introduction: The Gravity Recovery and Interior Laboratory (GRAIL) mission 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 the 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 deep mantle, a fluid core, and a suspected solid inner core. An accurate Love number mainly improves knowledge of the fluid core and deep mantle. In the future GRAIL will search for evidence of tidal dissipation and a solid inner core.

GRAIL Data: The GRAIL Prime 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] 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 (blocksize) of 13 km [3]. Three additional months of the EM resulted in an aggregate field of degree and order of at least 660. Advanced system calibrations have resulted in unprecedented data quality of better than 0.1 microns/sec 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 to 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 GM, but the DE421 value of 4902.80008±0.00010 km^3/sec^2 from lunar and planetary ephemeris fits [6] appears to have smaller uncertainty. The 0.012% uncertainty of the gravitational constant G [7] 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 is 3345.6±0.4 kg/m^3.

Moments of Inertia: The principal moments of inertia of the whole Moon are $A<B<C$. Expressions for the moments of inertia involve combining spacecraft-derived gravity coefficients J_2 and C_{22} and physical-libration-derived $(B-A)/C$ and $(C–A)/B$. Combinations of gravity coefficients and physical librations are always necessary. Two or three of the four parameters are required [8,9]. Moments result from combining spacecraft determinations of the degree-2 gravity field [4,5] and lunar laser ranging determinations of moment of inertia expressions $(B-A)/C$ and $(C–A)/B$.

A new lunar laser ephemeris and physical librations was generated with GRAIL gravity coefficients and Love number. This assured compatibility between the strongly-improved GRAIL field and the lunar laser physical librations [cf. 10].

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 subscript s stands for the solid crust, mantle and inner core of the Moon without the fluid core. The most accurately determined moments are solid Moon A_s, B_s, and C_s rather than whole Moon A, B, and C. The moments of inertia of the fluid core remain poorly known [10].

The average moment of inertia is $I=(A+B+C)/3$.

There are multiple ways to compute any of the moments, but only three ways are most independent. We evaluate and compare. 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 whole Moon is an order-of-magnitude more uncertain than the solid moment. For fluid moment fractions I_f/I from $2\text{x}10^{-4}$ to $9\text{x}10^{-4}$, the whole Moon I/MR^2 is $0.8\text{x}10^{-4}$ to $3.6\text{x}10^{-4}$ 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. [11] and Garcia et al. [12] have been presented. Their model Love number calculations used seismic P- and S-wave speeds deduced from Apollo seismology, along with suspected seismic reflections off of the fluid core. Fluid core radii are 330 km and 380 km, respectively. The model fluid 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 deep partial melt with lower seismic velocities, giving larger Love numbers than the Garcia et al. model which lacks a deep partial melt. The Weber et al. model has larger Love numbers despite the smaller core. A larger core or more extensive partial melt increases the model Love numbers.

Future Possibilities: The GRAIL analyses continue to advance and we anticipate improved solutions. This abstract has used Prime 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 $7\text{x}10^{-4}$ [13]. Detection of the monthly tidal dissipation is a future possibility for GRAIL. An inner core would produce a time variation in the gravity field [14]. The size of such a variation is very difficult to predict, but it should be looked for. Asymmetries in the Moon's properties would complicate the tidal response [15]. Such variations can also be searched for.

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References: [1] Zuber M. T. et al. (2012) *Space Sci. Rev.,* doi: 10.1007/s11214-012-9952-7. [2] Zuber M. T. et al. (2012) *Science* doi: 10.1126/science.1231507. [3] Zuber M. T. et al. (2013) abstract of the *Lunar and Planetary Science Conference XXXXIV,* The Woodlands, TX, March 18-22, 2013. [4] Asmar, S. W. et al, (2012) "The High Resolution Gravitational Field of the Moon from GRAIL and Implications for Interior Structure," G32A-02, AGU 2012. [5] Lemoine F. G. et al. (2013) abstract of the *Lunar and Planetary Science Conference XXXXIV,* The Woodlands, TX, March 18-22, 2013. [6] Folkner W. M. et al. (2008*) JPL 33R-08-003.* [7] Mohr P. J., Taylor B. N. and Newell D. B.(2012) CODATA recommended values of the fundamental physical constants: 2010, *Rev. Modern Phys. 84(4),* 1527-1605, doi:10.1103/RevModPhys.84.1527. http://physics.nist.gov/cuu/Constants/ [8] Williams J. G. et al. (1973) *The Moon 8*, 469-483 [9] Bills B. G. (1995) *J. Geophys. Res. 100*, 26297-26303. [10] Williams J. G. et al. (2008) JPL IOM 335-JW, DB, WF-20080314. [11] Weber R. C. et al. (2011) *Science 331*, 309-312, doi:10.1126/science.1199375. [12] Garcia R. F. et al. (2011) *Phys. Earth and Planetary Interiors 188*, 96-113, doi:10.1016/j.pepi.2011.06.015 [13] Williams J. G. et al. (2001) *J. Geophys. Res. 106,* 27,933-27,968. [14] Williams J. G. (2007) *Geophys. Res. Lett. 34*, L03202, doi:10.1029/2006GL028185. [15] Zhong S. et al. (2012) *Geophys. Res. Lett. 39*, L15201, doi:10.1029/2012GL052362.,