

OUTSTANDING QUESTIONS ON THE INTERNAL STRUCTURE AND THERMAL EVOLUTION OF THE MOON AND FUTURE PROSPECTS FROM THE GRAIL MISSION. M. T. Zuber¹, D. E. Smith², L. Alkalai³, D. H. Lehman³, M. M. Watkins³, and the GRAIL Team. ¹Department of Earth, Atmospheric & Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, (zuber@mit.edu); ²Solar System Exploration Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771; ³Jet Propulsion Laboratory, Pasadena, CA. 91109-8099.

Introduction: The structure of the lunar interior (and by inference the nature and timing of compositional differentiation and of internal dynamics) holds the key to reconstructing the thermal evolution of the Moon. Longstanding questions such as the origin of the maria, the reason for the nearside-farside asymmetry in crustal thickness, and the explanation for the puzzling magnetization of crustal rocks, all require a greatly improved understanding of the Moon's interior. Knowledge of the interior and evolution of the Moon, and by extension, other terrestrial planets, will be greatly advanced by the Gravity Recovery And Interior Laboratory (GRAIL) mission, which was recently selected as a new mission by NASA.

Lunar Interior Structure and Thermal Evolution: The Moon is a lynchpin for our comprehension of the evolution of silicate planetary bodies, and the early evolution of Earth is strongly tied to lunar origin. The Moon is a "baseline" silicate planet [1] that still displays the results of its primordial differentiation. It serves as a foundation to study planetary histories that may be similar (*e.g.*, Mercury), or have evolved significantly beyond this state (*e.g.*, Mars, Venus). The primordial differentiation of a planetary crust is a fundamental paradigm for understanding planetary evolution that is rooted in lunar science.

A recent review [2] summarized the state of knowledge of the Moon's global geophysical processes and summarized fundamental questions that need to be addressed by future investigations:

- What was the initial thermal state of the Moon?
- What was the cause of the global scale asymmetry?
- What was the depth of differentiation during the lunar magma-ocean stage?
- What are the characteristics of the lunar core?
- Is there an undifferentiated lower mantle?

As outlined in Table 1, reconstructing the thermal evolution of the Moon requires global models of the thickness of the crust and the effective elastic thickness of the lithosphere, which are derived from a combination of global, high-resolution gravity and topography data [*cf.* 3]. The volume of the crust provides the extent of melting of the magma ocean, and its distribution forms the basis of models of crustal evolution. The effective elastic thickness yields the thermal struc-

ture in the shallow Moon at the time features formed. Such analysis is particularly valuable in reconstructing the thermal state of the Moon during and subsequent to the late heavy bombardment for the lunar crust during the final stage of lunar accretion. Subtle long-period tidal and rotational perturbations provide information on the mass distribution and mechanical state of the deep interior.

The biggest impediment to progress in studies of lunar internal structure and evolution has been the lack of reliable farside gravity.

The GRAIL Mission: GRAIL is the lunar analog of the very successful GRACE [4] twin-spacecraft terrestrial gravity recovery mission that continues to operate. GRAIL will be implemented with a science payload derived from GRACE and a spacecraft derived from the Lockheed Martin Experimental Small Satellite-11 (XSS-11), launched in 2005.

GRAIL has two primary objectives: to determine the structure of the lunar interior, from crust to core; and to advance understanding of the thermal evolution of the Moon. These objectives will be accomplished by implementing the following lunar science investigations:

- Map the structure of the crust & lithosphere.
- Understand the Moon's asymmetric thermal evolution.
- Determine the subsurface structure of impact basins and the origin of mascons.
- Ascertain the temporal evolution of crustal brecciation and magmatism.
- Constrain deep interior structure from tides.
- Place limits on the size of the possible inner core.

In addition, as a secondary objective, GRAIL observations will be used to extend knowledge gained on the internal structure and thermal evolution of the Moon to other terrestrial planets.

As shown schematically in Figure 1, GRAIL will place two twin spacecraft in a low-altitude (50 km), near-circular, polar lunar orbit to perform high-precision range-rate measurements between them using a Ka-band payload. Subsequent data analysis of the spacecraft-to-spacecraft range-rate data will provide a direct measure of the lunar gravity, that will lead to a high-resolution (30x30 km), high-accuracy (<10 mGal) global gravity field.

The payload, flight system and mission design ensure that all error sources that perturb the gravity measurements are contained at levels well below those necessary to meet science requirements. Figure 2 illustrates performance margin between the science requirements (red and green), the allocated performance (black), and Current Best Estimate (CBE) performance (gold).

GRAIL's total mission duration (270-days) includes a planned launch in September of 2011, followed by a low-energy trans-lunar cruise for the dual-spacecraft check-out and out-gassing, and a 90-day gravity mapping Science Phase. Initial science products will be available beginning 30 days after the start of the Science Phase and will be delivered to NASA's Planetary

Data System (PDS) no later than 3 months after the end of the Science Phase.

References: [1] Solomon S. C. et al. (1981) in *Basaltic Volcanism on the Terrestrial Planets*, ed. T. R. McGetchin, R. O. Pepin & R. J. Phillips, Pergamon Press, Inc., NY. pp. 1129-1233. [2] Jolliff B. J. et al. (2001) *Advances in Lunar Science*, NASA. [3] Zuber M. T. et al. (1994) *Science*, 266, 1839-1843. [4] Tapley B. D. (2004) *Science*, 305, doi: 10.1126/science.1099192. [5] Kaula W. M. (1966) *Theory of Satellite Geodesy*, Blaisdellm Waltham, 124 pp.

Table 1. Lunar Science Objectives: From Crust to Core

Lunar Interior	Model or Meas.	Expected Science Results
Crust/Upper Mantle	-Global crustal structure from gravity and topography	- Global crustal volume; extent of melting - Crustal density structure (radial & lateral) - Depth of excavation of major basins. - Subsurface highland & basin structure - Brecciation evolution & relation to magmatism
Lithosphere	-Global distribution of effective elastic thickness from gravity and topography	- Temperature/mechanical structure of shallow interior at time of loading. - Impact basin compensation states - Origin of mascons
Deep Interior/Core	-Love number, k_2 -Second-degree gravity coefficients	- Elastic properties of deep interior - Size/extent of partial melting of outer core - Limits on size of possible solid inner core

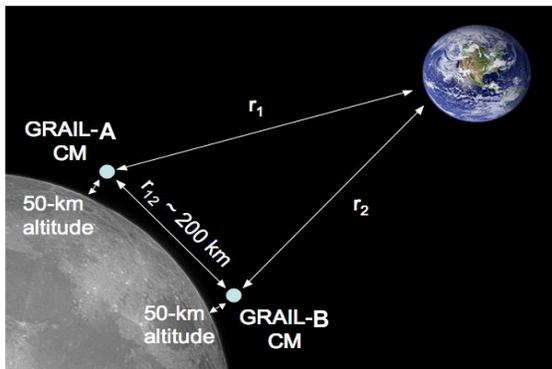


Figure 1. GRAIL gravity measurement model. GRAIL-A and -B correspond to the two GRAIL spacecraft.

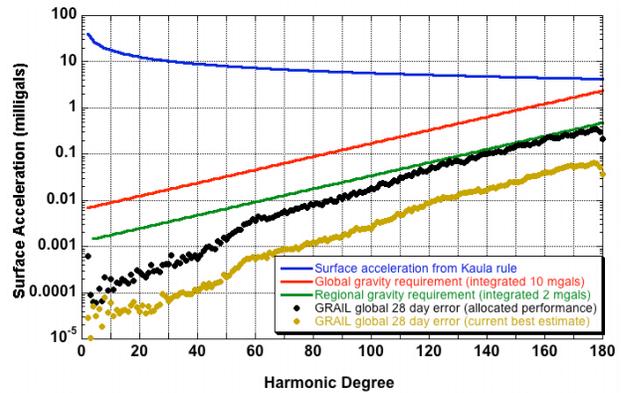


Figure 2. Error spectra from simulations illustrating margin between global (red) and regional (green) science requirements and the allocated (black) and current best estimate (gold) of GRAIL's performance. The blue line is the expected surface acceleration spectrum based on an empirical estimation of the power (Kaula's Rule) [5] of the Moon's gravitational field.