MISSION STATUS AND FUTURE PROSPECTS FOR IMPROVING UNDERSTANDING OF THE INTERNAL STRUCTURE AND THERMAL EVOLUTION OF THE MOON FROM THE GRAVITY RECOVERY AND INTERIOR LABORATORY (GRAIL) MISSION. Maria T. Zuber[1], David E. Smith[1], Sami W. Asmar[2], Alexander S. Konopliv[2], Frank G. Lemoine[3], H. Jay Melosh[4], Gregory A. Neumann[3], Roger J. Phillips[5], Sean C. Solomon[6], Michael M. Watkins[2], Mark A. Wieczorek[7] and James G. Williams[2], [1]Massachusetts Institute of Technology, Cambridge, MA 02129 (zuber@mit.edu); [2]Jet Propulsion Laboratory, Pasadena, CA 91109-8099; [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771; [4]Purdue University, West Lafayette, IN 47907; [5]Southwest Research Institute, Boulder, CO 80302; [6]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015; [7]Institut de Physique du Globe de Paris, 94100 Saint Maur des Fossés, France.

Introduction: The structure of the lunar interior (and by inference the nature and timing of compositional differentiation and internal dynamics) holds the key to reconstructing the thermal evolution of the Moon. Longstanding questions such the origin of the maria, the reason for the nearside-farside asymmetry in crustal structure, 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 planetary bodies, will be greatly advanced by the Gravity Recovery And Interior Laboratory (GRAIL) mission, which is on track for launch in September 2011.

Lunar Interior Structure and Thermal Evolution: The Moon is a linchpin 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 preserves the record 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 raised 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 structure 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 of 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 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 and 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.

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 lunar gravity that will lead to a high-resolution (30×30 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 1 illustrates performance margin between the science requirements, the allocated performance and Current Best Estimate (CBE) performance.

GRAIL's dual spacecraft are currently undergoing assembly and testing at Lockheed Martin Space Systems Division in Littleton, CO (see Figure 2). The total mission duration (270 days) includes a planned launch in September 2011, followed by a low-energy trans-lunar cruise for the dual-spacecraft check-out and out-gassing, insertion into lunar orbit on 31 December 2011 and 1 January 2012, a series of burns to circularize the orbit, a period to align the spacecraft into mapping configuration, 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 and R. J. Phillips, Pergamon Press, 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. et al. (2004) *Science, 305,* 503-505. [5] Kaula W. M. (1966) *Theory of Satellite Geodesy,* Blaisdell, Waltham, MA, 124 pp.

Table 1. Lunar Science Objectives: From Crust to Core

Lunar Interior	Model/Measurement	Expected Science Results
Crust/Upper Mantle	-Global crustal structure from gravity and topography	- Global crustal volume; extent of melting - Crustal density structure (radial and lateral) - Depth of excavation of major basins. - Subsurface highland and basin structure - Brecciation evolution and 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

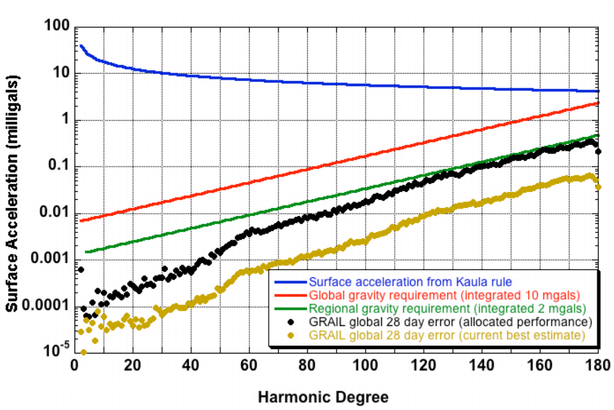

Figure 1. Error spectra from simulations illustrating margin between global (red) and regional (green) science requirements and the allocated (black) and current best estimate (gold) of GRAIL's performance. The blue line is the expected surface acceleration spectrum based on an empirical estimation of the power (Kaula's Rule) [5] of the Moon's gravitational field.

Figure 2. Completed GRAIL-A spacecraft bus.