COUPLING OF TIDAL FORCE WITH HETEROGENEOUS MANTLE STRUCTURE AND ITS IMPLICATIONS FOR USING GRAIL OBSERVATIONS TO CONSTRAIN LUNAR INTERIOR STRUCTURE. Shijie Zhong, Chuan Qin, Geruo A, and John Wahr, Department of Physics, University of Colorado at Boulder, Boulder, Colorado 80309, USA (szhong@colorado.edu).

Introduction: One of the main objectives of GRAIL mission is to constrain lunar interior structure and dynamics. A number of observations suggest that the lunar mantle and crust may have significant lateral variations in thermomechanical structures at long wavelengths. 1) Surface elevation is much higher on the farside than on the nearside, most likely reflecting a thicker crust on the farside [1]. 2) Mare basalts, the most important volcanism event in the lunar geological history, erupted predominantly on the nearside, while they are largely absent on the farside [2]. 3) Deep moonquakes (DMQ) are mostly located on the nearside at depths of ~800 km, although the nearside distribution of DMQ may be biased by the uneven distribution of Apollo seismic stations that are all on the nearside [3].

Crustal production and mare basalts volcanism reflected early (prior to 3.8 Ga) lunar mantle's thermochemical structures and dynamics. That is, the early lunar mantle may have been predominated by long-wavelength or hemispherically asymmetric structures that were responsible for the global asymmetry in crustal thickness variations and mare basalts distributions [4,5,6]. DMQ reveal deformation of present-day lunar mantle. Although DMQ are closely related to tidal forces [7], the mantle structure including heterogeneities and volatile distributions may also play an important role in giving rise to the spatial patterns in DMQ [8]. Recently, it was proposed that DMQ correlates with mare basalt distribution and that the present-day lunar mantle may still keep long-wavelength structure that was responsible for mare basalts genesis 3.8 Ga ago [9].

Recently launched GRAIL (Gravity Recovery and Interior Laboratory) satellites are designed to measure lunar gravity field at unprecedented accuracy with an ultimate goal of determine lunar interior structures [10]. Here we explore a possibility in using GRAIL observations to constrain lunar interior structures by determining gravity signals that are caused by tidal force applying to lunar mantle with lateral variations in elastic moduli. We suggest that GRAIL observations with their stated accuracy (<1% at long-wavelengths) may pose significant constraints on the extent of lateral variations of lunar interior structures that may help understand the dynamical evolution of the lunar mantle and guide future lunar missions.

Physical Model and Methods: Lunar tidal force is predominately at spherical harmonic degree 2 (e.g., l=2, m=0; and l=2 and m=2, where l and m are spherical harmonic degree and order) with characteristic periods [11]. When such a tidal force applies to a homogeneous or spherically symmetric planetary body, the response of the body must have the same spatial patterns at l=2 and corresponding m, as documented in the classical theory of elastodynamics, and the response is often expressed in terms of Love numbers (h and k for radial displacement and gravity, respectively) [12]. However, when lateral variations in elastic moduli (i.e., seismic wave speeds) exist in the planetary body, the response is no longer only at l=2, and the non-degree 2 gravity signals may emerge with amplitude that depends on the structure wavelengths and also the amplitude of the variations.

To determine the non-degree 2 responses, one must use either a perturbation theory [13] or numerical method to solve the deformation dynamics [14]. In this study, we use a finite element code CitcomSVE to compute the response [14]. This finite element method was originally designed for computing post-glacial rebound problems for Earth with 3-D viscoelastic structure [14,15]. For this study, we use the code to determine the elastic response of the Moon to degree-2 tidal force for a lunar mantle with degree-1 structure of different amplitudes.

Results and Discussions: We first compare the responses of gravity and radial displacement (i.e., Love numbers k and h) from CitcomSVE and classical theory for a homogeneous, incompressible lunar mantle and found an excellent agreement (<1%). Compressibility only has a small effect on our results. This benchmark calculation shows that our numerical method is accurate.

We then compute the response of the Moon with a lunar mantle that includes degree-1 variability in shear moduli μ. Such variations are expressed as a spherical harmonic function with l=1 and m=1, that best represents hemispheric variations. The amplitude of μ variations is a variable in the calculation. In practice, we express the variations in shear moduli μ as relative shear wave seismic speed variations dVs/Vs, knowing that $V_S = \sqrt{\mu / \rho}$, where ρ is the mantle density. Figure 1 shows that for tidal force at l=2 and m=0, the largest non-degree 2 response is at l=3 and m=1 and can be as large as 1% of l=2 response for dVs/Vs=~5%. The larger dVs/Vs, the larger degree 3 response is. The lateral variations also cause degree-2 Love numbers to change, but the relative change is <1% unless dVs/Vs reaches to ~20%. For tidal force at l=2 and m=2, the response at l=3 and m=3 becomes larger than that at l=3 and m=1 (not shown). Similarly, l=3 and m=3 response is >1% of l=2 response for dVs/Vs=~5%. We will also present calculations for a compressible mantle, but we expect similar results.

These calculations show that if seismic shear wave speed anomalies of ~5% exist in the lunar mantle at very long-wavelengths, GRAIL should be able to detect them by determining non-degree-2 tidal responses. In particular, these non-degree-2 responses, if caused by this particular physical mechanism, should have similar time dependence to the tidal force, thus giving them unique marks. On the Earth that has had a vigorous mantle convection, dVs/Vs>10% is found in the lithosphere and near CMB [16] and is often attributed to compositional anomalies or partial melting. GRAIL observations may provide unique constraints on lunar interior structures.

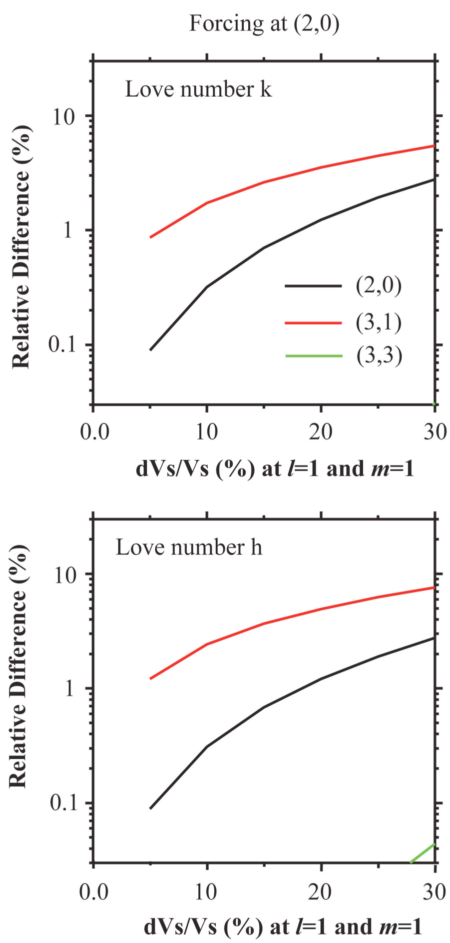

Figure 1. Tidal response at degrees 2 and 3 versus amplitude of l=1 and m=1 structure variations for tidal force at l=2 and m=0. The top and bottom panels are for gravity k and radial deformation h respectively.

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