GRAIL, LLR, and LOLA constraints on the interior structure of the Moon.

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Introduction: Planetary interior structure models suffer from an inherent non-uniqueness because there are more unknown model parameters than observational constraints. However, it is possible to constrain the likely range of interior structures using the available observational constraints. For the Moon, these constraints are derived from seismic, lunar laser ranging (LLR), magnetic, and gravity observations. The mean moment of inertia (MOI) is constrained by the combination of gravity and LLR observations [1], and the improved accuracy in the gravity data after the Gravity Recovery and Interior Laboratory (GRAIL) mission has reduced the MOI uncertainty significantly [2]. The Moon deforms in response to tidal forcing and this generates changes in topography and gravity that can be characterized by the tidal Love numbers. The amplitude of this deformation depends on the interior structure and therefore the tidal Love numbers provide additional interior structure constraints. The uncertainties in the tidal Love numbers were reduced significantly by analysis of GRAIL, LLR, and Lunar Orbiter Laser Altimeter (LOLA) data [2, 3, 4]. We infer the likely interior structures using Bayesian probability theory and the observed mass, mean solid MOI, and tidal Love numbers k_2 and h_2 as constraints.

Anelastic correction to the tidal Love numbers: The observed tidal Love numbers describe the lunar deformation at the tidal forcing frequency and contain both elastic and anelastic components. Therefore, the interior structure model must take into account the effects of anelasticity. However, evaluating both the elastic and anelastic components of the Love numbers requires specifying the viscosity of all the interior layers, which increases the number of interior structure parameters significantly. This in turn results in probability distributions that are significantly less resolved. Therefore, instead of calculating both the elastic and anelastic components of the Love numbers, we follow the approach of [5] and convert the observed Love numbers to elastic Love numbers.

Results: Interior structure parameters that affect the observed mass and mean solid MOI are generally better constrained because the uncertainties in these observational constraints are smaller than those of the elastic Love numbers by orders of magnitude. The mantle density is constrained to 3.36 ± 0.02 g cm^{-3} (uncertainties represent the 95% credible region), near the mean density of the Moon because the mantle occupies a large fraction of the total volume. The radius and density of the layer between the mantle and the liquid core are constrained to 490_{-117}^{+106} km and $3.7_{-0.3}^{+0.3}$ g cm^{-3}; the liquid core radius and density are constrained to 354_{-83}^{+112} km and $5.8_{-1.9}^{+1.7}$ g cm^{-3}; and the solid core radius is constrained to 187_{-182}^{+139} km.

The rigidities are constrained by the elastic Love numbers. The mantle rigidity is constrained to 66_{-5}^{+4} GPa with a strong preference for higher rigidities. The transition layer rigidity is weakly constrained with a preference for rigidities similar to that of the mantle. The elastic Love numbers decrease as the rigidity of any of the layers increases, and this dependence is large enough to provide a weak constraint on the transition layer rigidity.

The probability distributions of the solid core and crust rigidities are uniform, indicating that these interior structure parameters are not constrained by the elastic Love numbers. Although the elastic Love numbers decrease as the rigidity of these layers increases, this dependence is too weak to constrain the solid core and crust rigidities given the large uncertainties in the elastic Love numbers and the dependence on other parameters.

Conclusions: The observed mass and mean solid MOI provide the strongest constraints on the interior structure due to their small uncertainties relative to those of the elastic Love numbers. The elastic Love numbers provide constraints on the rigidities of the mantle and transition layer. Previous studies suggest the presence of a low rigidity ($\lesssim$ 30 GPa) transition layer between the liquid core and the mantle using the tidal Love numbers as constraints [5, 6, 7]. In contrast, we find a probability distribution that weakly constrains the rigidity of this layer and a slight preference for rigidities similar to that of the mantle (~ 70 GPa).

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