THE CORE OF THE MOON - MOLTEN OR SOLID?. A. Khan[1,3], K. Mosegaard[1], J. G. Williams[2], P. Lognonne[3], [1]*Niels Bohr Institute, University of Copenhagen, Denmark (amir@gfy.ku.dk)*, [2]*JPL, California Institute of Technology, Pasadena, California, USA*, [3]*DGSP, Institut de Physique du Globe de Paris, France*.

Introduction. While several studies beginning in the Apollo-era and continuing up to the present have tried to detect the lunar core, either geochemically, geophysically or geologically [e.g. 1, 2, 3, 4], it has so far proven somewhat elusive. The unambiguous detection of the lunar core is of prime importance as it holds the potential of distinguishing between the various theories for the formation of the Moon. The theory which currently enjoys the greatest success is the giant impact model, which has the Moon forming about 4.5 Gyr ago from the debris produced when a Mars-sized proto-planet collided with the proto-Earth [e.g. 5, 6]. Simulations reveal that the material from which the Moon is made up contains very little iron and consequently a lunar core, if it exists, should be small.

In a recent investigation of more than 30 years of lunar laser ranging (LLR) data, Wiiliams et al. [6] detected a displacement of the Moon's pole of rotation, indicating that dissipation is acting on the rotation. Two effects were proposed, one being due to solid-body tides raised by the Earth and the Sun and the other as stemming from a fluid core. Williams et al. found that in order to account for all dissipation terms a model including a liquid core had to be invoked. Using the approximate boundary layer theory of [7], maximum radii of 352 km for a liquid Fe core (ρ= 7.0 g/cm^3) and 374 km for a Fe-FeS eutectic (ρ=5.3 g/cm^3) were found, respectively. This argument that tides plus a fluid-core/solid-mantle interaction satisfactorily explain the lunar rotational dissipation data, is the main point put forward by Williams et al. in arguing for a present-day molten lunar core.

It is the purpose of the present paper to infer information about the deep interior of the Moon, not least to try to substantiate the existence of a liquid core, by inverting several geophysical observations obtained through LLR analysis and Doppler tracking of the Lunar Prospector spacecraft, specifically, the second degree tidal Love number, mass, moment of inertia and the tidal quality factor. Or paraphrased, the approach taken here, and detailed in [8], is to explore, in a quantitative manner, through a rigorous inversion, the implications of the solution parameters found by Williams et al. pertaining to lunar geophysics (notably k_2).

Method of Analysis. The inverse problem dealt with here of obtaining information on the lunar density and S-wave velocity profile from the four numbers follows our earlier investigations by employing an inverse Monte Carlo sampling method (see [8] for details). The basic question that we want to answer here, is the following

- how likely is it, given the observed data, their uncertainties as well as prior information, that the Moon has a molten, partially molten or solid Fe, Fe-S alloy or dense silicate core (the latter may contain elevated Fe and Ti abundances)?

Our model of the Moon is divided into 5 spherically symmetric shells. Each of these shells is physically described by the following set of parameters, density, bulk and shear moduli, local dissipation and layer thickness. In wanting to answer the above question, certain conditions are imposed on some parameters, notably the shear modulus in the innermost layer (taken to be the core). As the shear modulus is the parameter that physically distinguishes between solid and liquid material, it can only vary within certain intervals, which in terms of S-wave velocity translates into $v_S \in [0; 0.5]$ km/s (liquid core) and $v_S > 3.5$ km/s (solid core). In sampling the density profile, the assumption is also made that it increases as a function of depth. Apart from this, prior information concerning the remaining parameters is in the form of broad homogeneous probability density distributions (ppd's), reflecting the fact that little is assumed known about the interior of the Moon. We use Bayesian hypothesis testing in the form of the Bayes factor to evaluate, in the light of the data and the prior information chosen, which scenario, i.e. whether the core is solid or liquid, is the most likely. Bayesian hypothesis testing concerns itself with having to distinguish between competing hypotheses given data and prior information, such as is the lunar core molten (hypothesis i) or solid (hypothesis j)? The two hypotheses obviously correspond to different areas of the model space, M_i and M_j, respectively. If $\{\mathbf{m}_1, \mathbf{m}_2, \ldots, \mathbf{m}_k\}$ is a sample from M_i of $L(\mathbf{m})$ containing k points, and $\{\hat{\mathbf{m}}_1, \hat{\mathbf{m}}_2, \ldots, \hat{\mathbf{m}}_\ell\}$ is a sample from M_j of $L(\mathbf{m})$ containing ℓ points ($L(\mathbf{m})$ are integrated likelihoods, i.e. $L(\mathbf{m}) = \int_M L(\mathbf{m})d\mathbf{m}$), then the Bayes factor can be estimated using the expression

$$B_{\ell k} = \frac{\frac{1}{k}\sum_{r=1}^{k} \frac{1}{L(\mathbf{m}_r)}}{\frac{1}{\ell}\sum_{s=1}^{\ell} \frac{1}{L(\hat{\mathbf{m}}_s)}}$$

Consequently, the interpretation of the Bayes factor is such that if $B_{\ell k} > 1$, hypothesis j is relatively more plausible given $\mathbf{d}$; if, on the other hand, $B_{\ell k} < 1$, then hypothesis i has increased in relative plausibility. On a more technical note it just means running separate algorithms corresponding to the different hypotheses of interest and then using all the samples from these runs to evaluate the Bayes factor as given in the expression above.

Results. The Bayes factor was found to be B_{ij}=0.00014 and as B_{ij} <1, it signifies that hypothesis i is more plausible than hypothesis j or in words, that given data and prior information, a liquid core is more probable than a solid core. Our results are shown below in the form of posterior 2D marginals, showing cross correlations between several parameters. These figures highlight most probable state, size and density of the individual layers making up the Moon. From figure 1 it can be seen that there exists a high probability for a core with a radius of around 350 km and density ~7.2 g/cm^3. Other possibilites are of course also possible, most notably there seems to be a large probability for a core with a density of ∼6 g/cm^3 and radius around 400 km, although it has to be noted that the peak is much narrower and not as high as the other one. From figure 2 depicting the correlation between shear wave velocity and core radius, a notable spike is apparent at about r=350 km and v_s very close to zero. Figure 3 examines the correlation between the shear wave velocity and density in the individual layers and these indicate with a high probability a core with a density around 7.2 g/cm^3 and v_s close to zero as consistently inferred hitherto.

In conclusion, the most likely outcome of our study, based on the data, their uncertainties and prior information, is a central core with a most probable S-wave velocity close to 0 km/s, density of ∼7.2 g/cm^3 and radius of about 350 km. This is interpreted as implying the presence of a molten or partially molten Fe-core, in line with evidence presented earlier using LLR regarding the dissipation within the Moon.

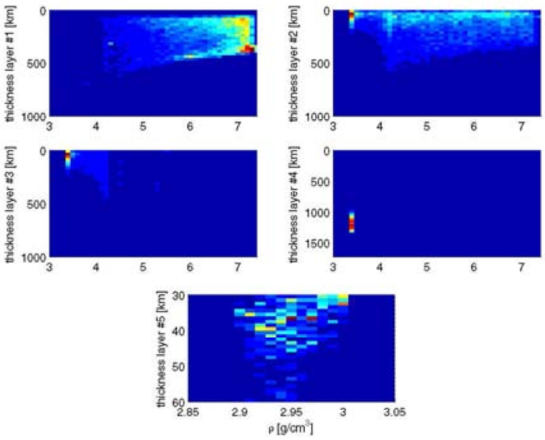

Figure 1: 2D posterior probability density showing the correlation between density and thickness for each individual layer. Layer #1 corresponds to the core and layer #5 to the crust. Colours indicate probability, with dark red signifying the most probable and dark blue the least probable solution. A significant amount of probability centered at a core radius of ∼350 km and density ∼7.2 g/cm^3 is apparent. Another possibility, although less probable, is also visible at a radius ∼400 km and density of ∼6 g/cm^3.

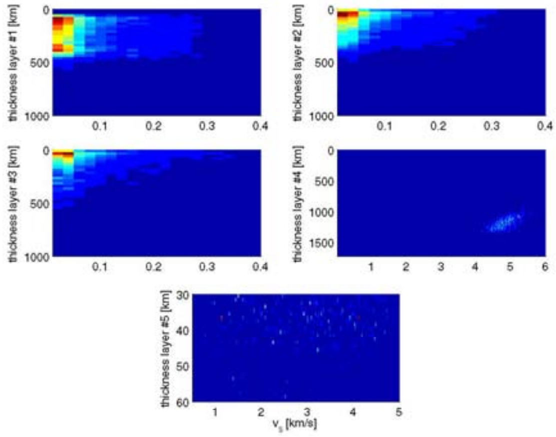

Figure 2: 2D posterior probability distribution showing the correlation that exists between the parameters v_S and thickness for each individual layer. Layer #1 corresponds to the core and layer #5 to the crust. Colour coding as in figure 1. A solution at a radius of ∼350 km and v_s close to 0 km/s is indicated.

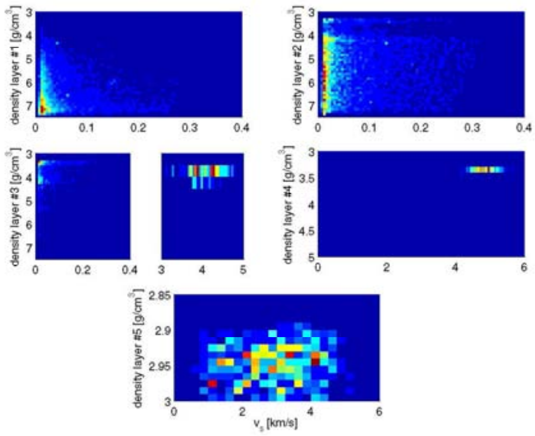

Figure 3: 2D posterior probability distribution showing the correlation that exists between the parameters v_s and density for each individual layer. Layer #1 corresponds to the core and layer #5 to the crust. Colour coding as in figure 1. A solution with a large probability at a density of ∼7.2 g/cm^3 and v_s close to 0 km/s is apparent.

References. [1] C. T. Russell et al., *Proc. Lunar Planet. Sci. Conf. XII*, 831, 1981. [2] K. Righter, *Icarus*, 158, 1, 2002. [3] L. L. Hood, *Geophys. Res. Lett.*, 26, 2327, 1999. [4] J. G. Williams et al., *J. Geophys. Res.*, 106, 27933, 2001. [5] A. G. W. Cameron, in *Origin of the Earth and Moon*, Univ. Arizona Press, Tucson, 2000. [6] R. M. Canup, *Icarus*, 168, 433, 2004. [7] C. F. Yoder, *Icarus*, 117, 250, 1995. [8] A. Khan et al., *J. Geophys. Res.*, 109, E09007, doi:10.1029/2004JE002294.