CONSTRAINING THE COMPOSITION AND THERMAL STATE OF THE MOON FROM AN INVERSION OF ELECTROMAGNETIC LUNAR DAY-SIDE TRANSFER FUNCTIONS. A. Khan[1], J. A. D. Connolly[2], N. Olsen[3], K. Mosegaard[1], [1]*Niels Bohr Institute, University of Copenhagen, Denmark (amir@gfy.ku.dk)*, [2]*Earth Sciences Department, Swiss Federal Institute of Technology*, [3]*Danish National Space Centre, Copenhagen, Denmark.*

Introduction. Constraining the present-day lunar thermal state is important as it holds the potential of providing valuable information on lunar origin and evolution. Moreover, temperature is a fundamental parameter in understanding the dynamic behaviour of the mantle in that it governs properties such as viscosity, density, convection, melting and electrical conductivity. However, there are presently few data available that directly constrain lunar thermal state and most of these provide only indirect constraints and include surface heat flow measurements [1], seismic Q-values inferred from the Apollo lunar seismic data [2] and maintenance of mascon anisostasy over a period of 3-4 b.y. [3]. Several theoretically predicted selenotherms have been disseminated over the years [e.g. 4-8] and show considerable scatter, due to the different prior assumptions that are usually a prerequisite in thermal modeling.

A method that, in principle, can be used to put limits on the present-day lunar temperature profile involves the use of electromagnetic sounding data, which, when inverted provide knowledge on the conductivity profile of the lunar interior [9]. As mineral conductivity measured in the laboratory has been found to depend inversely on temperature, limits on the selenotherm can be derived from the inferred bounds on the lunar electrical conductivity profile when combined with laboratory measurements of electrical conductivity as a function of temperature. Attempts along these lines have previously been undertaken [10,11], but were limited because of, among other things, uncertainty in bulk lunar composition and inverted electrical conductivity structure.

Purpose. Building upon earlier as well as recent laboratory measurements of mineral electrical conductivities [e.g. 12-14] our intent here is to invert measurements of the lunar inductive response to time-varying external magnetic fields during intervals when the Moon was in the solar wind or terrestrial magnetosheath in order to constrain the lunar thermal state and bulk chemical composition. Details are specified in [15]. Briefly, given the Moon's temperature profile and composition, equilibrium mineral modes and physical properties can be calculated by thermodynamic methods. When combined with laboratory electrical conductivity measurements and appropriate mixing laws, the bulk electrical conductivity of the Moon can be estimated. From a knowledge of the bulk conductivity the geomagnetic response at the lunar surface or in space can be evaluated. Whereas previous studies assumed both mineralogy, and hence compositon, and temperature as known *a priori*, our unknowns are composition and temperature, determining all other parameters.

The inverse method presented here is general and provides through the unified description of phase equilibria a way of constructing planetary models where the radial variation of mineralogy and density with pressure and temperature is naturally specified, permitting a direct inversion for chemical composition and temperature. Given these parameters mineralogy, Mg# (MgO/(MgO+FeO)$\times$100) and bulk physical properties are calculated.

Method of Analysis. We assume a spherically symmetric model of the Moon, which is divided into three layers whose thicknesses are variable. The three layers correspond to crust, mantle and core. The two outermost shells are described by the model parameters: thickness d, composition c and temperature T. The physical properties of the core are specified by the model parameters: size, density and electrical conductivity. The temperature T is defined at six fixed radial nodes. To determine the mineralogical structure and corresponding mass density it is also necessary to specify the pressure profile in addition to composition and temperature.

Crust and mantle compositions were allowed to vary within the system CaO-FeO-MgO-Al_2O_3-SiO_2 (hereafter abbreviated CFMAS). The lunar mineralogy is assumed to be dictated by equilibrium and is computed together with mineral densities from thermodynamic data for a given model pressure, temperature and bulk composition by Gibbs free energy minimization [16] from which physical properties are calculated using technicques as described in [17]. The equilibrium mineral modes are then combined with laboratory electrical conductivity measurements for the appropriate minerals to compute a bulk conductivity profile.

As laboratory measurements [10,18] have suggested that mineral electrical conductivity is influenced by composition, we augmented the well-established conductivity-temperature relationship by also considering a conductivity-compositional dependence. In particular, using first-order models to incorporate this dependence, we considered the electrical conductivity of olivine and orthopyroxene as functions of Fe content and Al content, respectively (details are given in [15]).

We invoke a Markov chain Monte Carlo (MCMC) sampling algorithm to solve the problem, which is formulated within a Bayesian framework, that is, through the extensive use of probability density functions (*pdf*'s) to delineate every item of information, as laid out by [19]. The solution to the inverse problem is defined as the conjunction of these *pdf*'s and contained in the posterior *pdf* [20].

Results. *Bulk composition and Mg#.* Bulk sampled compositions and Mg#s for the silicate part of the Moon are displayed in the histograms in Figure 1. In support of our results, we observe that independent inversion of the Apollo lunar seismic data set [21], employing similar methods as here, yields bulk lunar compositions that are largely consistent with those presently obtained. These results have strong implications for lunar origin as they indicate a silicate Moon with a composition different to that of the Earth's upper mantle, represented by the pyrolite composition [22]. This can be construed as implying that the Moon was derived from a provenance other than the Earth's upper mantle and as such is in agreement with recent giant impact models where >80% of the mass of the Moon stems from the impactor rather than from the terrestrial mantle [23].

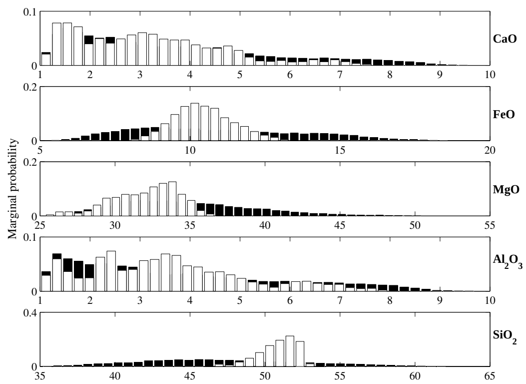

Figure 1: *Sampled mantle compositions. White and black bars denote prior and posterior probability distributions, respectively.*

Temperature. Temperature models are shown in Figure 2 using 1D marginal prior and posterior probability density functions.

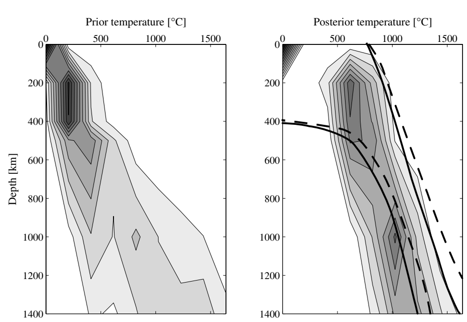

Figure 2: *Sampled prior and posterior thermal profiles. The contours directly reflect the probability of occurence of a certain temperature at a given depth, with white corresponding to least probable and black to most probable. Solid lines indicate the temperature bounds obtained previously [11] using pyroxenes containing 6.8 wt% Al2O$_3$ and dashed lines are for pyroxenes with 1.9 wt% Al2O$_3$.*

The posterior marginals (figure 2b) for T are seen to be significantly narrowed in comparison to the prior marginals (figure 2a), signaling that inversion of the data considered here are able to provide information on not only composition, but also thermal state. Our thermal profiles are broadly in agreement with previous work [10,11].

Bulk physical properties. Bulk physical properties, in the form of density and conductivity profiles are shown in Figures 3 and 4. Again, when compared to previous investigations of lunar electrical conductivity and density structure [10, 24] our results are in overall agreement.

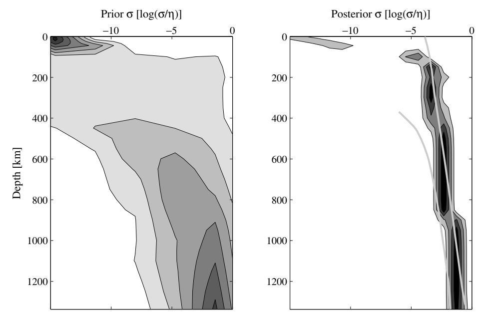

Figure 3: *Sampled prior and posterior conductivity models. Shades of gray as in figure 2. Solid gray lines indicate earlier derived bounds on conductivity [11].*

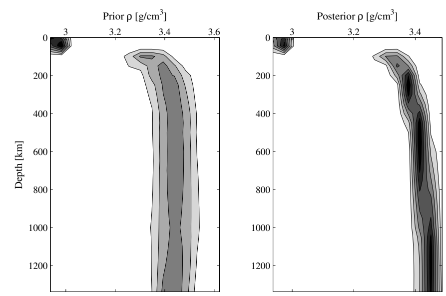

Figure 4: *Sampled prior and posterior density models. Shades of gray as in figure 2.*

References. [1] M. G. Langseth et al., *Proc. Lunar Planet. Sci. Conf. 7th*, 3143, 1976. [2] Y. Nakamura & J. Koyama, *J. Geophys. Res.*, 87, 4855, 1982. [3] S. Pullan & K. Lambeck, *Proc. Lunar Planet. Sci. Conf. 11th*, 2031, 1980. [4] M. N. Toksöz & S. C. Solomon, *Moon*, 7, 251, 1973. [5] G. Schubert et al., *Phil. Trans. R. Soc. Lond. A.*, 285, 523, 1977. [6] M. N. Toksöz et al., *Moon Planets*, 18, 281, 1978. [7] A. B. Binder & M. Lange, *J. Geophys. Res.*, 85, 3194, 1980. [8] T. Spohn et al., *Icarus*, 149, 54, 2000. [9] L. L. Hood et al., *J. Geophys. Res.*, 87, 5311, 1982a. [10] J. S. Huebner et al., *J. Geophys. Res.*, 84, 4652, 1979. [11] L. L. Hood & C. P. Sonett, *Geophys. Res. Lett.*, 9, 37, 1982. [12] T. J. Shankland & A. Duba, *Geophys. J. Int.*, 103, 25, 1990. [13] Y. Xu & T. J. Shankland, *Geophys. Res. Lett.*, 26, 2645, 1999. [14] Y. Xu et al., *Phys. Earth Planet. Inter.*, 118, 149, 2000a. [15] A. Khan et al., *Earth Planet. Sci. Lett.*, 248, 2006. [16] J. A. D. Connolly, *Earth Planet. Sci. Lett.*, in press, 2005. [17] J. A. D. Connolly & D. Kerrick, *Earth Planet. Sci. Lett.*, 204, 61, 2002. [18] Y. Xu et al., Science, 282, 922, 1998. [19] A. Tarantola & B. Valette, *J. Geophys. Res.*, 50, 159, 1982. [20] K. Mosegaard & A. Tarantola, *J. Geophys. Res.*, 100, 12431, 1995. [21] A. Khan et al., *Geophys. J. Int.*, in press, 2006. [22] W. McDonough & S. S. Sun, *Chem. Geol., 120*, (3-4), 223, 1995. [23] R. Canup, *Icarus*, 168, 433, 2004. [24] O. Kuskov et al., *Phys. Earth Planet. Int.*, 134, 175, 2002.