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The interior of the Moon: Thermodynamics vs seismology

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1. Introduction

This study is motivated by the availability of improved models of the seismic structure of the deep interior based on both *P* and *S* velocity models. Temperature is not modeled directly. To place constraints on the temperature distribution in the lunar mantle, we invert the Apollo P- and S-wave velocity models [1-4], making various assumptions regarding the lunar mantle composition.

2. Thermodynamic approach

The phase composition and physical properties of the mantle were modeled within the Na_2O-TiO_2-CaO-FeO-MgO-Al_2O_3-SiO_2 system. For the computation of phase equilibrium relations, we have used a method of minimization of the total Gibbs free energy [5]. Our forward and inverse calculations include anharmonic and anelastic parameters [6].

3. Results

T_P and T_S inverted from the *P*- and *S*-wave velocity models for a Ca–Al-depleted Ol-bearing pyroxenite composition are shown in Figs. 1a,b and for a Ca–Al-enriched pyrolite composition in Figs. 1c,d (Table 1). At 50-100 km depth, $T_{P,S}$ for the pyrolite composition vary between ~700-1300°C; this is clearly unrealistic for the real rigid Moon. The T_P and T_S values calculated from G11 agree with those from L05 and GB06 models only at depths greater than 200 km.

Table 1. Bulk composition models (wt%) of the lunar mantle in the NaTiCFMAS system

Composition	1	2	3	4
MgO	32.0	37.58	34.1	37.0
FeO	11.6	8.48	10.05	12.8
Al_2O_3	2.25	4.50	6.4	2.6
CaO	1.8	3.64	5.1	2.5
SiO_2	52.0	45.25	44.0	45.1
Na_2O	0.05	0.34	0.05	0.0
TiO_2	0.3	0.21	0.3	0.0
Mg#	83.0	88.8	85.8	82-83

1- Olivine pyroxenite [6], 2 - pyrolite [6], 3 -Ol-Cpx-Gar [6], 4 - homogeneous composition [7]

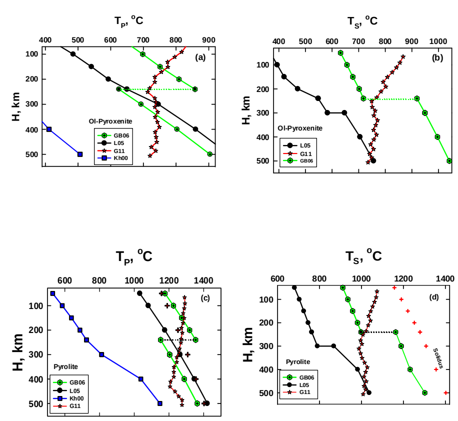

Figure 1. Comparison of the temperature profiles for the upper mantle of the Moon derived from the recent velocity estimates GB06 [1], Kh00 [2], L05 [3], G11 [4] for the Ol-pyroxenite and pyrolite compositions from Table 1. Crosses denote the peridotite solidus.

Our seismically derived temperature models (Fig. 2) are much colder than temperatures found by Keihm and Langseth [8]. We get the upper mantle heat flow value of 3.6

mW/m^2, which is not consistent with heat fluxes in the range of 7-13 mW/m^2 [8].

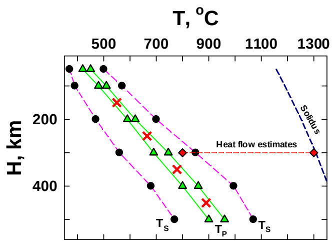

Figure 2. Upper mantle $T_{P,S}$ for the Ol-bearing pyroxenite inferred from the mean P-, S-wave velocity models. Crosses correspond to the optimal mantle temperature [6]. The range of temperatures at 300 km depth estimated in [8] is marked by the diamonds.

Temperatures calculated from the very preliminary reference Moon model of Garcia et al. [4] for four different compositions are shown in Fig. 3. Very high temperatures (800-1300^{o}C) immediately below the crust are not consistent with the rigid lunar mantle. Furthermore, the large discrepancy between T_P and T_S may be attributed to an inconsistency between *P*- and *S*-velocities.

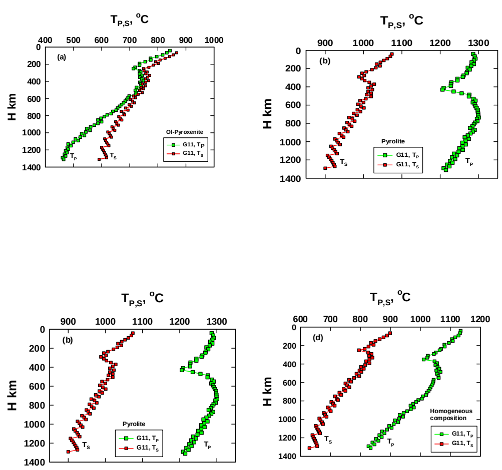

Figure 3. Comparison of *T* estimates for different compositions (Table 1) from the Moon model of Garcia et al. [4]. (a) - Ol-pyroxenite; (b) – pyrolite. (c) – Ol-Cpx-Gar, (d) - homogeneous mantle composition [7].

4. Conclusions

(1) The results lend support to a chemically stratified lunar mantle with a change in composition from a dominantly pyroxenite upper mantle depleted in Ca and Al (~2 wt% CaO and Al_2O_3) to a dominantly fertile lower mantle enriched in Ca and Al (~4-6 wt% CaO and Al_2O_3) with larger amounts of olivine, clinopyroxene and garnet.
(2) Disagreement between T_P and T_S can be attributed to inconsistency in the absolute velocities of seismic models.
(3) Compositional effects play a dominant role in determining the lunar temperatures from seismic models.
(4) Upper mantle heat flow is not consistent with that found in [8].

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