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Constraining the composition, core sizes and thermal state of the Moon for the models of the magma ocean

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1. Introduction

The composition of the mantle and the bulk Moon, though the subject of intense geochemical interest, remains largely a mystery. The Moon and the Earth have similarity in oxygen and chromium isotopes and distinctly different siderophile element patterns. Area of controversy includes suggestions that the lunar mantle is enriched in FeO and refractory elements (Al, Ca). Some investigators believe that the lunar mantle is enriched in FeO and refractory elements (Al, Ca); others suggest that the lunar mantle is enriched in FeO by a factor 1.2-1.5, but not enriched in refractories. In spite of the limited amount of information and appreciable divergence of seismic data, a few studies have used the totality of the available geophysical data to constrain the composition and temperature of the lunar interior [1-6]. In the present work, we suggest a new model of constitution and internal structure of the Moon. This model is based on the hypothesis of chemical differentiation of the Moon as a result of partial melting of initially homogeneous material (hypothetical magma ocean); it involves modern mathematical processing of the P - and S-velocities [1, 6].

2. Computer simulation and result

The mass, moment-of-inertia factor, seismic velocities and the hypothesis of magma ocean are used to model the internal structure of the Moon. We consider here a five-layer model of the internal structure of the Moon, including a silicate crust (H=40-50 km, ρ=2.9-3.1 g cm^{-3}), a three-layer mantle at depths of 40-50 - 250 km (upper mantle), 250 - 625-750 km (middle mantle), 625-750 km - core-mantle boundary (lower mantle), and a Fe–10 wt.% S-core (ρ=5.7 g cm^{-3}). The chemical composition of the lower (undifferentiated) mantle, which is not affected by melting, is assumed to be similar to the average composition of the overlying lunar shells and to reflect the bulk composition of the silicate portion of the Moon. Crust model is adopted from Taylor (1982). Thermodynamic modeling of phase relations and physical properties in the multicomponent mineral system CaO-FeO-MgO-Al_2O_3-SiO_2 was used to develop a method for solving the inverse problem. The concentrations of major oxides for the entire mantle varied in the ranges 2 ≤ CaO and Al_2O_3 ≤ 8%, 25 ≤ MgO ≤ 45%, 40 ≤ SiO_2 ≤ 54%, 6 ≤ FeO ≤ 20%. A Monte-Carlo inversion procedure has been used to estimate the distributions of the density, composition and velocities in the mantle and Fe-FeS core radii. We use the method of the Gibbs free energy minimization adapted to calculations of phase equilibria in multisystems with phases of variable composition representing multicomponent solid solutions of minerals. The equations of state of minerals are calculated in the Mie-Grüneisen-Debye quasiharmonic approximation, with the Born–Mayer potential approximating the equation of state potential part. Equilibrium compositions of phase assemblages, elastic wave velocities, and density were calculated with the use of the THERMOSEISM software complex [3]

3. Summary and Conclusions

The bulk composition, the size of a core, and the concentrations of main oxides in the models of the Moon depend on the constraints imposed on the sought solution. We investigate the following lunar models:

1. Models constrained by the mass, moment of inertia, and seismic velocities in the upper and middle mantle.
2. Models constrained by the mass, moment of inertia, seismic velocity, and oxide concentrations in the upper and middle mantle.
3. Models constrained by the mass and moment of inertia.

4. Models constrained by the mass, moment of inertia and seismic velocities in the upper, middle and lower mantle. The temperature for the entire mantle varied in the ranges: $450^{o}C \leq T \leq 750^{o}C$ at a depth of 150 km, $750\,^{o}C \leq T \leq 1200\,^{o}C$ at 500 km, $950\,^{o}C \leq T \leq 1400\,^{o}C$ at 1000 km.

Temperature distributions for models (1, 2, 3) were taken from [4, 5].

Having solved the inverse problem, we obtain a range of models, which meet all the conditions stated. The distributions of density, concentrations and velocities are found for all mantle zones and the radius of the Fe-10%S core is estimated. The major results of our investigations are following:

1. The constitution of the Moon, which has been initially homogeneous and then experienced differentiation due to partial melting, is studied by numerical modeling. The mineral composition and physical properties of the lunar mantle are reconstructed by the Monte-Carlo inversion of the gravity and seismic constraints. The phase composition and the physical parameters of the mantle are calculated using the method of the Gibbs free energy minimization and the equations of state for the mantle material in the system CaO-FeO-MgO-Al_2O_3-SiO_2. The models of the Moon with different degree of constraints on the desired solution are considered. In all models, the geophysically and geochemically permissible distributions of seismic velocities and chemical concentrations are determined for three mantle zones, and the radius of the Fe-10%S core is estimated. The effects in the solution, which are caused by the variations in the main input parameters of the models, are evaluated.
2. Based on the analysis of the models only constrained by the moment and the mass of the Moon, it has been shown qualitatively that the internal structure of the Moon is radially symmetric. Moreover, the seismic models and the zonal structure of the lunar interiors, which have been inferred from the local observations at the Apollo landing sites, apply for the entire Moon as well.
3. The main parameters of the crust, mantle and core are estimated. The crustal density is likely 2.9 g/cm^3, the crustal thickness is 50 km, and the radius of Fe-10%S core is 340 ± 30 km. The chemical boundary between the middle and the lower mantle is identified at a depth of 620-750 km. It is shown that the models of the Moon with and without a chemical boundary at a depth of 250-300 km are both possible. The seismic velocities at a depth of the lower mantle fall within the intervals $7.88 < V_P < 8.10$ km/s and $4.40 < V_S < 4.55$ km/s.
4. Our results indicate that the mantle composition of the Moon is different from that of the Earth's upper mantle. The mantle of the Moon is chemically stratified, and the concentrations of FeO, Al_2O_3 and CaO in the different zones of the mantle are different. The silicate portion of the Moon (crust + mantle) probably contains 3.5-5.5% Al_2O_3 and 10.5-12.5% FeO.
5. Temperature effects play a dominant role in determining the composition from seismic models.

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