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Thermochemical and magmatic evolution of a heterogeneous lunar mantle

Brian Doherty (1,2), Ana-Catalina Plesa (1), Sabrina Schwinger (1), Doris Breuer (1)
(1) German Aerospace Center (DLR), Berlin, Germany (brian.doherty@dlr.de) , (2) Freie Universität Berlin, Germany

Abstract

We model the thermo-chemical evolution of the Moon as a 3480 km diameter sphere with 780 km diameter iron core using the mantle convection code Gaia with a 2D quarter cylinder geometry. Our models start with a layered compositional structure as a result of the fractional crystallization of the lunar magma ocean (LMO). Post-crystallization temperature and density distribution in the mantle are calculated with alphaMELTs, and are used as initial conditions in our models. Additionally, depletion of components will be calculated and traced within the mantle and minimum melt estimates obtained. Our models investigate the dynamics of the heterogeneous lunar mantle for up to 1 billion years after the solidification of the LMO.

1. Introduction

The early stages of lunar evolution have been characterized by the cooling and crystallization of a liquid magma ocean. The fractional solidification of the magma ocean led to the formation of an unstably stratified interior, which can largely affect the subsequent thermo-chemical evolution of the Moon [1].

Previous studies have mostly focused on the overturn of a high-density ilmenite-bearing cumulates layer (IBC), which upon magma ocean solidifaction is initially situated close to the surface [1, 2]. In this study, we investigate the first Gyr of the lunar thermo-chemical history by taking into account the initial layering and the associated temperature distribution produced by the fractional crystallization of the LMO.

2. Initial Conditions

The structure of the mantle is initialized as seen in Fig. (1), with a variation in density across the layers. We employ an initial temperature profile, as seen in Fig. (2), which is consistent with the initial interior layering.

We trace each individual mantle component (i.e., Opx, Ol, IBC and Cpx) together with its corresponding solidus and liquidus temperatures. By computing and tracing the depletion due to melting of each mineral, we update the initial solidi and liquidi at each time step of our simulation and calculate minimum melt estimates.

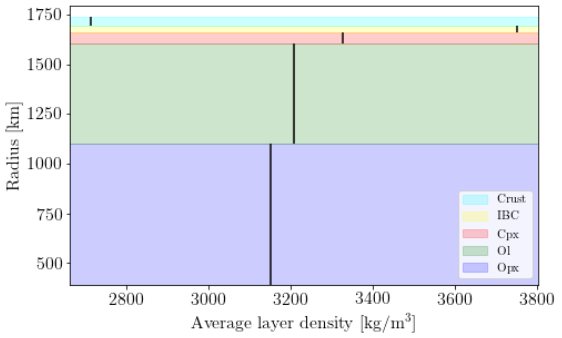

Figure 1: Initial compositional layering scheme with average density values calculated for each component layer [3].

3. Model

The thermo-chemical evolution of the lunar mantle is modelled using the convection code GAIA [4], using a 2D geometry and for a quarter cylinder domain. Convection problems are solved using conservation of mass, momentum, energy and composition equations, which in non-dimensional form read:

$$\nabla \cdot u = 0 \tag{1}$$

$$\nabla \cdot [\eta(\nabla u + (\nabla u)^T])] + (RaT - Ra_C C)e_r - \nabla p = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + u \cdot \nabla T - \nabla^2 T - \frac{Ra_Q}{Ra} = 0 \tag{3}$$

$$\frac{\partial C}{\partial t} + u \cdot \nabla C = 0 \tag{4}$$

where u is the velocity, η the viscosity, T is the temperature, Ra and Ra_C are the Rayleigh numbers associated with thermal and compositional buoyancy, p is the

dynamic pressure, t is the time, RaQ is the Rayleigh number associated with internal heating due to radioactive elements. The Boussinesq approximation is assumed and all equations are non-dimensionalised, as in [5].

The temperature and depth-dependent viscosity is calculated with an Arrhenius law for diffusion creep.

Mantle parameters used in this study are similar to the ones adopted by [6], in exception to radioactive heat sources, where a laterally homogeneous setup was used. In addition, we include compositional effects due the crystallization of the LMO, which is consistent with the initial temperature profile shown in Fig. (2). Core cooling and radioactive decay are taken into account as appropriate for thermal evolution modeling.

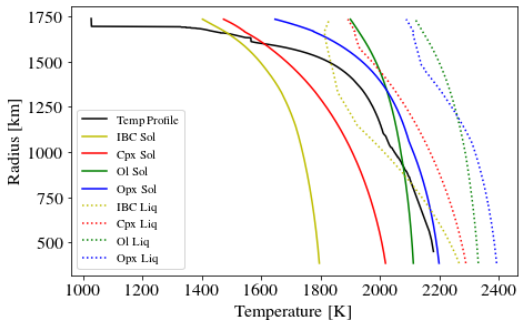

Figure 2: Initial temperature, solidus and liquidus profiles used in simulations. Based on data calculated with the alphaMELTs software [7].

Each component has its own density and solidus and liquidus temperatures. Using a particle-in-cell (PIC) method, as in [8] we trace the advection of each component. Here, 25 particles are initialized into each cell of the GAIA grid. At each timestep particles are advected, using a fourth order Runge-Kutta method and particle values are re-interpolated from the cell center value using an inverse distance weight. This method is suitable as it is less susceptible to numerical diffusion compared to grid-based methods. In our models we will vary the thickness and corresponding $\Delta\rho$ of the IBC layer between $\sim$ 15 km and $\sim$ 40 km.

We compute melt fractions for each component using:

$$\phi_i = \frac{T - T_{sol,i}}{T_{liq,i} - T_{sol,i}}, \tag{5}$$

where $T_{sol,i}$ and $T_{liq,i}$ are the solidus and liquidus for each mineral. In a further set of simulations, the latent heat of melting will be taken into account, as done by [9]. The depletion of components, as melting occurs, will then be traced for 1 Gyr of evolution, with the aforementioned PIC method and used to update the initial solidi and liquidi at each timestep during the simulation, with:

$$T_{sol,i}^{n+1} = T_{sol,i}^{init} + \phi_i^n \Delta T_i, \tag{6}$$

$T_{sol,i}^{init}$ is the initial solidus temperature and ΔT_i is the difference between the initial solidus and liquidus. The melt fraction, ϕ_i, is limited between 0 and 1. Additionally at each timestep, the simulation temperature is set back to the lowest solidus temperature of any component not fully depleted, if it rises above it.

4. Summary and Outlook

With this model we will investigate the thermochemical evolution of a heterogeneous lunar mantle for the 1 Gyr post magma ocean crystallization. Our model accounts for individual component melting and appropriate initial mantle conditions after the LMO solidification. Moreover, the effects of various IBC layer thicknesses and associated densities will be considered.

Melt estimates calculated using this model will produce a minimum estimate, as eutectic melting is not considered. In the next stages, a more detailed approach to calculating solidi and liquidi temperatures could be used to yield maximum melt estimates. Furthermore, these simulations will be used as a basis for including additional compositional heterogeneities due to melting of the mantle produced by large-scale impacts.

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