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Early thermal history of Rhea: the role of serpentinization and liquid state convection

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Intorduction:

Thermal history of Rhea from the beginning of accretion is investigated. The numerical model of convection combined with the parameterized theory is developed. Melting of the satellite's matter, gravitational differentiation and serpentinization of silicates are included. The role of the following parameters of the model is investigated: time of beginning of accretion, duration of accretion, viscosity of ice close to the melting point, activation energy in the formula for viscosity E, thermal conductivity of silicate component, ammonia content X, and energy of serpentinization.

1. Numerical model: In our calculations we use numerical model developed by Czechowski (2012) (see e.g. description in [1]). The model is based on parameterized theory of convection combined with 1-dimensional equation of the heat transfer in spherical coordinates:

$$\rho c_p \frac{\partial T(r,t)}{\partial t} = \mathrm{div}(k(r,T)\ \mathrm{grad}T(r,t)) + Q(r,T),$$

where r is the radial distance (spherical coordinate), ρ is the density [kg m^{-3}], c_p [J kg^{1} K^{-1}] is the specific heat, Q [W kg^{-1}] is the heating rate, and k[W m^{-1} K^{-1}] is the thermal conductivity. $Q(r,t)$ includes sources and sinks of the heat. The equation is solved in time dependent region [0, R(t)]. During accretion the radius $R(t)$ increases in time according to formula: $R(t) = at$for t_{ini}<$t <\quad t_{ac}$, and $R(t) = R_{sat}$ for $t >\quad t_{ac}$, i.e. after the accretion (see e.g. [2]), where t_{ini}denotes beginning of accretion and t_{ac} denotes duration of this process.

If the Rayleigh number in the considered layer exceeds its critical value *Ra*$_{cr}$ then convection starts. It leads to effective heat transfer. The full description of convection is given by a velocity field and temperature distribution. However, we are interested in convection as a process of heat transport only. For solid state convection (SSC) heat transport can be described by dimensionless Nusselt number *Nu*. We use the following definition of the *Nu:*

Nu= (True total surface heat flow)/(Total heat flow without convection).

The heat transport by SSC is modelled simply by multiplying the coefficient of the heat conduction in the considered layer, i.e.:

k_{conv} =*Nu k*.

This approach is used successfully in parameterized theory of convection for SSC in the Earth and other planets (e.g. [3], [4]).

Parameterization of liquid state convection (LSC) is even simpler. *Ra* in molten region is very high (usually higher than 10^{16}). The LSC could be very intensive resulting in almost adiabatic temperature gradient given by:

$$\frac{dT}{dr} = \frac{g\alpha_m T}{c_{pm}},$$

where α_m and c_{pm} are thermal expansion coefficient and specific heat in molten region, g is the local gravity. In Enceladus and Mimas the adiabatic gradient is low and therefore LSC region is almost isothermal.

2. Results:

1. We found that time of beginning of accretion and duration of accretion are crucial for early evolution, especially for differentiation.

2. Viscosity of ice close to melting point, activation energy in formula for viscosity E, and ammonia content X are very important for evolution, but not dramatic differences are found if realistic values are considered.

3. The energy of serpentinization is important for evolution, but its role is also not dominant.

4. LSC operating in molten part could delay the differentiation and the core formation for a few hundreds Myr.

5. The gravity data could be interpreted that Rhea is fully differentiated only if its core has high porosity and low density $\sim$1300 kg m^{-3}. In fact, there is not mechanism that could remove the water from molten core and the core of Rhea is probably porous.

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