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On the onset of convection and differentiation in the hydrated cores of icy moons

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Abstract

We will present new simulations of the thermal evolution, dehydration process, differentiation, and onset of convection in the hydrated cores of large icy satellites. The motivation is to investigate whether convection can start before dehydration starts in the cores. Such a process would prevent differentiation. The viscosity of antigorite, the hydrated silicate supposed to compose the hydrated cores, is strongly non-Newtonian and weakly temperature-dependent. The cores are volumetrically heated by natural radioactivity. We have adapted the theory developed by Solomatov (1995) [1] for non-Newtonian fluids heated from below to the case of volumetrically heated fluids. A recent review [2] of the physical parameters relevant to the thermal evolution of hydrated cores made of antigorite provides values quite different from those used in previous studies [3,4], which seriously modifies the results of previous simulations including the predicted present interior structure of the large icy satellites. One key parameter is the amount of potassium present in the hydrated silicates. This study investigates ratios of K/U that span a broad range from earthlike to solar. It is shown that convection can start but is limited to the outer layer of the hydrated core. In the center, temperatures are large enough for dehydration to start.

1. Introduction

The Galileo mission to Jupiter and the Cassini/Huygens mission to Saturn have revealed that the three large Jovian icy moons and Titan, Saturn’s largest satellite, are at least partly differentiated. Their normalized moments of inertia (C/Ma^2 in Table 1) are smaller than 2/5, which is the value for undifferentiated moons. However, the value is quite different for Ganymede than for Callisto. The low value for Ganymede is consistent with a fully differentiated body consisting of an inner iron rich core, a silicate shell, a high-pressure ice shell, a liquid shell and an outer low pressure (ice I) layer [5]. The case of Europa is different since its lower mass and its large density imply a much thinner outer H_2O layer. One explanation for the larger values of the moment of inertia of Titan and Callisto is that they have not undergone complete differentiation and that their interior would be, at least partly, composed of hydrated silicates [3,4] which are much less dense than the silicates that compose the mantle of terrestrial planets. The present study models the thermal evolution of such cores. It investigates whether convection processes, that would prevent dehydration and differentiation, can happen.

	Titan	Callisto	Ganymede	Europa
Mass (10^{23} kg)	1.345	1.076	1.485	0.481
Radius (km)	2575	2403	2634	1569
density	1881	1851	1940	2970
C/Ma2	0.342	0.358	0.311	0.347
Eccentricity (%)	2.92	0.7	0.15	1.01
Prot (days)	15.95	16.7	7.15	3.55

Table 1: characteristics of Europa, Ganymede, Callisto and Titan.

2. Thermal evolution model

The simulations start after the accretion phase during which temperatures were large enough to allow for partial melting and the formation of a hydrated core. The core heats up due to the decay of radioactive elements. The amount of ^{40}K is a free parameter because potassium is easily leached during processes involving circulation of water. The simulations use thermal parameters recently reviewed [2]. For example, the specific heat is about half the value used by [3], which means that the temperature increases much more rapidly with time for the same amount of internal heating. These values are based on several laboratories studies on antigorite whose properties play a key role in the geodynamics of subduction zones on Earth [6]. As the interior temperature increases, the density profile may become unstable to convection processes. The stability of the density profile depends on the competition between the density decrease due to temperature increase and the density increase due to pressure increase. For amounts of ^{40}K in the range of values expected in the hydrated minerals in the outer solar system, the temperature increase is indeed large enough to overcome the effect of pressure.

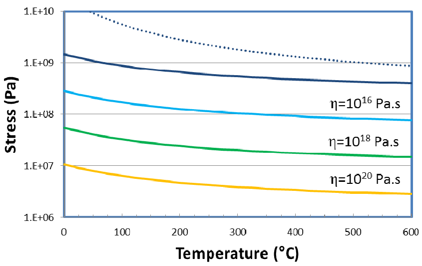

Figure 1: Viscosity of antigorite extrapolated from laboratory experiments [6]. It shows that the viscosity is strongly stress-dependent (non-Newtonian viscosity) and weakly temperature-dependent.

3. Onset of convection

Convection processes can start if the density profile is unstable (density decreases with pressure because of the temperature increase) and if the viscosity of the material is low enough for buoyancy forces to overcome viscous forces. It starts when the Rayleigh number becomes larger than a critical value that depends on the viscous behaviour of the material [1]. The viscosity of antigorite is very strongly stress-dependent (Fig. 1). The value of the critical Rayleigh number for non-Newtonian viscosity with no temperature dependence has been estimated using both laboratory and numerical data [1]. It must be noted that in such fluids, the meaning of the boundary between conductive and convective regimes is that if the Rayleigh number is below some critical value, no convective motion is possible with any initial conditions; if it is above this critical value, convection is possible but initiation of convection requires sufficiently large initial perturbations. In the icy moons Europa, Ganymede, Titan or Callisto, the perturbations may be the tidal forces acting on the core. If the amount of ^{40}K is large (CI chondrites) the critical value can be reached in less than 1 Gyr (Fig. 2). With an Earth-like amount of ^{40}K, the critical value is reached much later. In both cases, convection would only affect the outer layer of the core while the inner core would be subject to dehydration. The implications for the evolution of the interior structure are being investigated.

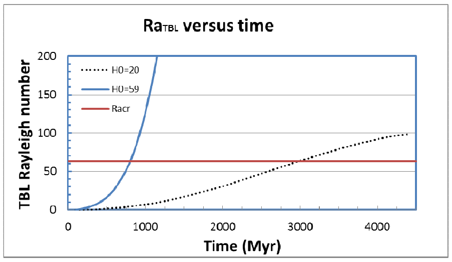

Figure 2: Evolution of the Rayleigh number with time for the chondritic case (blue curve) and Earth-like case (dotted line).

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