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Thermal convection in high-pressure ice layers beneath a buried ocean within Titan and Ganymede

G. Choblet, G. Tobie and M. Dumont
Laboratoire de Planétologie et Géodynamique, CNRS-Université de Nantes, France (gael.choblet@univ-nantes.fr)

Abstract

Deep interiors of large icy satellites such as Titan and Ganymede probably harbor a buried ocean above high-pressure (HP) ice layers. The nature and location of the lower interface of the ocean involves equilibration of heat and melt transfer in the HP ices. It is ultimately controlled by the amount of heat transferred through the surface ice Ih layer. We describe 3D spherical simulations of thermal convection in these HP ices layers that address for the first time this complex interplay.

1. The ocean/HP ices interface

While observations by the *Galileo* and *Cassini-Huygens* missions have revealed that deep oceans of liquid water could be buried within several of the icy moons in the Jupiter and Saturn systems, two configurations can be considered: for smaller moons or moons with a smaller water content, as Enceladus and Europa, the water ocean is directly in contact with the rocky mantle. For more massive satellites, hydrostatic pressure leads to the formation of high-pressure (HP) ices separating the ocean from the deep rock interior. Whether such environments provide favorable conditions for deep habitats remains largely enigmatic. Such questions will be addressed by the *JUICE* mission prepared by ESA, which goal is to scrutinize Ganymede's interior as an emblematic example of this class of bodies. Modeling efforts focusing on thermal and chemical transport through the HP ice layers are therefore required to accompany the forthcoming observations.

A significant part of the heat transfer could be achieved via the mass flux of warm liquid through the global phase boundary, a process not much different from the *heat-pipe* mechanism first introduced to explain the paradoxical relief of Io observed by the *Voyager* spacecraft, given the huge heat power at the surface [3]. Indeed, as will be shown below in the case of Titan or Ganymede, the Rayleigh number associated to HP ice layers is expected to be much larger than the critical value and thermal convection should develop. The presence of a cold boundary layer in the uppermost part of the HP ice layer with a radial temperature gradient much steeper than the expected melting temperature (Fig. 1) however implies that classical subsolidus convection is not a viable mechanism.

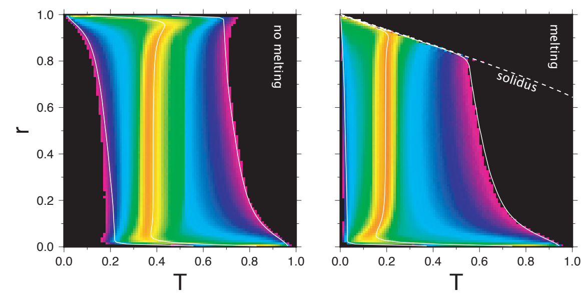

Figure 1: Effect of melting with an instantaneous melt extraction on thermal convection. *left* - no melting. *right* - melting. The three white curves indicate the minimum, average and maximum temperature at a given radius (statistical distributions at a given radius are denoted by colors).

2. Numerical experiments

Set-up - Here, we perform numerical simulations of thermal convection dedicated to this configuration. The problem is solved in one block of the spherical shell of lateral angular extent $\pi/6$, using the OEDIPUS numerical tool [1] with typically 128^3 grid cells. We focus on dimensions typical of Titan or Ganymede with a silicate core of radius 1840 km and a radius corresponding to the ocean/HP ices boundary ranging between 2175 and 2250 km. Considering reasonable viscosities for HP ices leads to Rayleigh numbers between 1.5×10^8 and 2.2×10^9.

In a first series of calculations, melt production and transport are simply neglected in order to provide reference cases of subsolidus convection. We then consider identical configurations in terms of geometry and dimensionless parameters and melt production is introduced with the following model: temperatures T exceeding the melting temperature T_m at a given depth are set back to T_m and a fraction $x_m = c_p(T - T_m)/L$ of liquid water is produced per unit time, with L, latent heat of fusion and c_p heat capacity of HP ice. Melt is then instantaneously extracted. The major consequence of the introduction of this simple melting model is the global cooling of the layer. In the example shown in Figure 1, the temperature of the convecting interior is reduced by half.

Scaling for heat and melt for an isoviscous layer- The cooling effect of melt production/extraction can be described as follows: If volumetric heating (typically tidal dissipation) is neglected, the heat balance implies that the power conducted through the top and bottom boundaries are equal. When melting is introduced, our calculations show that the prescribed melting temperature almost entirely controls the diffusive heat flux (Fig. 1). The remaining transport of heat required to match the power through the basal interface is achieved via melting and melt extraction. We propose scaling relationships to describe this configuration for a large range of Rayleigh numbers and solidus curves (to keep things simple here, we focus on isoviscous convection with a prescribed basal temperature).

Preliminary results for Titan and Ganymede- As a second step, we focus on a more realistic set-up where a basal heat flux (instead of a basal temperature) is prescribed. Thermal history models for Titan [4] indicate that the power out of the rocky core could reach a maximum of 1.5 TW (i.e. a heat flux of 40 mW.m^{-2}) corresponding to the onset of convection after $\sim$ 2 Gyr of evolution. As a lowermost bound, we envision a composition of the rocky core depleted in radiogenic elements and neglect its secular cooling, i.e. $\sim$ 5 mW.m^{-2}. In addition, we introduce the temperature and pressure dependence of viscosity for HP ices proposed by Durham et al. (1997) [2].

Our preliminary results (Fig. 2) tend to show that ancient periods with a heat flux of 40 mW.m^{-2} should be characterized by melting in the outer part of the HP ice layer, with noticeable consequences on heat transfer: the bulk temperature is approximately twice smaller when compared with the case without melting and $\sim$ 85 % of the heat transfer occurs via melt extraction. The bulk temperature lies well below the solidus value at depth so that chemical transport from the rocky core to the surface would only be achieved via solid-state advection. Moreover, the effect of melting is negligible for the case with a very low heat flux

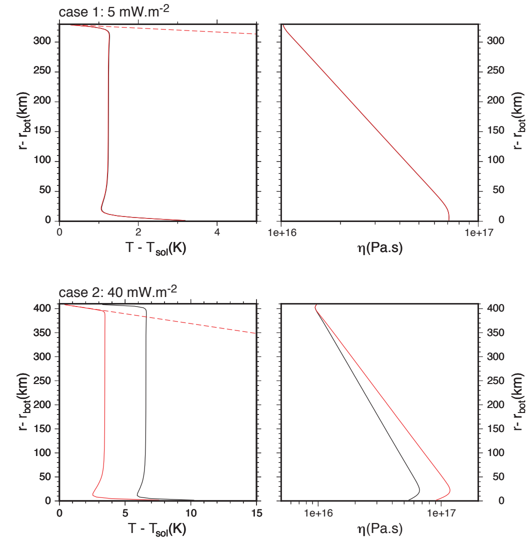

Figure 2: Two endmembers corresponding to the thermal history of Titan. Case 1 (*top*): low basal heat flux. Case 2 (*bottom*): high basal heat flux. For both cases, the left panel displays the average temperature at a given radius with (red curve) or without (black curve) melt extraction. The right panel displays the associated viscosity profiles [2].

value of 5 mW.m^{-2}. More results will be presented with different rheologies and basal heat fluxes. General consequences for the long term evolution will be discussed, noticeably in connexion with heat transfer in the shallow ice Ih layer.

Acknowledgements

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