HEAT FLOW FROM AN EUROPA'S CONVECTIVE ICE LAYER TIDALLY HEATED.

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Introduction: Two end-member models have tried to explain geological features observed on Europa's surface. These are the thin-shell model and the thick-shell model. The first one suggests the existence of an ice shell few kilometers thick, where conduction is the only mechanism of heat transfer. Locally, this thin shell could be thinner so melt-through of the whole shell would expose an inner ocean at the surface [1-4]. On the other hand, the thick shell model proposes the existence of a thick layer of ductile ice underlying a brittle lithosphere. The lower part of the ductile ice layer could be convective and could overlay or not a internal ocean [5-7].

The analysis of Galileo spacecraft observations of the Europa's surface points out that the thickness of the brittle lithosphere is probably no more than 2 km [6]. To put the brittle-ductile transition at ≤ 2 km deep vertical heat flows throughout the lithosphere of at least ~100-200 mW m^{-2} are required [6,8,9]. These heat flow values are clearly higher than those estimated from tidal heating models (≤ 50 mW m^{-2}) [10-13]. Tidal heating of a warm icy convective layer [9,14], or a rock and metal core [14] could explain these high heat values.

Important questions about Europa's crust dynamics arise from high surface heat flows. An ice shell thinner than 10 km [15], could prevent the onset of convection. The onset of convection would require heat flow values of ≤ 60 mW m^{-2} [15]. In consequence, if the onset of convection occurred most of heat dissipation takes place in the nearly isothermal core of convective layer. But, if the main heating contribution derives from the rock and metal core, convection cannot occur within the ice shell, and the shell is few kilometers thick.

In this work, we analyze the consistency between a thin brittle lithosphere characterized by high heat flows and the existence of convection in the Europa's ice shell. It has been suggested [16] that if the ice shell is thinner than ~30 km tidal heating in a convective layer can give rise a heat flow of F ~ 200 mW m^{-2} if energy balance conditions are considered, but this result do no take account tidal stresses or tidal strain rates influence on the ice viscosity.

Convection on the icy shell of Europa: Recently [17], it has been suggested that Callisto's outer ice shell could be stable against solid-state convection if non-Newtonian viscosities are considered, then, an internal ocean, evidenced from magnetic observations [18], could avoid freezing. Thus, the onset of convection in large icy satellites would be more difficult than previously thought. Dominant stresses in the deeper interior of Callisto's outer shell are due to thermal buoyancy. The same method cannot be applied to Europa because tidal stresses are higher than those due to thermal buoyancy. According to *McKinnon* [15], the convective state of an ice shell on Europa can be investigated considering Newtonian viscosities if an appropriate average effective viscosity based on tidal strain rates is estimated. This author found that convection could start in an ice shell ≥10 km thick.

Heat flows from a convective layer tidally heated: For a convective layer heated from within *Turcotte and Schubert* [19] found the following theoretical relations

$$\theta = \frac{2k(T_i - T_t)}{Hb^2} \quad , \qquad (1)$$

$$\theta = 2.98\, \mathrm{Ra_H}^{-1/4} , \qquad (2)$$

where θ is the dimensionless temperature ratio, k is the thermal conductivity, T_i and T_t are the temperatures in the convective interior and at the top of the convective layer, respectively; H is the volumetric heating rate (in this case the tidal dissipation rate), b is the thickness of the convective layer, and $\mathrm{Ra_H}$ is the Rayleigh number defined for a layer internally heated.

Starting from theoretical arguments and numerical experiments *Grasset and Parmentier* [20] obtained T_i - T_t for a layer heated from within

$$T_i - T_t = 2.23 \frac{RT_i^2}{Q} \quad , \qquad (3)$$

where R = 8.3145 J mol^{-1} K^{-1} is the gas constant, and Q is the activation energy for creep deformation. Under tidal stresses ice can behave like a viscoelastic (Maxwell) solid; then from [13] the tidal volumetric dissipation rate is

$$H = \frac{2\eta_{\mathrm{tidal}}\dot{\varepsilon}^2\mu^2}{\mu^2 + \omega^2\eta^2_{\mathrm{tidal}}} \quad , \qquad (4)$$

where $\dot{\varepsilon}$ is the strain rate, $\mu = 4 \times 10^9$ Pa is the ice rigidity, ω is the frequency of the forcing (for the case $\omega = 2.05 \times 10^{-5}$ rad s^{-1}, the Europa mean motion value). Ice tidal viscosity (if ice behaves like a non-Newtonian material) of a convective sublayer can be obtained from tidal strain rate,

$$\eta_{\mathrm{tidal}} = \frac{1}{3}\left(\frac{d^p}{A\dot{\varepsilon}^{n-1}}\right)^{1/n} \exp\left(\frac{Q}{nRT_i}\right) \quad , \qquad (5)$$

where d is the grain size, p, A, and n are experimentally established constants depending on the creep mechanism. For Europa, *Ojakangas and Stevenson* [13] calculated tidally induced strain rates in a floating ice shell. Depending on colatitude and longitude, strain rate ranges between 1.2×10^{-10} s^{-1} and 2.5×10^{-10} s^{-1}. In calculations, a strain rate value of 2×10^{-10} s^{-1} can be used without varying significantly the results. In turn, $\mathrm{Ra_H}$ can be defined as

$$\mathrm{Ra_H} = \frac{\alpha\rho g H b^5}{k\kappa\eta} \quad , \qquad (6)$$

where α is the thermal expansion coefficient, ρ = 930 kg m^{-3} is the water ice I density, g = 1.31 m s^{-2} is the gravity acceleration on Europa, b is the layer thickness, κ is the thermal diffusion coefficient, and η is the effective viscosity. According to [15], the average effective viscosity is $\eta = \eta_{\mathrm{tidal}}\, n^{-1/2}$.

Thus, heat flow out of the convective layer can be obtained from

$$F = Hb = 0.59k\left[\frac{\alpha\rho g (T_i - T_t)^4}{\kappa\eta_i}\right]^{1/3} \quad ; \qquad (7)$$

k, α and κ, are functions of temperature: $k = k_0 T^{-1}$, $\alpha = \alpha_0 T$ and $\kappa = \kappa_0 T^{-2}$, where the constant values are 567 W m^{-1} [21], and $\alpha_0 = 6.24 \times 10^{-7}$ K^{-2}, and $\kappa_0 = 9.1875 \times 10^{-2}$ m^2 K^2 s^{-2} [22]. k, α and κ and tidal and effective viscosities can be determined by setting $T = T_i$, and after [15] T_i = 260 K.

Although, this scenary does not account for the stagnant lid of convective system, the procedure is appropriate because most of the convective sublayer is nearly isotherm and then, almost isoviscous. Besides this, the real thickness of the layer is $\cong b$ since thermal conductivity is nearly constant. On the other hand, the base convective layer is heated from within and a certain amount of heat flow comes into the convective layer from below. This bottom heat flow has not taken into account since surface heat flow mostly generates (in this setting) in the warm icy isothermal core of the convective ice crust. Thus, the method is a valid approximation for convective heat flow estimations.

Results: Convective heat flows were estimated for superplastic flow [23] and dislocation creep [24]. At temperatures up to ~255-258 K [23,25], both mechanisms have enhanced rate creep regimes (characterized by large activation energies and probably related to ice premelting effects), but the results for these regimes are not shown since heat flow obtained are lower than those given in Table 1. Under low differential stresses, superplastic flow appears to be the prevailing mechanism in the icy satellites interior [23] and, in particular of Europa interior [15,26]. However, it has been suggested that dislocation creep could also be relevant in this icy satellite [25].

Superplastic flow is a creep mechanism grain size sensitive, and heat flow estimations must account for different grain sizes. Here, we were taken d = 0.1 mm and d = 1 mm. A grain size lower than 0.1 mm does not seem reasonable if there are no impurities that constrain ice crystal growth [15]. A grain size higher than ~1 mm implies the start of a most important role of dislocation creep [25].

Table 1 shows surface heat flows estimation results. Superplastic flow (Q = 49 kJ mol^{-1}) is the only mechanism that satisfies the high surface heat flows of Europa. Depending on grain size heat flows obtained vary from 100 to 170 mW m^{-2}. A different ice rheology or a significant tidal heat generation in the rock and metal core would prevent the onset of convection; then the whole crust is thermally conductive and it is few kilometers thick.

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Table 1. Results

	Superplastic flow		Dislocation creep	
	Q = 49 kJ mol^{-1} d = 0.1 mm	Q = 49 kJ mol^{-1} d = 1 mm	Regime A	Regime B
F (mW m^{-2})	173	95	44	66
b (km)	66	12	6	10
T_t (K)	234	234	246	239