ONSET OF CONVECTION, HEAT FLOW AND THICKNESS OF THE EUROPA’S ICE SHELL

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Abstract. The observational evidence given by Galileo spacecraft about Europa supports an icy rigid layer of several kilometers over another ductile layer of ice in convection, which floats over an internal ocean of liquid water. Before the onset of convection, heat is transmitted into the crust by conduction. The heat flow analysis in the potentially convective layer gives values higher than those obtained previously by tidal dissipation models, and suggests that the ice may be limited to a thin layer of ∼4 km total thickness.

1. Introduction

Recent observations from Galileo spacecraft show that there is a mechanical decoupling between the ice crust and the rocky interior of Europa, Galilean satellite of Jupiter (Carr et al., 1998; Pappalardo et al., 1998; Geissler et al., 1998; Sullivan et al., 1998). This involves the existence of a layer of ductile ice or liquid water below the rigid ice of the crust. The images showing fractured blocks, which moved and rotated in the Conamara Chaos region and were bounded in a finer texture “matrix”, indicating the existence of water below the surface and suggesting a ∼2 km thickness rigid crust from the height of the emerged part of the blocks (Carr et al., 1998). All the evidence suggests that the thickness of the crust is $\leq$2 km (Pappalardo et al., 1998).

In other respects, both solid state convection in the ice shell and the ascent of diapirs from a ductile ice layer are the mechanisms proposed by Pappalardo et al. (1998) to explain the origin of domes, pits and dark spots observed by Galileo spacecraft near Conamara Chaos region. They would be related to the late stages of the geologic activity in Europa, which may persist today extended over huge regions (Carr et al., 1998).

If the origin of the domes, pits and dark spots is related with columns of ascent material from a convecting layer, then the typical spacing of the features, that is ∼5–20 km, must be around two times the thickness of the convecting layer (Pappalardo et al., 1998). Pappalardo et al. (1998) analyzed the onset of convection assuming that the ice shell floats over the water layer. They fixed both the temperature of the top of potentially convective layer at 197 K (calculated from the activation energy of creep in ice) and at 273 K at its base. The difference is taken

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to calculate the thickness of the initial convecting layer. They obtain a thickness range of ∼2–8 km for this layer. This is consistent with the spacing observed in the features, but they point out that it is unclear that the convective state of the ice shell when the deformation occurred was related to the state of the starting convection.

The heat flow through Europa's ice shell and the possible thickness of this shell in the onset of convection are going to be analyzed in this work. It is assumed that the shell is buoyant over an internal liquid water ocean and that the spacing among domes, pits and dark spots are correlated to the thickness of the layer that begins the convection, as Pappalardo et al. (1998) suggest.

2. Methodology

Before the onset of convection, all the crust is in a conductive regime. The temperature at the different levels is due to this situation. This allows us to calculate the heat flow through the crust, F, in the moment when the convection starts from the depth of the affected layer, h,

$$F = (k_0/h)\ln(T_b/T_t), \tag{1}$$

where T_b is the lower boundary temperature of the potentially convective layer, T_t is the upper temperature of the convective layer, and $k_0 = kT$ (where k is the thermal conductivity of the water ice). Otherwise, it is possible to calculate the surface temperature, T_s, at the onset of convection, for a fixed F and the depth of the rigid layer l,

$$T_s = T_t\exp(-lF/k_0) = T_t\exp[-(l/h)\ln(T_b/T_t)]. \tag{2}$$

It is clear that there is a lineal relationship between l and h from Equation (2),

$$l = h\ln(T_t/T_s)/\ln(T_b/T_t). \tag{3}$$

3. Results

The preceding equations have been calculated for a range of h between 1 and 10 km. The maximum value was established from the observed spacing among domes, pits and spots. $k_0 = 567$ W m^{-1} (Klinger, 1980), $T_t = 200$ K and $T_b = 273$ K are assumed. In Equation (2), $l = 2$ km. In Equation (3) two different surface temperatures are considered, 100 K as the representative mean temperature on the Europa surface (Ojakangas and Stevenson, 1989) and 130 K, as approximated temperature of a possible isolating layer of regolith (Shoemaker et al., 1982; Ross and Schubert, 1987). The obtained results are shown in Figures 1 and 2.

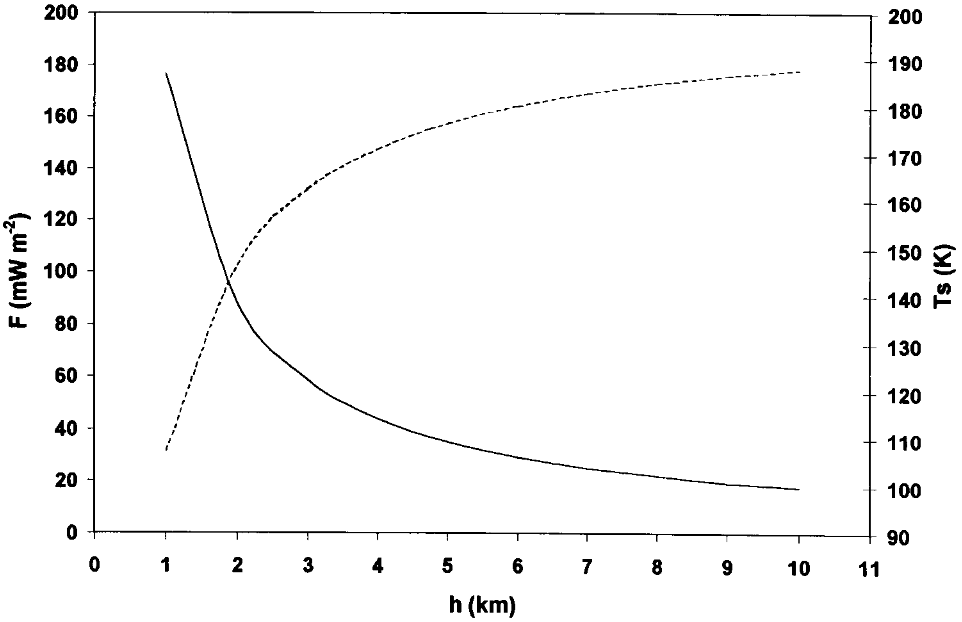

Figure 1. Heat flux through the Europa’s ice shell, F (solid line), and surface temperatures, T_S (dashed line), at the onset of convection, in terms of thickness of the potentially convective layer, h.

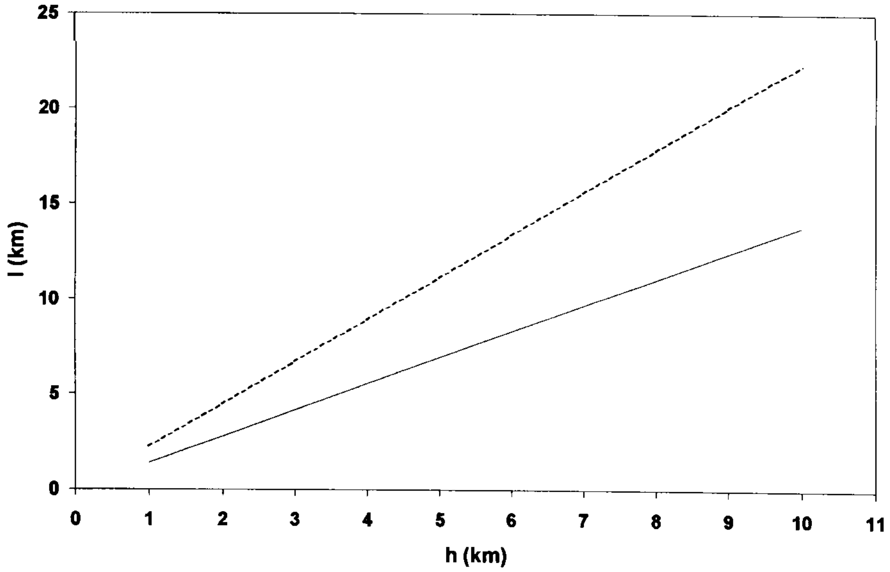

Figure 2. Thickness of rigid ice layer at the onset of convection, l, in terms of thickness of ductile ice layer initially convective, h, calculated for two different surface temperature values, T_S, 100 K (dashed line) and 130 K (solid line).

4. Discussion

The combined analysis of the F and T_s in terms of h, with $l = 2$ km, shows that the estimations for F are high if the ordinary values of T_s are considered. The existence of high heat flows when the deformation occurred was already suggested by Pappalardo et al. (1997) from the evidence on behalf of a thin rigid crust.

If the mean surface temperature is between 100–140 K (the higher value is not usual but reasonable; Squyres et al., 1983), then the heat flow required in the onset of convection should be $\sim$100–200 mW m^{-2}. This is much higher than any other estimation for the heat flow of Europa based on tidal heating. Thus, the value of $F \sim 52$ mW m^{-2} obtained by Squyres et al. (1983) is considered by Ross and Schubert (1987) as an overestimation. Inversely, for $F < 52$ mW m^{-2}, $T_s > 165$ K. If values of $l < 2$ km are taken, the situation is more extreme, giving surface temperatures even higher. Otherwise, the l values calculated in terms of h and T_s are very high for the rigid crust inferred by the Galileo data.

Based on that, the thickness of the affected layer in the onset of convection is $\sim$2 km for $T_s \sim 140$ and $F \sim 100$ mW m^{-2}, scarcely consistent with the surface spacing among domes, pits and dark spots. Thus, a $\sim$4 km for the total thickness of the ice in Europa may be taken as a compromise value. If values of h similar to observations are used, then T_s values become too high if better h. This thickness is lower than 16–35 km obtained from theoretic analysis of the ice crust stability against solid state convection (Cassen et al., 1982; Squyres et al., 1983; Ojakangas and Stevenson, 1989; McKinnon, 1997), and is between $\sim$3–10 km from Pappalardo et al. (1998).

On the other hand, the distribution of dome size near Conamara Chaos shows a maximum for $\sim$3 km radius (Rathbun et al., 1998), that implies that, if the diapirs arise from a $\sim$2 km thick convective layer, they should overlap between them. That is why it is difficult to suppose that dome formation has taken place in a generalized way in accordance with the onset of convection. If diapirism is induced from a layer where convection is actively established, with a Nusselt number (convective and conductive heat flow ratio) greater than 1, the thickness of this layer would be greater than $\sim$2 km, and this might be in better agreement with the separation observed among domes, pits and dark spots. In any case, it doesn't decrease the $\sim$100–200 mW m^{-2} heat flows required by a $\sim$2 km thick conductive lithosphere.

Another possibility is that the base of the rigid crust doesn't belong to the base of the stagnant lid of the convective system. The consequence of it might be that the calculation of heat flows might be overestimated, because temperature at the base of the lithosphere should be less than 200 K, and the total thickness of ice greater. With respect to this, preliminary analysis of the brittle-ductile transition in Europa's ice shell, by means of rheological profile techniques, involves, independently of existence or non-existence of convection, a $\sim$100 mW m^{-2} minimum heat flow for a $\sim$2 km brittle crust (Ruiz and Tejero, 1999).

5. Conclusions

If the formation of domes, pits and dark spots occurred as a consequence of diapir intrusions from an ice convection layer, and if the spacing among the features is related to this layer state when the convective movement starts (as Pappalardo et al., 1998, suggest), then when deformation occurs: (1) the heat flow through the ice crust was substantially higher than that predicted by tidal models or, (2) the surface temperature was higher than today. But these features are probably young (Carr et al., 1998), so it could be unreasonable to expect temperatures different from the present ones (Pappalardo, personal communication). Although the values of T_s obtained according to h do not seem to fit well to the observational data, a compromise solution can be chosen where T_s and h are a bit different (still reasonable) than expected, and involve an ice shell for Europa whose thickness is only $\sim$4 km.

Finally, if domes, pits and dark spots were originated in relation to a layer in active convection, or if temperature at the base of the rigid crust doesn't belong to temperature at the base of the stagnant lid of the convective system, the total thickness of ice might be greater, but the heat flows involved might persist in being very high.

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