SEAS UNDER ICE: STABILITY OF LIQUID-WATER OCEANS WITHIN ICY WORLDS

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Abstract. The present-day existence of internal oceans under the outer ice shell of several icy satellites of the Solar System has been recently proposed. The presence of antifreeze substances decreasing ice's melting point (and tidal heating in Europa's case) has been generally believed to allow the stability of such oceans; limited cooling of the water (ice plus liquid) layer, due to stability against convection or to stagnant lid convection in the icy shell, have been also considered. Here we propose that even pure liquid-water oceans could survive today within several icy worlds, and we consider some factors affecting thermal modeling in these bodies. So, the existence of such oceans would be a natural consequence of the physical properties of water ice, independently from the addition of antifreeze substances or any other special conditions. The inclusion of these substances would contribute to expand the conditions for water to stay liquid and to increase ocean's volume.

Keywords: icy bodies, internal oceans, solid-state convection, water ice thermal conductivity, water ice viscosity

1. Introduction

The possible existence of internal oceans in several icy bodies of the outer Solar System (Figure 1) has been suggested in the last few years on the basis of diverse observations that cover a wide range of evidences: induced magnetic fields in Europa and Callisto (Khurana, et al., 1998; Kivelson et al., 2000; Zimmer et al., 2000; Schilling et al., 2004), and maybe Ganymede (Kivelson et al., 2002), which originate from Jupiter's plasma environment influence on an electrically conductive layer close to the surface of these satellites, which is likely salty water; spectroscopic data consistent with hydrated minerals on the surface of Europa (McCord et al., 1998) and Ganymede (McCord et al., 2001) suggest the presence of water on the surface in the past, probably from an internal source; geological evidences of a low viscosity layer existing a few kilometers beneath the surface of Europa (for a

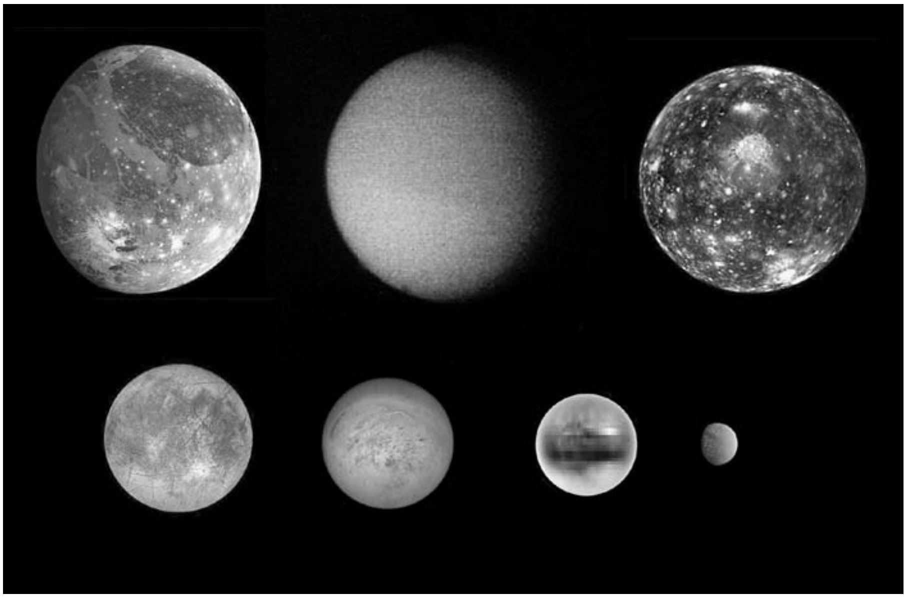

Figure 1. The main icy bodies proposed to have an internal ocean beneath their outer ice shell, classified by size. Top (from left to right): Ganymede, Titan and Callisto; bottom (from left to right): Europa, Triton, Pluto and Enceladus.

review and evaluation of geological evidence for a internal ocean on Europa see Pappalardo et al., 1999); or a young surface of Triton deduced by its low density of craterization (Stern and McKinnon, 2000; Zahnle et al., 2003), which could be an indication of recent geological activity and maybe of an internal liquid layer (Stern and McKinnon, 1999).

The nature of the proposed liquid layers could be very different, although the own existence of internal oceans could be a common phenomena. In fact, the conditions invoked to enable the stability of seas under ice include tidal heating for Europa (e.g., Cassen et al., 1982; McKinnon, 1999); the presence of substances such as ammonia or salts, which could greatly decrease the ice melting point (e.g., Lewis, 1971; Cassen et al., 1982; Ross and Schubert, 1989; Grasset and Sotin, 1996; Hogenboom et al., 1997; Grasset et al., 2000; Kargel et al., 2000; Spohn and Schubert, 2003), and stability of the outer ice shell against convection (Ruiz, 2001) or stagnant lid convection (Spohn and Schubert, 2003; Rainey and Stevenson, 2003; Freeman et al., 2004), limiting cooling of the water (ice plus liquid) layer.

Here we review some factors that affect thermal modelling of icy bodies, in order to show that pure liquid-water oceans could survive today under the outer ice shell of several icy worlds. We only consider the possible existence of liquid-water layers, without considering the possible implications from geological features on the surface. The case of Europa is not considered here, as this satellite has already been the subject of a great amount of work.

2. Stress-Dependent Viscosity

The earliest models of the thermal structure of icy satellites only take into account thermally conductive outer ice shells (e.g., Lewis, 1971; Consolmagno and Lewis, 1978), obtaining thick liquid layers inside the largest satellites. Subsequent works (e.g., Reynolds and Cassen, 1979; Cassen et al., 1982; Schubert et al., 1986) concluded that an ice shell floating over an ocean in a large icy satellite would be unstable against solid-state convection, which should result in total freezing of any liquid water layer in ~10^8 years, a time one order of magnitude shorter than the age of the Solar System. So, in absence of tidal heating as an additional heat source (which can be present in the case of Europa; e.g., Cassen et al., 1982; Mckinnon, 1999), an internal ocean could not survive presently in an icy body.

But those early works considered the ice viscosity (and so its capacity for convection) to be temperature-dependent only (i.e., Newtonian viscosity), while laboratory experiments (e.g., Durham and Stern, 2001; Goldsby and Kohlstedt, 2001), indicate that it is also stress-dependent (i.e., non-Newtonian viscosity). Recently, it has been argued (e.g., McKinnon, 2001; Rainey and Stevenson, 2003) that under low differential stress conditions inside large ice satellites as Callisto, diffusion (Newtonian) creep would be the main flow mechanism for water ice. But diffusion creep has not been experimentally observed; so we follow the interpretation of Goldsby and Kohlstedt (2001) and Durham and Stern (2001), and consider water ice flow to be mainly non-Newtonian under planetary conditions.

An analysis for the case of Callisto (Ruiz, 2001) yielded that its outer ice shell should be stable against convection if non-Newtonian viscosity is taking into account for water ice. This implies that the modest amount of heat provided by radioactive elements in the rocky fraction is enough to allow an internal ocean to escape total freezing. The argument can be extended to other icy worlds of the outer Solar System.

The criterion for the onset of convection of a layer with Newtonian viscosity is given by the Rayleigh number, which can be defined for the viscosity at the base of the layer as

$$Ra_{\mathrm{b}} = \frac{\alpha \rho g h^3 \Delta T}{\kappa \eta_{\mathrm{b}}}, \tag{1}$$

where α is the thermal expansion coefficient, ρ is the density, h is the layer thickness, g is the gravity (taken in general as the surface value), $\Delta T = T_{\mathrm{b}} - T_{\mathrm{s}}$ is the temperature difference between the base and the surface of the layer, κ is the thermal diffusion coefficient, and η_{b} is the effective viscosity at the layer base. Equivalently, for non-Newtonian viscosities a Rayleigh number can be defined at the layer base as (Solomatov, 1995)

$$Ra_{\mathrm{b}} = \frac{\alpha \rho g h^{(n+2)/n} \Delta T}{\kappa^{1/n} b^{1/n}} \exp(\theta/n), \tag{2}$$

where b is a parameter that depends on creep mechanism and temperature, n is a constant that depends on creep mechanism, and θ is the Frank-Kamenetskii parameter, which describe the viscosity contrast through the layer due to temperature differences, and it is defined as

$$\theta = Q\Delta T/RT_i^2, \tag{3}$$

where Q is the activation energy of creep deformation, R is the gas constant, and T_i is the temperature in the nearly isotherm interior in the case of convection. In turn, b can be estimated from

$$\eta = (d^p/A)\sigma_{\mathrm{II}}^{1-n} \exp(Q/RT) = b\sigma_{\mathrm{II}}^{1-n} \exp(-QT/RT_i^2), \tag{4}$$

where d is the grain size, p and A are experimentally established constants, and σ_{II} is the second invariant of the deviatory stress tensor. If Ra_{b} of a conductive ice shell reaches a certain critical value, this ice shell becomes unstable against convection. Flow of water ice is strongly temperature-dependent. So, if convection occurs in an icy satellite, it is in the stagnant lid regime (McKinnon, 1998; Spohn and Schubert, 2003), in which the convective perturbation only affects the lower part of the ice shell, and over which a cold and immobile lid exists. (In the classical works the convective, or potentially convective, ice layer was taken as isoviscous.)

To illustrate this point, here we apply the methodology for non-Newtonian viscosities described in Ruiz (2001) to Titan, using the characteristics of this satellite as given in Morrison et al. (1986). Calculations have been performed for two possible deformation mechanisms for water ice, superplastic flow (in which grain boundary sliding is the dominant process; this flow mechanism is grain size-dependent) and dislocation creep (grain size-independent), whose rheological properties are given in Durham and Stern (2001) and Goldsby and Kohlstedt (2001). For superplastic flow, decreasing grain sizes diminish the b value, thus conversely increasing Ra_{b}, as well as layer instability. For that reason, in the calculations we have taken a grain-size of 0.1 mm: smaller grain sizes does not seem a realistic possibility for the interiors of large icy satellite if there are no impurities, which limit the crystal growth (McKinnon, 1999), and therefore this value implies a reasonable upper limit in the Ra_{b} estimation for superplastic flow.

Figure 2 show Ra_{b} values for the outer ice shell of Titan, in terms of the depth to the base of outer ice shell, which are compared with the corresponding Ra_{b}^* values, for both superplastic flow and dislocation creep. It is

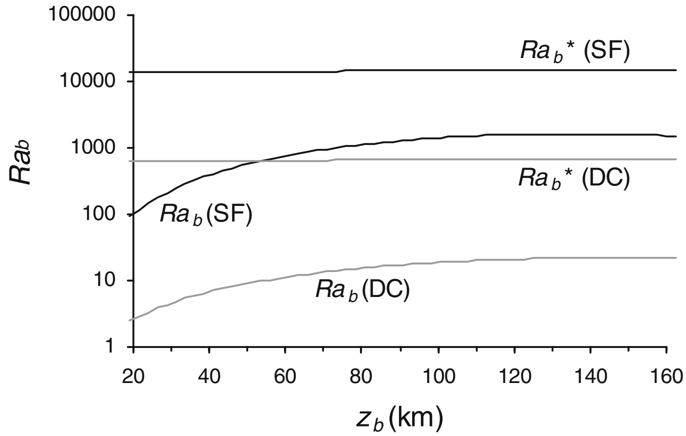

Figure 2. Rayleigh number defined at the layer base (Ra_b) for Titan's outer icy shell, estimated as a function of the shell thickness (z_b), compared to the critical Rayleigh number (Ra_b^*) required for the onset of convection. SF indicates superplastic flow as dominant flow mechanism, and DC indicates dislocation creep. For superplastic flow (which is grain size dependent) the calculations have been performed for 0.1 mm. See text for further details.

clear that Ra_b does not reach a value high enough for the onset of convection. So, a pure liquid-water layer should have survived to date, escaping the deep freezing, at a depth of ~135 km, the conductive equilibrium thickness for present-day radioactive heat sources (which originate a surface heat flow of ~4 mW m^{-2}; Sohl et al., 2003).

Very recent works, as much for Newtonian (Spohn and Schubert, 2003; Rainey and Stevenson, 2003) as for non-Newtonian (Freeman et al., 2004) viscosities, find that stagnant lid convection limit cooling of the ice shell, and favor both warmer interior temperatures and preservation of internal oceans in large icy satellites. These works are very interesting, but it is worth mention again that the onset of convection for strictly non-Newtonian viscosity is difficult.

3. Tidal Straining

McKinnon (1999) has shown that tidal stresses reduce viscosity for non-Newtonian viscosities (see equation 4), which could allow the onset of convection in the outer shell of Europa. Ganymede may have experienced past episodes of important tidal (Showman and Malhotra, 1997), and so tidal stresses in these episodes could have favored the onset of convection (McKinnon, 2001).

Here we have used the methodology described in Ruiz and Tejero (2003) in order to analyze the crustal thickness required for the onset of convection in the outer icy shell of a tidally strained ancient Ganymede, taking into account a possible range of tidally induced strain rates. The chosen upper limit, ~10^{-10} s^{-1}, is similar to the present-day tidal strain rates on Europa, (Ojakangas and Stevenson, 1989). The lower limit, 10^{-15} s^{-1}, is a strain rate considered typical of many geological processes. Ganymede's radius and mass are taken from Davies et al. (1998), and the mean surface temperature is assumed as 130 K. Tidal straining constitutes a potential heat source, depending on strain magnitude. Ojakangas and Stevenson (1989) have shown that tidal heating for ice is strongly temperature-dependent. In a conductive icy shell the main contribution to the total tidal heating is arising from the warm ice close to the base, and so, the shell can be considered heated from below. In this case, to calculate the Rayleigh number of the ice shell is sufficient to specify the shell thickness (Ruiz and Tejero, 2003). Tidal heating concentrated toward the shell base would reduce total ice thickness, contributing to both stability against convection of the shell and preservation of an internal ocean. Tidal heating in the rock/metal core should have a similar effect.

The calculations have been performed for both superplastic flow (using a grain size of 0.1 mm; see previous section) and dislocation creep. Results are shown in Figure 3. It is obtained that high strain rates allow the onset of convection in thinner ice shells. For comparison, a conductive equilibrium thickness of ~95 km corresponds to Ganymede's present-day radioactive heat flow (~4 mW m^{-2}; Spohn and Schubert, 2003).

If convection starts due to viscosity reduction by tidal stresses, then tidal heating within the convective core (warm and nearly isotherm), must be taken into account. So, although in some moments of the history of Ganymede tidal

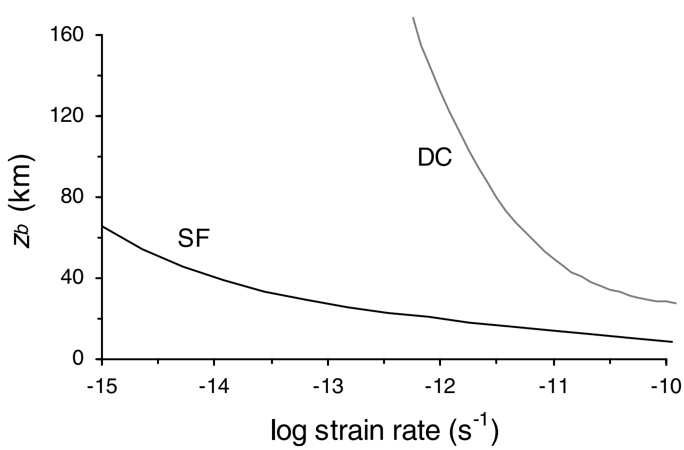

Figure 3. Critical thickness for the onset of convection in a floating ice shell on a tidally strained ancient Ganymede, calculated in terms of a possible range of tidal strain rates. As in Figure 1, SF indicates superplastic flow and DC indicates dislocation creep.

straining could have diminished the effective ice viscosity and allowed the onset of convection, it can be argued that the corresponding tidal heating in the warm convective interior of the ice shell could contribute to stabilize an internal ocean.

Ruiz and Tejero (2003) calculated thermal equilibrium states for tidally heated convection in the ice shell of Europa. Here we apply the methodology of these authors to the Ganymede case. We use the faster strain rate (10^{-10} s^{-1}) in the range used above for an ancient phase of tidal straining, in order to maximize the role of both tidal straining and tidal heating. For superplastic flow we use grain sizes of 0.1 and 1 mm, since dislocation creep becomes an important flow mechanism when grain sizes are bigger than ~1 mm. We obtain that, for superplastic flow in grain size of 1 mm and dislocation creep, tidal heating stabilizes a shell ~20–30 km thick; for superplastic flow in grain size of 0.1 mm tidally heated convection stabilizes a shell ~85–90 km thick (decreasing grain size reduces viscosity, which in turn increasing heat transfer efficiency). So, although convection could start under these conditions, total freezing of an internal ocean would not occur.

4. The Effect of the Spherical Geometry on the Temperature–Depth Profile in Small-Size Bodies

In works about icy worlds, the outer ice shell is frequently treated as a horizontal, "flat", layer. In this case, and taking into account that the thermal conductivity of water ice is a function of temperature as $k = k_0/T$ (where $k_0 = 567$ W m^{-1}; Klinger, 1980), the temperature profile in the shell would be calculated using

$$T_z = T_s \exp\left(\frac{zF}{k_0}\right), \tag{5}$$

where T_s is the surface temperature, z is depth, and F is the vertical heat flow through the layer. On the other hand, in a spherical shell in thermal conductive equilibrium heated from below, the vertical heat flow to a depth z is $F_z = Fr^2/(r - z)^2$, where r is the body radius. This implies that a more formally correct description of the temperature-depth profile of an icy body is given by

$$T_z = T_s \exp\left[\frac{rFz}{k_0(r - z)}\right] \tag{6}$$

Although equation (5) is accurate enough for large satellites, in the case of small-size satellites, as Enceladus, the effect of the real spherical geometry cannot be forgotten. This is so because in a small-size satellite, for fixed values of surface heat flow and temperature, the quotient $r/(r-z)$ is higher than for large satellites.

The young appearance of the surface of Enceladus indicates a thermally evolved body (Morrison et al., 1986), which suggests a differentiated interior. In fact, tidal heating calculations for Enceladus that includes an internal liquid layer suggests that a high heat flow, perhaps even ~5 mW m^{-2}, could be possible from the present-day orbital eccentricity (Ross and Schubert, 1989); for comparison, the component of the present-day surface heat flow due to radiogenic heating would be ~0.1 mW m^{-2} (Schubert et al., 1986).

The solid curve in Figure 4 shows the temperature profile in an outer ice layer on Enceladus, calculated by means of equation (1) assuming a surface temperature of 80 K (Ellsworth and Schubert, 1983) and a surface heat flow of 5 mW m^{-2} (it is necessary remind that this heat flow value is an upper limit). Ice melting temperature (assumed as 273 K), is reached at ~140 km depth. If the temperature profile is calculated for a spherical geometry using equation (6) and a radius for Enceladus of 250 km, the dotted curve shown in Figure 4 is obtained. It can be clearly seen that temperature increases more rapidly with depth when a spherical geometry is taken into account. In this case, the water ice melting temperature is reached at ~90 km depth, which increases the possibility of an internal liquid water layer for this small satellite.

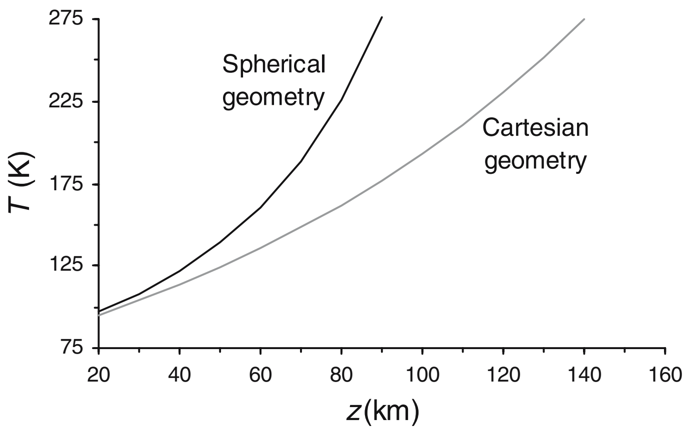

Figure 4. Temperature-depth profiles for Enceladus calculated for Cartesian and spherical geometries, assuming a vertical heat flow through the ice shell of ~5 mW m^{-2}.

5. Insulating Layers on the Surface

If over the surface of an icy world exists a regolith layer (Shoemaker et al., 1982) or if a solid-state greenhouse is working (Matson and Brown, 1989), the related thermal insulating effect could result in a significantly elevated temperature very close to the surface, which is equivalent to an effective surface temperature higher than the observed surface temperature. These effects, frequently cited by the icy Galilean satellites (e.g., Shoemaker et al., 1982; Squyres et al., 1983; Ross and Schubert, 1987), could contribute to retain internal heat, favoring the existence of an internal ocean.

Similarly, the possibility of a surface layer rich in low thermal conductivity ices raising the effective surface temperature and contributing to a hotter interior on Triton has been mentioned by McKinnon et al. (1995). It is widely accepted that Triton, in the past, was a body in heliocentric orbit and later captured by Neptune (see McKinnon et al., [1995] for a comprehensive review of this topic). Triton may retain part of the heat generated in the extreme tidal heating associated to the capturing process. Indeed, heat flows deduced from surface features are clearly higher than radioactive contributions, and an internal ocean can currently exist at a depth of ~20–30 km (Ruiz, 2003). (From the sparse amount of impact craters, the surface age seems to be very young, maybe as young as tens of millions of years [Zahnle et al., 2003]. Such recent surface ages suggest that deductions for surface features could be roughly applicable to the current state of this icy world.)

Therefore, Triton is an unusual body. For this reason we have chosen the case of Pluto (the Triton's twin) to illustrate the effect on the depth of a possible internal ocean caused by the rise of effective surface temperature.

In addition to water ice, the presence of nitrogen-, carbon monoxide-, and methane-ices on Pluto's surface has been reported (e.g., Cruikshank et al., 1997). These ices have a thermal conductivity clearly lower than water ice (Ross and Kargel, 1998). For example, the thermal conductivity of nitrogen (which is the dominant species observed on the surface) is ~0.2 W m^{-1} K^{-1}, or two orders of magnitude less than the thermal conductivity of water ice at temperatures typical of Pluto's surface.

We calculate, using equation (6), the depth at which the water ice melting temperature is reached, assumed again as 273 K. Pluto's bulk properties are only crudely known, and we assume the radius, mass and silicate/ice proportion as in McKinnon's (1997) preferred differentiated model. So, in the calculations we take $r = 1180$ km and $F = 3$ mW m^{-2} (this value corresponds to a chondritic radioactive heating rate [Spohn and Schubert], increased by a factor 1.5 from core cooling [McKinnon et al., 1997]). According to the discussion in Section 2 we did not take into consideration convection in the outer ice shell. A possible complication in the calculations of the thermal structure of the ice layer is that lower temperatures favor the transition from water ice I

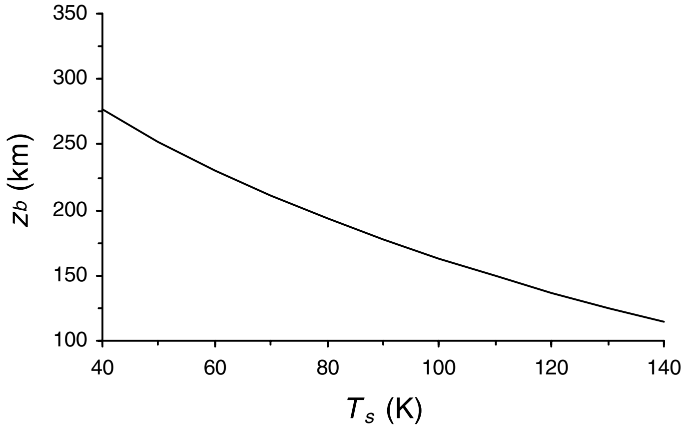

Figure 5. Depth to a possible internal ocean on Pluto as a function of the effective surface temperature.

to denser water ice II. However, in McKinnon's (1997) model the temperatures within the ice layer are warm enough to prevent the existence of water ice II, thereby eliminating this complication. Finally, we made calculations for an effective surface temperature range of 40–140 K: 40 K is the surface temperature of Pluto (Tryka et al., 1994), and 140 K is close to the temperature often ascribed to the base of a regolith layer (~130 K; Shoemaker, 1982).

Results are shown in Figure 5. It can be seen that if the effective surface temperature is close to the observed surface temperature, then melting of water ice is reached at a depths of ~280 km, which is similar to the whole thicknesses of ~320 km estimated for the water ice I layer by McKinnon et al. (1997) for their preferred model. Otherwise, a more elevated effective surface temperature allows reaching water melting at shallower depths, for example a melting depth of ~125 km would correspond to an effective surface temperature of ~130 K. So, higher effective surface temperatures greatly increase the chance of an internal ocean existing.

6. Conclusions

The existence of liquid oceans within icy satellites can be a natural consequence of the physical properties of water ice, especially if an insulating layer exists over their surfaces. Hence, the addition of antifreeze substances or any other special conditions would not be required. Moreover, it is possible that the internal dynamics of some of these bodies could be very different than is usually considered.

Furthermore, the incorporation of significant quantities of substances as ammonia or salts seems to make internal oceans almost inevitable: salts could reduce the melting temperature importantly, and ammonia would depress the melting point to ~176 K, or even as low as ~153 K if methanol is present. Also, the low thermal conductivity of these substances (Ross and Kargel, 1998; Lorentz and Shandera, 2001; Prieto and Kargel, 2002) gives shallower melting depths for the case of conductive temperature profiles (Kargel and Pozio, 1998; Lorentz and Shandera, 2001), and therefore thinner outer shells.

In any case, it seems guaranteed that different and varied seas exist under ice in the outer Solar System.

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