Thermal Diapirism and the Habitability of the Icy Shell of Europa

Javier Ruiz · Lilia Montoya · Valle López · Ricardo Amils

Abstract Europa's chaos and lenticulae features may have originated by thermal diapirs related to convective plumes. Warm ice plumes could be habitable, since their temperature is close to the ice melting temperature. Moreover, thermal plumes intruding into the lower stagnant lid warm several kilometers of country ice above 230 K for periods of 10^5 years, and hundreds of meters above 240 K for periods of 10^4 years. Diapir coalescence generating chaos areas should provide a large zone with temperature above ~240 K for thousands of years. A temperature above ~230 K is potentially interesting for astrobiology, since it corresponds to the lowest temperature at which microbial metabolic activity in Antarctic ice has been reported. So, the warming by thermal plumes could cause an aureole of biological activation/reactivation in the country ice. Adaptation of life to either high salinity or low temperature is similar: it requires the synthesis of compatible solutes, like trehalose or glycerol, which are efficient cryoprotectants. We therefore propose that the future astrobiological exploration of Europa should include the search for compatible solutes in chaos and lenticulae features.

Keywords Astrobiology · Compatible solutes · Europa · Habitability · Thermal diapirism

J. Ruiz (✉)
Instituto de Astrofísica de Andalucía, CSIC, Camino Bajo de Huétor 50, 18008 Granada, Spain
e-mail: ruiz@iaa.es

L. Montoya · R. Amils
Centro de Biología Molecular, CSIC-Universidad Autónoma de Madrid,
28049 Cantoblanco, Madrid, Spain

V. López
Seminario de Ciencias Planetarias, Facultad de Ciencias Geológicas,
Universidad Complutense de Madrid, 28040 Madrid, Spain

R. Amils
Centro de Astrobiología, INTA, 28855 Torrejón de Ardoz, Madrid, Spain

Introduction

Biological organisms may exist, active or latent, inside the icy shell of Europa, at places such as fractures, veins or liquid reservoirs (e.g., Greenberg et al. 2000; Marion et al. 2003; Lipps and Rieboldt 2005). Beneath this shell an internal ocean may exist, as suggested by geological evidence (e.g., Pappalardo et al. 1999), and strongly implied by the magnetic signature of a conductive electric layer within a few tens of kilometers at most of the surface (Kivelson et al. 2000; Schilling et al. 2004). This internal ocean could be habitable (e.g., Reynolds et al. 1983; Chyba 2000; Chyba and Phillips 2001, 2002; Schulze-Makuch and Irwin 2002; Marion et al. 2003). The shell composition, and hence the potential habitats, may include, at least locally, large amounts of non-water ice components, maybe magnesium and sodium sulfate hydrates (e.g., McCord et al. 1998; Kargel et al. 2000), sulfuric acid (Carlson et al. 1999), or mixtures of both (Spencer et al. 2006).

The icy shell is an evolving environment that should affect the viability, activity and evolution of any possible organism or biological community living inside. Geological mapping suggests that surface deformation and modification styles have changed through the recorded geological history from tectonic resurfacing, with ridge plains and bands formation, to terrain disruption that would lead to chaos areas and lenticulae, including domes, pits, and microchaos features (e.g., Prockter et al. 1999; Kadel et al. 2000; Figueredo and Greeley 2004; for a review of the Europa geology see Greeley et al. 2004) (Fig. 1).

This change in geological characteristics seems to be related to a progressive thickening of the icy shell. For example, younger ridges are wider, higher and further apart than older ones (Kadel et al. 2000; Figueredo and Greeley 2004). The most popular explanation for the origin of domes and microchaos features is surface upwarping and disruption by thermal diapirism related to convection in the lower part of the icy shell (Pappalardo et al. 1998; Pappalardo and Head 2001). In addition, differential tidal heating of warm ice or compositional differences could contribute to the buoyancy of upwelling plumes (Sotin et al. 2002; Pappalardo and Barr 2004). In this scenario, large chaos areas would be formed by coalescence of diapirs (Spaun et al. 1998; Schenk and Pappalardo 2004). Convection in the icy shell starts when the shell is sufficiently thick (e.g., McKinnon 1999), and then a

Fig. 1 Galileo image showing the chaotic area named Conamara Chaos (*upper right corner*) and numerous features collectively referred to as lenticulae, which include microchaos and domes. The area dimensions are 100×140 km

stagnant, cold and thermally conductive lid develops above the actively convective layer. Thermal diapirism would imply putting into contact the cold stagnant lid with ice plumes whose temperatures are close to the ice melting temperature (convective upwellings originate in the lower boundary layer of the convective system). This would have significant implications for the habitability of the upper part of the ice shell of Europa, as well as for the evolution of putative europan ecosystems. Thus, in this paper we consider the effect of thermal diapirism on the habitability of the ice shell of Europa, as well as its possible implications for astrobiological exploration.

The Lowest Temperature for Biological Activity and the Habitability of the Stagnant Lid

Price and Sowers (2004) have recently discussed evidence for microbial metabolic activity in Antarctic glacial ice at −40°C. Those authors found no threshold temperature below which metabolism would cease, and they found similar metabolic rates (for equal temperature) for microbes in water, soil, sediment, permafrost or ice. These results notably lower the minimum temperature for microbial metabolism below the usually cited value of around −20°C (e.g., Rothschild and Mancinelli 2001; Marion et al. 2003). As a consequence, life on Europa is more likely than before.

Thus, here we consider ice above ~230 K as potentially interesting for astrobiology. A small amount of liquid water can be shown to be available in veins in Europa's ice shell at temperatures as low as 230 K, since the presence of non-water ice substances lowers the melting point of the ice. For example, the eutectic of the water-sulfuric acid is 211 K (e.g., Kargel et al. 2000), and chloride salts can have a eutectic as low as 223–230 K (e.g., Bodnar 2001). Similarly, liquid water at similar temperatures exists in terrestrial polar ice and permafrost (e.g., Dash et al. 1995; Price 2000). Deming (2002) has speculated that life could be possible as long as liquid water is available, and she has coined the term "eutectophiles" for organisms living at liquid veins or reservoirs close to the eutectic point of water containing impurities. Although it is an interesting possibility, here we limit our considerations to temperatures above ~230 K.

The temperature at the base of the stagnant lid would be between 230 and 250 K, depending on the convective model and adopted ice rheology (e.g., Ruiz and Tejero 2003; Tobie et al. 2003). Due to these low temperatures, the possible biological activity inside the stagnant lid would be restricted, at most, to its lowest part, although convection in the ice shell could facilitate communication and material interchange between the base of the stagnant lid and the internal ocean. Thermal upwelling plumes transport materials (which could include nutrients, metabolic products, or microorganisms) from the lowest ice shell, and potentially from the ice shell/internal ocean interphase, to the upper ice shell, and even to the surface if the terrain is sufficiently disrupted (Pappalardo and Head 2001; Lipps and Rieboldt 2005). Thermal diapirs might themselves be habitable (Price 2003). The initial temperature of a thermal upwelling in the ice shell would be at least ~260 K, a typical value for the nearly isothermal interior of the convective layer (McKinnon 1999). This temperature permits microbial life in terrestrial ice environments (see Marion et al. 2003, and references therein). Subsequent plume cooling reduces (or even suppresses) the potential for life.

Thermal plumes must also have thermal effects in the country ice where they intrude, and they could generate transient brines (Pappalardo et al. 1998). The total lifetime for thermal diapirs with a radius of a few kilometers is ~10^7 years at most (Gaidos et al. 1999;

see also the next section). For this reason, Gaidos et al. (1999) have considered it unlikely that a global biosphere could be sustained in this way, although in any case thermal diapirs could have effects on habitability in the vicinity of plumes. The thermal history of an ice plume and its surroundings is analyzed in the next section.

Warming by Thermal Plumes

Figure 2 shows the thermal history of a vertical cylindrical intrusion of square section and its effects on the country ice. Calculations were performed using the classical theory for thermal histories of intrusions and their surroundings (e.g., Jaeger 1964, 1968). We used a vertical intrusion since it is a good analog for a thermal plume. Results for cylinders with square cross-section are very similar to those obtained for circular cylinders (e.g., Jaeger 1968), and the mathematical treatment is simpler. This simplification is justified since our goal is to obtain an approximate estimation of the warming effect instead of a detailed modeling.

For a vertical intrusion of square cross-section, and assuming equal thermal properties for the country and intrusive ice, the temperature at the time t following the intrusion

Fig. 2 Thermal history of an ice plume and their surroundings, shown for two ambient temperatures. The ice plume is assumed to be cylindrical, with square section, and 6 km width. Distances are given perpendicular to the face midpoints. *Labels* indicate time in years, and the intrusive process is instantaneous
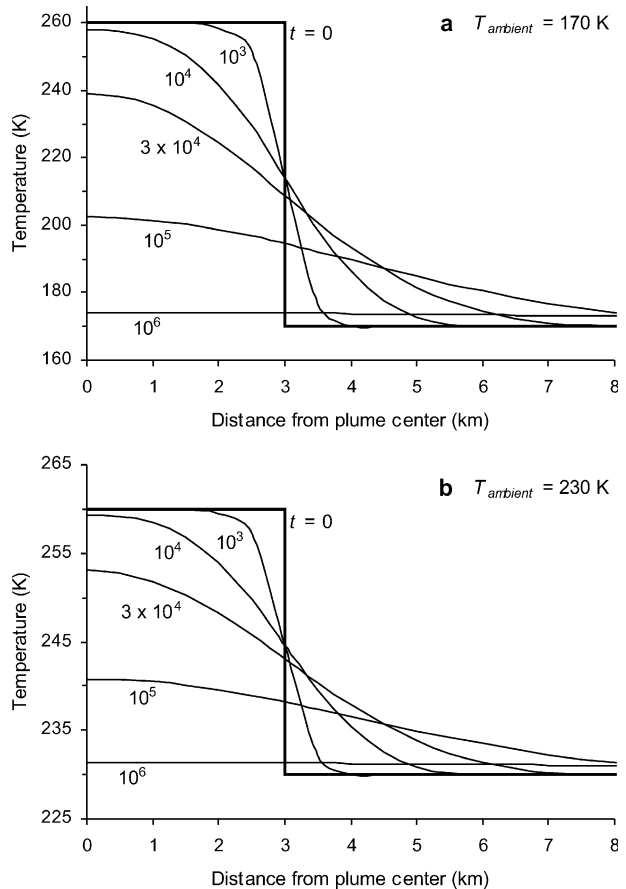
(which is considered to occur instantaneously at $t=0$), at a point with coordinates x, y, is given by

$$T(x, y, t) = T_0 + (T_i - T_0)\,\phi\,(x, t)\,\varphi\,(y, t), \qquad (1)$$

where x and y are the distances along the corresponding axes, which are perpendicular to the face midpoints (the origin of coordinates is in the center of the figure section), T_o is the temperature of the initial country material, and T_i is the initial temperature of the intrusion. The function $\phi\,(x, t)$ is given by

$$\phi\,(x, t) = \frac{1}{2}\left[\operatorname{erf}\left(\frac{x+a}{2(\kappa t)^{1/2}}\right) - \operatorname{erf}\left(\frac{x-a}{2(\kappa t)^{1/2}}\right)\right], \qquad (2)$$

where

$$\operatorname{erf}(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-w^2}\mathrm{dw},$$

a is the plume half-width and κ is the thermal diffusivity; the function $\varphi\,(y, t)$, for $y=0$ (temperatures calculated along axis x), is

$$\varphi(y, t) = \frac{1}{2}\left[\operatorname{erf}\left(\frac{a}{2(\kappa t)^{1/2}}\right) - \operatorname{erf}\left(\frac{-a}{2(\kappa t)^{1/2}}\right)\right]. \qquad (3)$$

These calculations do not include thermal effects due to the upper and lower ends of the intrusion, since these effects have limited influence on lateral temperature variations.

The calculations have been performed for a square plume 6 km width (the size of the lenticulae is typically between 4 and 8 km; Spaun et al. 2004), with an initial temperature of 260 K (typical of the actively convective layer; McKinnon 1999), intruding into country ice with temperature of 170 or 230 K. The higher value is representative of both the lower part of the stagnant lid and the lower temperature in which metabolic activity has been reported; in turn, 170 K is the approximate intermediate value between the surface temperature (~100 K) and the temperature at the base of the stagnant lid. Finally, the coefficient of thermal diffusion was taken as 2×10^{-6} m^2 s^{-2}, a value roughly valid for water ice near to 200 K (see for example Kirk and Stevenson 1987).

Figure 2 shows that warming of the country ice by thermal plumes is limited. However, convective plumes intruding close to the stagnant lid base can warm several kilometers of country ice above 230 K during periods of 10^5 years, and hundreds of meters above 240 K during periods of 10^4 years. Consequently, if there are organisms inside the ice shell, a thermal plume could cause an aureole of biological activation or reactivation in the country ice, in a way similar to that by which a terrestrial magmatic intrusion causes an aureole of contact metamorphism.

If chaos areas have originated due to coalescence of diapirs, then the disrupted ice in these areas may be an adequate habitat for microorganisms. Indeed, close packing of intrusions produces a generalized rise of temperature, which peaks close to the mean temperature between the initial country material and intrusion temperatures (see Jaeger 1968). Diapirs that have coalesced near the base of the stagnant lid should therefore give an extended zone (even hundreds of kilometers across) above ~240 K during tens of thousands of years.

Discussion and Implications for Astrobiological Exploration

It has been suggested that variations in orbital parameters could cause episodic changes in tidal heating and hence in ice shell dynamics and thickness, with oscillations between a thin and thermally conductive state and a thick and convective one (Hussmann and Spohn 2004). If the ice shell is thick and convective, an increase of eccentricity could generate so much tidally dissipated heat that it could not be efficiently transported by convection. In this case, the ice shell heats, melts from this base and thins, and convection ceases. As a consequence, thermal diapirism, and material interchange between the stagnant lid and the internal ocean potentially driven by convection ceases too (although liquid water could ascent through fractures). A subsequent decrease of eccentricity would lead to a progressive cooling and thickening of the ice shell, and to convection and thermal diapirism and their potential effects for biological activity. Thus, the habitability conditions could cyclically vary in the ice shell of Europa.

Chaos areas are considered to be favorable places for the search of biomarkers on Europa, based on evidence for material interchange between surface and subsurface, presence of non-ice components, and possibly melting (e.g., Chyba and Phillips 2001; Figueredo et al. 2003). A similar argument can be proposed for individual lenticulae and microchaos features. Additionally, terrain disruption leading to chaos and microchaos features would favor the arrival of organisms and/or metabolic products at the surface, especially if the stagnant lid is only a few kilometers thick, as suggested by high surface heat flow deduced from geological indicators (Ruiz and Tejero 2000; Ruiz 2005), or deformation induced by plume upwellings (Nimmo and Manga 2002).

Life at very low temperature requires the presence of cryoprotectant substances. It is known that terrestrial life at low temperature is adapted to low water activity in the same way as it is adapted to high osmolarity or desiccation conditions (e.g., Potts 1994; Thomas and Dieckmann 2002). This implies that a decrease in temperature would be equivalent to an increase in osmolarity or desiccation. A typical physiological response to these conditions

Fig. 3 Intracellular accumulation of compatible solutes by organisms living in hypothetical habitats within Europa's ice shell: **a** the stagnant lid warmed by thermal diapirs, and **b** the diapirs themselves. *Dots* indicate the relative importance of both compatible solute accumulation and their interchange with the environments
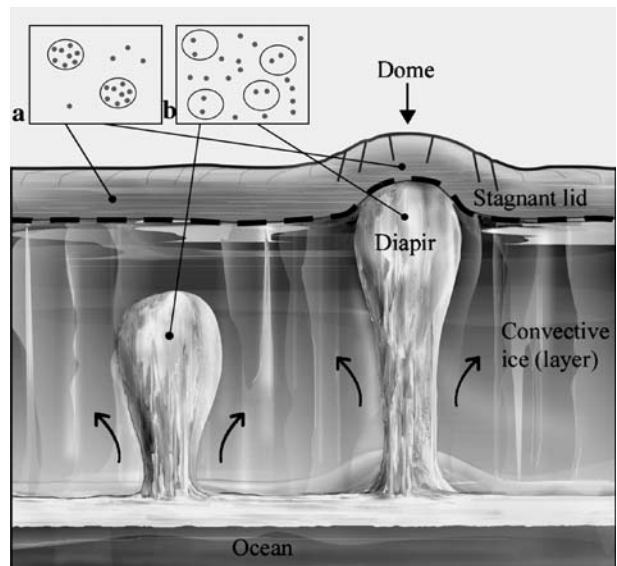
is intracellular accumulation of compatible solutes, which can reach high intracellular concentrations (Kempf and Bremer 1998; DasSarma and Arora 2002; Elbein et al. 2003). In consequence, the synthesis of compatible solutes, like trehalose, glycerol or glycine betaine, in response to freezing conditions could result in an important survival strategy for any organism living within the ice shell of Europa (Fig. 3), since these substances are efficient cryoprotectants (Welsh 2000; Elbein et al. 2003; Cleland et al. 2004; Yancey 2005). In a similar way, Stan-Lotter et al. (2003) have experimentally shown that the presence of glycerol enhances the survival rate of halophilic archeobacteria during deep freezing–drying in simulated Martian atmosphere conditions.

The synthesis of compatible solutes is widely observed on the Earth, and it has originated several times in distant phylogenetic groups, for example methanogenic, halophilic and hyperthermophilic archaea, halophilic bacteria, yeasts, plants, insects, and fishes (e.g., Roberts 2000; Roeßler and Müller 2001; Grant 2004; Hincha and Hagemann 2004). This suggests the synthesis of compatible solutes as a potential universal metabolic strategy for hypersaline, desiccation or low temperature conditions. Moreover, the effect of osmolyte synthesis could be doubly advantageous, because of the property of these substances of sustaining latency in some organisms (Welsh 2000).

We therefore propose that a future europan lander should prospect for the signature of compatible solutes and that lenticulae and chaos features are the most promising places for such inspection. The detection of compatible solutes can be performed through Raman spectroscopy, as has been shown for trehalose in Antarctic samples (Wynn-Williams and Edwards 2000; Edwards et al. 2005). Aqueous solutions of compatible solutes have a relatively wide range of eutectic temperatures (for example, trehalose and glycerol have eutectic temperatures of 244 and 227 K respectively). So, although eutectic temperature can be lowered further by adding other impurities (e,g., salts), chaos regions where close diapirism seems to have occurred (Schenk and Pappalardo 2004) would have more potential for detection of low-temperature eutectic substances than isolated lenticulae, where the effects of thermal plumes must be more limited. Thus, chaos and lenticulae are major objectives for the search of biomarkers on Europa, and maybe for understanding the evolution of the habitability of its upper ice shell.

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