Icarus 253 (2015) 16–24

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Constraining the thickness of Europa's water–ice shell: Insights from tidal dissipation and conductive cooling

Lynnae C. Quick [a,b,*], Bruce D. Marsh [b]

[a] Johns Hopkins University, Earth and Planetary Sciences Department, 3400 North Charles Street, Baltimore, MD 21218, United States
[b] The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, United States

ARTICLE INFO

Article history:
Received 6 October 2014
Revised 29 January 2015
Accepted 16 February 2015
Available online 24 February 2015

Keywords:
Europa
Geophysics
Interiors
Tides, solid body
Jupiter, satellites

ABSTRACT

The time of crystallization of a 100 km thick ocean on Europa is estimated using a Stefan-style solidification solution. This solution is then extended to estimate the present thickness of the ice shell. It is assumed that the shell is initially in a steady-state conductive regime, and the ocean is taken to be an infinite liquid half space cooling from above. We find that in the absence of tidal heating and without the presence of low-eutectic impurities to serve as anti-freezes, a 100 km thick ocean solidifies in about 64 Myr. Conversely, when considering the present thickness of Europa's ice shell, if tidal heating is included at a global dissipation rate of ~1 TW, the shell is found to be, on average, approximately 28 km thick. However, if this dissipative heating is solely restricted to the shell, the local rate of heating may vary significantly due to crustal compositional heterogeneities and it is shown that this process may, in turn, produce thermal maxima in the crust, which could lead to local melting and structural instabilities, perhaps associated with the formation of chaos regions. Our approach is also extended to Ganymede and Callisto in order to estimate the time of solidification of their putative subsurface oceans and the current thicknesses of their ice-I shells.

1. Introduction

Estimated thicknesses for Europa's ice shell range from a few kilometers or less (Carr et al., 1998; Greenberg et al., 1998, 1999; Williams and Greeley, 1998; Turtle and Pierazzo, 2001; O'Brien et al., 2002) to $\geqslant$10 km (Ojakangas and Stevenson, 1989; Pappalardo et al., 1998; Rathbun et al., 1998; McKinnon, 1999; Schenk, 2002; Figueredo et al., 2002; Sotin et al., 2002; Schenk, 2002; Hussmann et al., 2002; Tobie et al., 2003). Europa's crustal thickness is central to understanding the formation and development of various surface features such as chaos and lenticulae, and also for regulating the potential for ascent and eruption of cryomagmatic melts. Therefore, placing firmer constraints on its value is vitally important to obtaining a more complete understanding of the various geophysical processes that are currently occurring, or that may have recently occurred, on the icy moon.

Complete solidification of Europa's ocean must be forestalled by a high degree of internal heating due mainly to tidal effects in the Jovian system. This process, clearly being in a near or quasi steady state and having existed for billions of years, has likely contributed greatly to the ongoing evolution of the ice shell. Judging from the heterogeneous nature of Europa's surface features (Greeley et al., 1998, 2000; Pappalardo et al., 1999), the crust itself is also likely to be highly heterogeneous. Although later we will consider the possible sequence of events leading to Europa's present state of an extensive ocean underlying a relatively thin crust, here we simply use this state as an initial condition.

We therefore assume that Europa's icy shell was formed by the gradual freezing of its ocean from above, and employ a Stefan-style (i.e., Neumann's solution) solidification solution to analyze three slightly different situations: first, in order to set an upper bound on the solidification timescale, an estimate is made of the time of solidification of the subsurface ocean in the absence of any internal heat sources; second, bounds are placed on the thickness of the ice shell assuming a global dissipation rate as a steady heat source; and third, when dissipation is restricted to solely take place within the ice shell, the thermal regime of the shell is investigated as a function of its thickness and the local heating rate, both of which may vary due to compositional heterogeneities in the shell. These results are then employed to discuss possible present day geological processes on Europa.

---

* Corresponding author at: NASA Goddard Space Flight Center, Code 698-Planetary Geodynamics Laboratory, 8800 Greenbelt Road, Greenbelt, MD 20771, United States.

E-mail address: lynnae.c.quick@nasa.gov (L.C. Quick).

http://dx.doi.org/10.1016/j.icarus.2015.02.016
0019-1035/© 2015 Elsevier Inc. All rights reserved.

Finally, we extend our analyses to investigate the potential for internal oceans in Ganymede and Callisto and the corresponding thicknesses of their icy crusts.

2. The Stefan problem

The change of phase of water from liquid to solid and the resulting release of latent heat involved in the growth of Europa's shell is akin to the process of cooling of a sheet of magma, which has long been studied (e.g., Jaeger, 1965, 1968; Marsh, 1989, 2007). The striking differences, of course, are: (1) the water–ice system solidifies at a specific temperature, whereas silicate magmas have a pronounced liquidus and solidus which are separated by 200° or more, and (2) the ensuing solid in silicate systems is more dense, and thus of smaller volume, than the melt from which it came. Nevertheless, this method of analysis is applicable to investigating the crystallization of Europa's ocean.

Here, Neumann's solution of the Stefan Problem is considered, which describes the cooling and solidification of an infinite half space of liquid where solidification takes place at the solidification front, i.e., the well-defined boundary separating solid and liquid phases, along which the liquid crystallizes to a single, pure compound. The solidification front is thus the plane that moves in response to the addition and subtraction of heat from the system. Assuming an initially ice free, pure water ocean on Europa, the solidification front, $S(t)$, measures the position of the ice–water interface over time, which defines the instantaneous thickness of the ice shell in response to the gradual cooling of the ocean (Fig. 1). The full solution to the Stefan Problem is given in the Appendix A. This solution is obtained by solving the diffusion equation in each medium, ice and water, and subsequently matching the solutions at the interface (i.e., at $S(t)$) through the boundary condition that the upward heat flux out of the ice is balanced by the sum of the heat flow from the underlying water and latent heat released during the progressive freezing of the ocean (see boundary conditions (iv) and (v) in the Appendix A). A well-known result of Neumann's Solution is that the position of the solidification front is given exactly by:

$$S'(t) = 2b\sqrt{F_1} \tag{1}$$

(see (A8) in the Appendix A) where $S'(t) = (S(t)/L)$ is the non-dimensional form of $S(t)$, and $F_1 = \kappa_1 t/L^2$, where κ_1 is the ice thermal diffusivity and L is the ice shell thickness. The constant b contains all the effects of both the latent heat (H) and the contrasting thermal diffusivities (κ_1 and κ_2) between ice and water. This equation states that the ice shell grows in direct proportion to the product of the square root of the dimensionless Fourier number ($\kappa_1 t/L^2$) and the constant b, which is always of order unity (i.e., $0 < b < 1$). After applying the appropriate boundary conditions, the transcendental equation for determining the constant b as a function of all the thermal properties and the prevailing temperatures in the system emerges, namely:

$$be^{b^2} erf(b) = \frac{c_{p_1}(T_{melting} - T_{cold})}{H\sqrt{\pi}} \tag{2}$$

where c_{p_1} is the specific heat at constant pressure of the solid phase (i.e., ice), $T_{melting}$ is the temperature at which the liquid phase melts, and T_{cold} is the surface temperature. The mathematical procedure necessary to obtain this expression is reviewed in detail in the Appendix A.

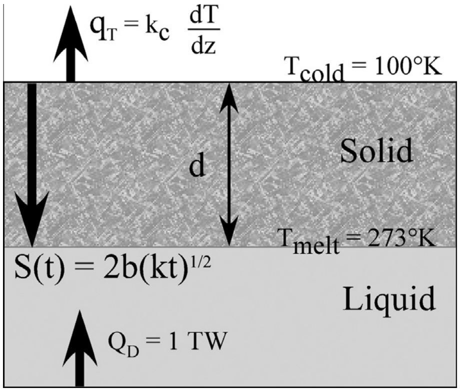

Fig. 1. Geometry for solidification of Europa's subsurface ocean. Here, the ice shell is represented as the solid layer, while the subsurface ocean is represented as the layer of liquid. The upper surface of the crust is assumed to have the constant temperature, $T = 100$ K, while the boundary between the crust and ocean has a constant temperature, $T = 273$ K. Here, q_T represents the conductive heat loss that promotes advancement of the solidification front. Basal heating from tidal dissipation is added to the system at a rate of ~1 TW.

In the following sections, we will apply (1) and (2) to estimate the timescale for complete crystallization of Europa's ocean and the thickness of the ice shell.

3. Solidification of Europa's ocean

To estimate the time of complete solidification of Europa's ocean, the ocean itself is taken to be an initial liquid half space freezing from the top down, with no internal heating. Since Europa's hydrosphere is thin (~100 km) relative to the radius of the moon itself, solidification may be approximated as a flat ice slab overlying a sheet of water. The rate of freezing of the ice shell may then be measured by the temporal progression of the solidification front, $S(t)$ (Fig. 1).

The temporal progression of the solidification front is described above by (1). Recalling that $S'(t) = S(t)/L$ and $F = \kappa t/L^2$, (1) may be rewritten to yield the time, t, of complete solidification, namely,

$$t = \frac{[S(t)]^2}{4\kappa b^2} \tag{3}$$

Here, $\kappa = 6.4 \times 10^{-6}$ m^2/s is the thermal diffusivity of water ice at 100 K (Hobbs, 1974) and the constant b may be obtained from a plot of $be^{b^2} erf(b)$ vs. b as described in the Appendix A.

Taking $c_p = 833$ J/kg K (Petrenko and Whitworth, 1999) as the specific heat of the ice shell at $T_{cold} = 100$ K, $H = 330$ kJ/kg as the latent heat of fusion of ice at 273 K (Carslaw and Jaeger, 1959; Hobbs, 1974), $T_{melting} = 273$ K, and employing (2) as described above to determine b, returns $b = 0.438$ (Fig. 4-31 of Turcotte and Schubert, 2002; Marsh, 1989, in preparation).

Taking the initial depth of Europa's ocean to be $S(t) = 100$ km (Anderson et al., 1998; Pappalardo et al., 1999) and using these parameters in (3) returns a time for complete solidification of approximately 64 Myr. This result is reasonable under these conditions, and illustrates that in the absence of tidal heating, it is highly unlikely that any ocean would persist in Europa until the present day. The presence of a substantial liquid layer inside Europa today clearly reflects the significance of tidal heating, and to a much lesser extent, the likelihood of sulfate or chloride salts and/or mineral acids, acting as low-eutectic contaminants (Kargel, 1991a; Hogenboom et al., 1995; Kargel et al., 2000; Zolotov and Kargel, 2009; Brown and Hand, 2013).

4. Thickness of Europa's ice shell

As previously mentioned, the prevailing thickness of Europa's crust reflects a balance between local thermal and compositional regimes and outward global heat loss. The thickness of the ice shell places fundamental constraints on the proximity of water to the surface and the ease with which any subsurface melts may extrude