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Convective–conductive transitions and sensitivity of a convecting ice shell to perturbations in heat flux and tidal-heating rate: Implications for Europa

Giuseppe Mitri [a,b,*], Adam P. Showman [a]

[a] Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA
[b] International Research School of Planetary Sciences, University G. d'Annunzio, Pescara, Italy

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Abstract

We investigate the response of conductive and convective ice shells on Europa to variations of heat flux and interior tidal-heating rate. We present numerical simulations of convection in Europa's ice shell with Newtonian, temperature-dependent viscosity and tidal heating. Modest variations in the heat flux supplied to the base of a convective ice shell, ΔF, can cause large variations of the ice-shell thickness $\Delta\delta$. In contrast, for a conductive ice shell, large ΔF involves relatively small $\Delta\delta$. We demonstrate that, for a fluid with temperature-dependent viscosity, the heat flux undergoes a finite-amplitude jump at the critical Rayleigh number Ra_{cr}. This jump implies that, for a range of heat fluxes relevant to Europa, two equilibrium states—corresponding to a thin, conductive shell and a thick, convective shell—exist for a given heat flux. We show that, as a result, modest variations in heat flux near the critical Rayleigh number can force the ice shell to switch between the thin, conductive and thick, convective configurations over a $\sim 10^7$-year interval, with thickness changes of up to $\sim$10–30 km. Depending on the orbital and thermal history, such switches might occur repeatedly. However, existing evolution models based on parameterized-convection schemes have to date not allowed these transitions to occur. Rapid thickening of the ice shell would cause radial expansion of Europa, which could produce extensional tectonic features such as fractures or bands. Furthermore, based on interpretations for how features such as chaos and ridges are formed, several authors have suggested that Europa's ice shell has recently undergone changes in thickness. Our model provides a mechanism for such changes to occur.

Keywords: Europa; Geophysics; Ices; Interiors; Satellites of Jupiter; Thermal convection; Thermal histories

1. Introduction

We investigate the response of a conductive and convective ice shell to changes of heat production in the silicate mantle and in the ice shell of Jupiter's satellite Europa. Estimates of Europa's ice-shell thickness range from $\sim$3 to 50 km (Turtle and Ivanov, 2002; Schenk, 2002; Hussmann et al., 2002; Tobie et al., 2003; Williams and Greeley, 1998; Greenberg et al., 1998, 1999). This uncertainty in thickness translates directly into an uncertainty in the heat-transfer mechanism: if the shell is thick, the rigid surface could be underlain by a layer of convecting water ice (Cassen et al., 1979; McKinnon, 1999; Pappalardo et al., 1998; Showman and Han, 2004; Tobie et al., 2003), whereas a thin shell would instead transport the heat by conduction (Greenberg et al., 1998, 1999). Interestingly, most estimates of the shell thickness (10–40 km) imply that the ice-shell Rayleigh number is near the critical Rayleigh number, which is $\sim 10^6$ for realistic temperature-dependent viscosities (e.g., McKinnon, 1999).

The implications of surface landforms for the configuration of the ice shell remain controversial (Pappalardo et

* Corresponding author.
E-mail addresses: mitri@lpl.arizona.edu (G. Mitri), showman@lpl.arizona.edu (A.P. Showman).

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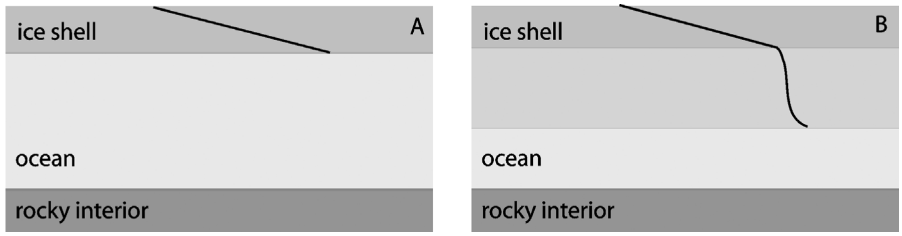

Fig. 1. Structures and temperature profiles for two possible configurations of the ice shell of Europa. The heat generated in the interior of the planet might be shed by simple conduction through a relatively thin ice shell directly overlying a subsurface ocean (A), or transported equally well through a much thicker ice shell containing of an actively convecting layer (B). Because of the large viscosity near the surface, the ice shell in B develops a stagnant lid at the surface; the convective motions are confined to a sublayer of the ice shell. The states (A) and (B) could have very similar heat fluxes.

al., 1999). Numerous small (3–30-km diameter) pits, uplifts, and disrupted spots, as well as larger chaos terrains such as Conamara Chaos and the Mitten, have been attributed to convection in an ice shell at least 10-km thick (Pappalardo et al., 1998; Head and Pappalardo, 1999; Collins et al., 1999, 2000; Figueredo et al., 2002). But other authors have suggested that chaos results instead from melt-through of a thin ice shell (Williams and Greeley, 1998; Greenberg et al., 1999, 2003; O'Brien et al., 2002; Melosh et al., 2004). Similarly, some formation mechanisms for ridges require a thin-ice shell (Greenberg et al., 1998), while other ridge-formation mechanisms allow a thicker shell (Melosh and Turtle, 2004; Nimmo and Gaidos, 2002). Figueredo and Greeley (2004), Prockter et al. (1999), Pappalardo et al. (1999), and others have shown that tectonic resurfacing (i.e., ridge building) decreased rapidly after ridged-plains formation and that chaos formation has increased with time. These authors suggest that the transition from tectonic- to chaos resurfacing resulted from the gradual thickening of the ice shell. On the other hand, Greenberg et al. (1999, 2000, 2003) suggests a different scenario where the chaos and tectonic terrains form concurrently and continually resurface Europa.

Fig. 1 shows the schematic structures and temperature profiles for the two plausible configurations of the ice shell (conductive and convective). Both structures have a steep temperature gradient within the top layer and lose heat conductively through this layer. Within the conductive regime, heat flux follows a rough inverse proportionality to layer thickness, so thicker layers transport smaller heat fluxes. In layers thicker than a critical value, δ_{crit}, the Rayleigh number exceeds the critical Rayleigh number, and convection begins. The assumption is often made that the heat flux near this transition is a continuous function of the layer thickness. In this case, the heat flux of the conductive solution (A) would exceed that of the convective solution (B). However, laboratory experiments in a fluid with temperature-dependent viscosity indicate that, at the critical Rayleigh number, the convection jumps directly to a finite-amplitude regime (Stengel et al., 1982), implying that the heat flux for a convective layer infinitesimally thicker than δ_{crit} *exceeds* that for a conductive layer infinitesimally thinner than δ_{crit}. This implies that the heat flux for a convective layer infinitesimally thicker than δ_{crit} will be *equal* to the heat flux for a conductive state that is substantially thinner than δ_{crit}. Therefore, for a range of conditions near the critical Rayleigh number, two solutions—one a thin, conductive shell and the other a thick, convective shell—exist for a given basal heat flux. The existence of two solutions for a given heat flux raises an obvious question: What determines which of the two states Europa occupies? And can Europa switch between these states? Furthermore, in the convective regime, how sensitive is the ice-shell thickness to perturbations in the basal heat flux and internal tidal-heating rate? Answers to these questions have important implications for the time history of Europa's ice-shell thickness, and hence for Europa's surface geology.

These questions become even more relevant considering that Europa's heat-production rate may vary in time. Io's measured heat flux exceeds that possible in steady state, which may result from $\sim 10^8$ year oscillations in Io's eccentricity and tidal-heating rate caused by coupled orbital-geophysical feedbacks (Greenberg, 1982; Ojakangas and Stevenson, 1986). Similar feedbacks may be relevant for Ganymede (Showman et al., 1997) and Europa (Hussmann and Spohn, 2004). (In any case, oscillations of Io's eccentricity would cause oscillations in Europa's eccentricity and tidal-heating rate even in the absence of any feedbacks in Europa.) The observational suggestion that Europa's geology has shifted from ridge to chaos formation over the past 50 Myr (Pappalardo et al., 1999; Prockter et al., 1999; Greeley et al., 2000; Kadel et al., 2000; Figueredo and Greeley, 2004) supports the idea that variations in Europa's internal heating rate and ice-shell thickness have occurred over time.

Here we present two-dimensional numerical simulations of convection in Europa's ice shell, including tidal heating, to investigate the sensitivity of the ice-shell thickness to perturbations in basal heat flux and interior tidal-heating rate. Our simulations confirm Stengel et al.'s (1982) result that the heat flux undergoes a finite-amplitude jump at the critical Rayleigh number; furthermore, this occurs at heat fluxes relevant to Europa ($\sim$0.02–0.06 $\mathrm{W\,m^{-2}}$ depending on the viscosity and tidal-heating rate). We determine the amplitude of the heat-flux jump and discuss the consequences for the thermal evolution of the ice shell. We show that, if the system is near the critical Rayleigh number, small changes in the heat flux can force the system to switch from conductive to convective configurations with large variations in