Modelling the shells of icy moons: thermoviscous thin-layer dynamics

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Numerous icy moons exist throughout our solar system and may potentially harbour life. Observations of Enceladus, a small icy moon of Saturn, have shown that the moon is dynamic, with geysers and an inferred liquid ocean that is maintained by tidal heating (Spencer and Nimmo, 2013). Similarly, Europa, an icy moon of Jupiter, likely contains a liquid ocean between a rocky core and a thin ice shell (figure 1). The dynamic nature of these moons begets questions of their formation history, which requires a precise understanding of the temperature structure and flow dynamics of the outer shell. The outer shell is much wider than thick, allowing us to treat the shell as a thin viscous layer. Moreover, the temperature variation is on the order of 200 K, leading to a considerable variation in the ice viscosity. Thus, in this project, we will analyse the fluid mechanics of a thin viscous shell with large variations in viscosity.

Drawing an analogy between the shells of icy moons and ice shelves of Antarctica, we will derive the leading-order, depth-integrated flow equations for the flow of the shell while simultaneously solving for the variation in the shell viscosity with temperature. The resulting system involves a rich three-part cyclic coupling between the viscous fluid mechanics of the shell, the transport of the temperature field and of the free surfaces, the softening (reduction in viscosity) of the flow by differential heating, which couples back to the viscous fluid mechanics. We will conduct the first comprehensive fundamental fluid-mechanical analysis of viscous thin-layer flows with temperature transport and thermal softening.

It has been proposed that the cold outer boundary condition of an icy moon produces a no-slip boundary condition, with the rest of the shell flowing as a viscous gravity current pinned on one side (e.g. Ashkenazy et al., 2018). Alternatively, the thermal regime can produce leading-order free-stress conditions, creating an extensional flow regime where the viscosity field is height dependent, as found in ice shelves (Pegler and Worster, 2012). Here we will demonstrate that the extensional regime is more consistent with viscosity structures resulting in thermoviscous boundary layers (Ockendon and Ockendon, 1977). The project addresses the general fluid mechanics of differentially heated viscous layers, forming a theoretical basis for (a) examining the effects of differential melting on the long-term evolution of icy moons, and (b) new problems addressing differentially heated thin-viscous-layer dynamics undergoing internal convection (Spencer and Nimmo, 2013).

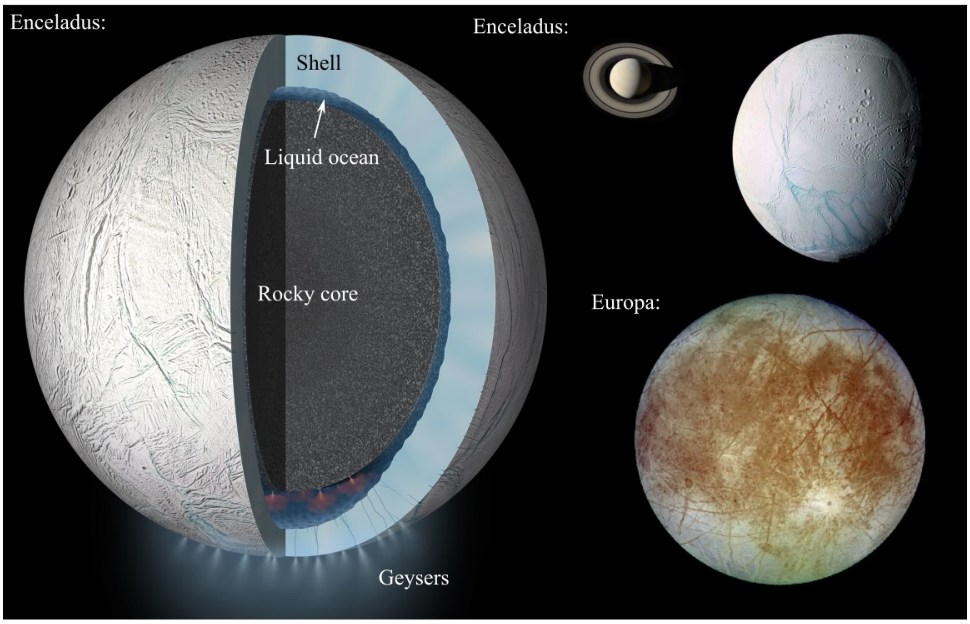

Figure 1: A cross-section of Enceladus showing the outer shell exterior to a liquid ocean. Europa, a moon of Jupiter, likely has a similar structure.

References

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