EFFECT OF A SUPERFICIAL POROUS BRITTLE LAYER ON THE THERMAL EQUILIBRIUM OF EUROPA'S ICE SHELL. R. Himo[1], S. Carpy[2], G. Tobie[2] and C. Castelain[1], [1]Université de Nantes, CNRS, Laboratoire de thermique et énergie de Nantes, LTeN, UMR 6607, F-44000 Nantes, France. (rawad.himo@univ-nantes.fr), [2]Université de Nantes, CNRS, Laboratoire de Planétologie et Géodynamique, LPG, UMR 6112, F-44322 Nantes, France..

Introduction: Magnetic and gravity data acquired by the Galileo mission revealed that Europa harbors a salted water ocean underneath an ice shell and in direct contact with the silicate mantle [1, 2]. Recent reanalysis of the gravity data [3] indicates that the hydrosphere (ocean+ice) may be thinner than initially estimated, but the relative thickness of the ice shell and the ocean still remain poorly constrained. Inferring the current thickness of Europa's ice shell and its evolution through time is a long standing debate [4–8]. The equilibrium thickness depends on the amount of energy inside Europa, comprising both radiogenic and tidal power, as well as the efficiency of heat transfer through the ice shell. Excessive heating could lead to thinner ice shells, which are predominantly conductive. Tidal heating in both icy shell and rocky mantle varies with latitude and is expected to be much higher at the poles than the equator [6, 9]. Both tidal dissipation and heat transfer in the ice shell are controlled by the rheology of water ice. Furthermore, the radiogenic heat power in the rocky mantle is also a key factor for constraining the ice shell thickness.

Hence, some surface features have been attributed to convective motions, requiring a thick ice shell [10–12], while others implies thin and conductive ice shell [13, 14]. However, other geological evidence hinted the presence of a brittle lithosphere [14, 15]. Nevertheless very few studies on Europa have addressed the complex behavior of brittle dynamics. The latter is not volume conservative, cracks and micro-pores increase or decrease depending on the flow [16]. Consequently the strength of the material is expected to vary accordingly. Additionally, only a few models have tried to account for the changes in the thermal properties of brittle porous ice. In this study, we investigate the effect of a superficial porous low-conductivity brittle layer on the ice shell thickness.

Numerical Model: The current numerical model is developed in-house using the Finite Element Method. The mass, momentum and heat conservation are solved, considering variable thermal conductivity and melt/crystallization process at the ice/ocean interface and within the layer. In addition, the porous brittle dynamics is modeled using a non-volume-conservative approach to model the generation, propagation and closing of small porous cracks in the upper part of the icy shell.

Heat fluxes from the rocky mantle including both radiogenic and tidal power are imposed on the bottom, along with volumetric tidal heating and an upper surface isotherm consistent with solar illumination. The temperature-dependent viscosity is modelled assuming a diffusional flow law[17]. Thermal properties and rheology depend not only on temperature of the ice, but also on the porosity in the brittle lithosphere, which strongly reduce the near-surface thermal conductivity. The superficial porous brittle layer affects the thermal state and dynamics of the entire shell by increasing the near-surface thermal gradients and by making the near-surface more deformable.

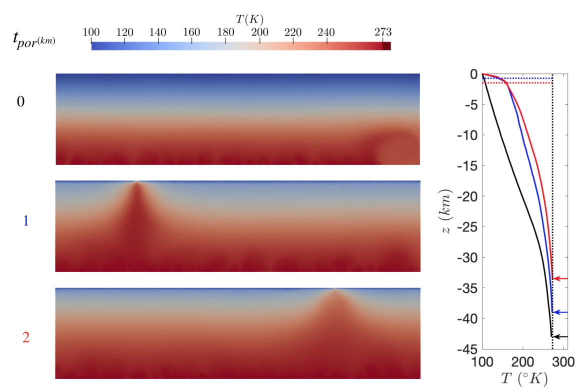

Figure 1: Contour plots (left) show three temperature distributions for three tested brittle porous layer thicknesses, namely 0, 1 and 2 km from top to bottom respectively. The average thermal profile is shown on the right. Black, blue, and red curves refer to the thermal profile for a brittle porous layer thickness equal to 0, 1 and 2 km, respectively. The blue and red horizontal dotted lines refer to the 1 and 2 km depths respectively, and the vertical dotted line refers to the 273 K isotherm.

Results: An example set of numerical simulations is shown in Figure 1, where three different porous brittle layers are tested, namely 0, 1 and 2 km. For all three cases, the grain size is 0.5 mm (controlling the viscosity), the heat flux coming from the silicate mantle is set to 5 mW/m^2, and the maximum tidal heating is 2 μW/m^3, corresponding to the typical tidal heating rate in the equatorial region at present [6, 9]. It can be seen from temperature distributions on the left that convection is more prominent in the presence of a porous layer, even if the total layer thickness reached in this case at equilibrium is about 10 km smaller.

The presence of a brittle porous layer has two effects:(1) the near-surface low conductivity reduces the conductive lid thickness and hence increase the thickness of convective sublayer, (2) the reduced surface strength promotes the local rise of warm materials near the surface, as illustrated on Figure 1 for the two examples with 1 and 2 km thick porous layers.

To investigate the possible thermal state of Europa's ice shell, we have systematically varied the grain size (0.5-5 mm), the porous layer thickness (0-2 km), the tidal heating rate (0.25-30 μW.m^{-3}), heat flux from the silicate mantle (5-15 mW.m^{-2}) over a wide range of values corresponding to different periods during Europa's evolution. The whole set of simulation results and their implications for the past evolution and present thermal state and equilibrium thickness of Europa's ice shell will be presented at the conference.

References: [1] Khurana K. et al. (1998) *Nature*, 395(6704):777–780. [2] Anderson J. D. et al. (1998) *Science*, 281(5385):2019–2022. [3] Gomez Casajus L. et al. (2020) *Icarus*, 114187. [4] Ojakangas G. W. and Stevenson D. J. (1989) *Icarus*, 81(2):220 – 241. [5] Hussmann H. et al. (2002) *Icarus*, 156(1):143 – 151. [6] Tobie G. et al. (2003) *Journal of Geophysical Research*, 108(E11). [7] Nimmo F. et al. (2007) *Icarus*, 191(1):183 – 192. [8] Howell S. M. et al. (2020) *Lunar and Planetary Science Conference* 2957. [9] Behounkova M. et al. (2021) *Geophys. Res. Lett.*, in press. [10] McKinnon W. B. (1999) *Geophysical Research Letters*, 26(7):951–954. [11] Pappalardo R. T. and Barr A. C. (2004) *Geophysical Research Letters*, 31(1). [12] Schenk P. M. and Pappalardo R. T. (2004) *Geophysical Research Letters*, 31(16). [13] Greenberg R. et al. (1998) *Icarus*, 135(1):64–78. [14] Nimmo F. and Manga M. (2009) *Europa*, 381–404. [15] Pappalardo R. T. et al. (1998) *Nature*, 391(6665):365–368. [16] Durham W. B. et al. (1997) *Journal of Geophysical Research: Planets*, 102(E7):16293–16302. [17] Goldsby D. and Kohlstedt D. L. (2001) *Journal of Geophysical Research: Solid Earth*, 106(B6):11017–11030.

Acknowledgments: This work is part of the EXPRODIL project funded by the ”Région Pays de la Loire”, France. The authors also acknowledge funding from CNES for the preparation of the NASA Europa Clipper and ESA JUICE mission.