SNOW, SLUSH, OR SOLID? LATENT HEAT TRANSFER THROUGH POROUS HIGH-PRESSURE ICE LAYERS IN ICY SATELLITES AND OTHER WATER WORLDS. J. C. Goodman, Wheaton College, Norton MA 02766 USA (goodman_jason@wheatoncollege.edu).

Introduction: It has long been recognized that the deep water layers of large icy satellites (Ganymede, Callisto, Titan) [1] and hypothetical terrestrial exoplanets with sufficiently deep oceans [2] probably have high-pressure ice phases in equilibrium with liquid in their depths, but the ratio of solid to liquid is not constrained by thermodynamic equilibrium. Are these layers mostly solid with liquid-containing pores, or mostly liquid with a bit of solid "snow"? The various icy satellites and the high-pressure ices they contain are physically similar enough that "back-of-the-envelope" calculations can constrain all of them: we pick pure-water oceans on Ganymede as a concrete example, but extend the idea to other worlds and to brine oceans as well. We use a convective stability argument to rule out "snow" layers for pure water oceans, and solve a porous flow model to estimate the liquid fraction of a mostly-solid layer. We show that latent heat transport by percolation through very slightly porous ice can carry these worlds' radiogenic/tidal heat flux on its own, and discuss the astrobiological and geological significance of this porous flow.

Geophysical high-pressure ice layers are two-phase mixtures: The melting point of high-pressure ice (III, V, or VI; HP ice hereafter) increases with pressure much more rapidly than an adiabat in liquid water; thus, sufficiently deep convecting water oceans have a HP ice layer below some pressure horizon. However, this layer cannot be completely solid: for all these worlds, the temperature gradient needed to carry radiogenic heat through the HP ice by conduction is steeper than the phase equilibrium line: were any amount of entirely solid ice present, it would insulate so well that its lower surface would promptly melt away. Thus, as has been recognized for decades [3], HP ice layers in water worlds must be solid/liquid mixtures that lie along the melting curve. Also, heat from the silicate interior cannot be transported by conduction alone. (Other authors [4] find that a convecting HP ice layer should also be partially molten.)

However, any liquid/solid fraction is possible on the melting curve. Is this layer a few crystals of "snow" falling through liquid, a slush, or nearly solid with tiny pores of liquid?

Solid ``snow" falling through liquid is convectively unstable: If the two-phase mixture is primarily liquid, it will convect, because the melting $T(P)$ curve is steeper than the liquid adiabat. A fluid parcel at the top of the two-phase mixture must partially freeze as it descends, releasing latent heat to keep the mixture along the melting curve; rising parcels must melt. We calculate that ~10% of an initially liquid parcel would freeze if it descended to the silicate interior. At least some of this solid fraction would gravitationally settle to the seafloor and be unavailable to cool the parcel as it reascends: we find that this would lead to runaway convection that would transport heat upward and HP ice downward until the entire two-phase region became (mostly) solid.

Slightly porous ice allows stable latent heat transport: In a mostly-solid HP ice layer, the temperature gradient along the melting curve is too weak to transport a large icy satellite's internal heat through conduction alone: material transport of sensible or latent heat must play a role. Other authors [4] consider solid-state convection, in which HP ice can flow, carrying a liquid fraction locked within it. Here, we consider the opposite extreme, in which liquid percolates through stationary ice.

Porous flow (with fluid velocity w) through a mushy layer [5] is driven by the relative buoyancy of the liquid (density ρ_l) with respect to the solid (density ρ_s) via a Darcy flow law:

$$w = \frac{\Pi}{\mu}\left[(1-\chi)(\rho_s-\rho_l)g\right] \qquad (1)$$

where χ is the liquid volume fraction or porosity, Π is the permeability, μ is the liquid viscosity, and g is gravitational acceleration. (For ice III, V, and VI in equilibrium with their melt, $(\rho_s - \rho_l)$ ~ 120 kg/m^3 [6]) Since we assume the ice is not convecting, radiogenic heat from the silicate interior Q ~ 15 mW/m^2 [6] must be transported through the mushy layer by either conduction or latent heat of rising liquid:

$$-k\frac{dT}{dz} + \chi\rho_l wL = Q \qquad (2)$$

where L is the latent heat of fusion and $k\ dT/dz$ is thermal conduction through the mushy material along the melting curve: we find this term is small compared to Q, so latent heat transport must dominate. To solve, we need a relationship between permeability Π and porosity χ for HP ice. This is not known, so we must rely on analogues. Liquid flow through porous partial melts like terrestrial sea ice I [7] and magma [8] are well described by the Kozeny-Karman equation:

$$\Pi = \frac{\chi^3 a^2}{K(1-\chi^2)} \quad (3a)$$

where a is the solid grain size (we assume ~1 mm) and K~1000. A different model supposes that the matrix is impermeable below a critical porosity, when the pores are too sparse to interconnect. For terrestrial sea ice,

$$\Pi = 3 \cdot 10^{-8} (\chi - \chi_c)^2 \quad (3b)$$

fits experimental data quite well [6], with a critical porosity χ_c ~ 5%.

Solving (1)-(3a) for porosity χ leads to two solutions: an invalid one with χ close to 100%, expressing the idea that a "snow" solution would be dynamically consistent, and one with porosity χ ~1%. For the critical porosity model (3b), $\chi \sim \chi_c + 0.03\%$.

In either case, we find that latent heat of liquid rising through very slightly porous HP ice can transport a large icy satellite's entire radiogenic heat output on its own, with no need for solid-state convection of the ice itself. An alternative model [4] that focuses on convection produces liquid fractions of ~10%, for which porous flow probably cannot be ignored. A numerical model that included both processes would be invaluable.

High-pressure ice layers are permeable to astrobiological materials: In contrast to the usual assumption that HP ice layers isolate the ocean from the silicate interior [10,11], we predict a permeable layer, in which liquid is constantly melting from the base of the HP ice layer and rising up through it, as ocean water freezes to the top. Astrobiologically significant chemicals from the silicate interior could be exchanged with the ocean via this process. The time τ needed to recycle the HP ice layer is simply the time needed to melt all of it using the body's geothermal heat flux (less heat lost to conduction, which is small):

$$\left(Q + k\frac{dT}{dz}\right)\tau = L\rho_s h$$

where h is the HP ice layer thickness. For a nominal Ganymede case (h~400 km of ice V and/or VI [9]), we find τ ~ 850 Ma, so the ice layer may have recycled several times since Ganymede was formed.

Porosity feedbacks promote localized upwelling: As discussed earlier, since the melting curve is steeper than a liquid adiabat, rising liquid will become warmer than the local melting point, and will tend to melt away ice, increasing the local porosity. Likewise, as a liquid/solid mixture descends it will freeze, decreasing porosity. This creates a positive feedback that tends to make it easier for fluid to rise in areas where it is already rising, which may focus the upwelling melt into narrow channels or vents. Thus, the HP ice layer may have a rich volcanic geology.

Dissolved species may enrich the dynamics: While our general conclusions apply for pure water oceans on all large icy satellites, and to water-rich terrestrial exoplanets as well, adding salt, ammonia, or other species to the liquid can change the story. Small amounts of solute will lower the melting point, leading to a thinner HP ice layer [9], but our conclusions still hold. (Our predicted porosity is insensitive to modest changes in liquid density, being roughly proportional to $(\rho_s - \rho_l)^{1/4}$ for equation 3a.) But as [9] points out, if the liquid is salty enough, it may be denser than Ice III. In this case, the "snow" argument above is reversed: the HP snow will float upward and melt, stabilizing the mixed-phase layer against convective heat transport. The complex dynamics of salty oceans containing HP ice is only beginning to be explored.

References: [1] Sohl, F. et al. 2010 *Space Sci. Rev* 153:485. [2] Leger, A. et al. (2004) *Icarus* 169:499. [3] Cassen, P. et al. (1980) *Icarus* 44:232. [4] Kalousová K. et al. (2015) *AGU Fall Meeting 2015*, P31C-2078. [5] Worster, M. G. (1997) *Ann. Rev. Fluid. Mech* 29:91. [6] Sotin, C. and Tobie, G. (2004) *C. R. Physique* 5:769. [7] Golden, K. M. et al. (2007) *Geophys. Res. Lett.* 34:L16501. [8] McKenzie, D. (1984) *J. Petrology* 25:713. [9] Vance, S. et al. (2015) *Planet. Space Sci.* 96:62. [10] Grasset, O. et al (2013) *Astrobiology* 13:991. [11] Barr, A. et al. (2001) *LPSC XXXII* 1781.

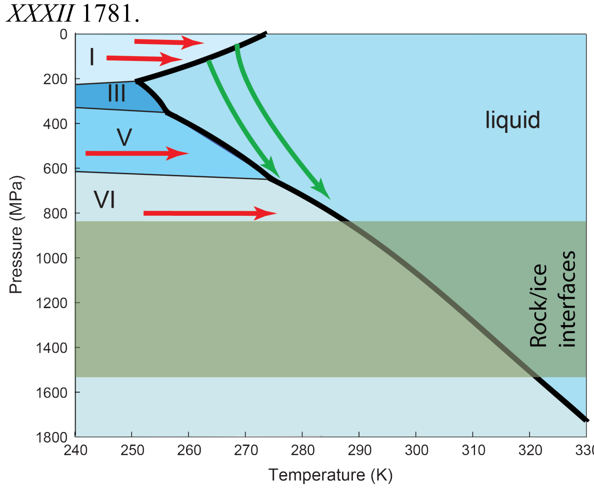

Figure 1: H_2O phase stability diagram [9]. Red arrows: approximate slope of conductive thermal gradient in ices for large icy satellites. Green arrows: adiabatic thermal gradient in liquid ocean. Olive band: pressure range of rock/ice interfaces. As depth and pressure increase, adiabatic and conductive gradients force the system toward the HP ice melting line.