The Enceladus's ice shell geometry: how it could form and what it tells us.

W. Kang[1], G. Flierl[1], T. Mittal[1], S. Bire[1], J. Campin[1], J. Marshall[1], [1] Earth, Atmospheric and Planetary Science Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

Introduction: Beneath the icy shell encasing Enceladus, a small icy moon of Saturn, a global ocean of liquid water [1] ejects geyser-like sprays into space through fissures concentrated near the south pole [2], making it one of the places with the highest potential of finding extraterrestrial life. The existence of an ocean has been attributed to the heat generated in dissipative processes associated with the deformation of Enceladus by tidal forcing [3,4]. However, it remains unclear 1) what gives rise to the dramatic asymmetry between the northern and southern hemispheres, and 2) under what configurations -- in particular, what ocean salinity and how heat production is partitioned between the ice shell and silicate core -- the observed ice geometry can be sustained. Answering these questions is crucial to our understanding of the satellite's evolution, heat budget, ocean chemical environment, and ocean dynamics, which will determine how biosignatures are transported. In particular, the salinity of the ocean decides whether water expands or contracts upon warming. The paradigm of an ocean filled with convective plumes may be no longer relevant if the ocean is fresher than 22 psu due to the anomalous expansion of water near freezing point.

Arising of hemispheric asymmetry [5]: To achieve the first goal, we construct an idealized ice sheet evolution model, considering the heat loss by heat conduction through the ice shell being balanced by the tidal dissipation in the ice shell and a uniform heat flux from the ocean and considering the down-gradient ice flow in appearance of ice thickness variations. We found that, through an instability mode growth, infinitesimal asymmetry in the ice shell thickness due to random perturbations can amplify over million-year time scale, ending up significantly thinning the ice shell at one of the poles, thereby allowing fracture formation there. The key to have the hemispherically asymmetric mode grow and dominate involves two components. On one hand, the rheology feedback of ice dissipation [4] makes the parts of ice shell that is thinner and therefore weaker to generate more heat, which in turn reenhance the initial thickness variation. On the other hand, the ice flow is more efficient smoothing out thickness variations with small spatial scales than those with large scales. As a result, the hemispheric asymmetry, who is the largest possible structure on the satellite, dominates.

Shown in Fig. 1 is a possible final state of ice shell thickness profile. The south pole (in fact this is equally likely to occur on the north pole) ice shell becomes much thinner than anywhere else, and the equatorial ice sheet features a wavenumber-2 variation with thicker ice around the sub-Saturn and anti-Saturn point. This is broadly in consistency with the ice geometry constructed by gravity and topography measurements [6].

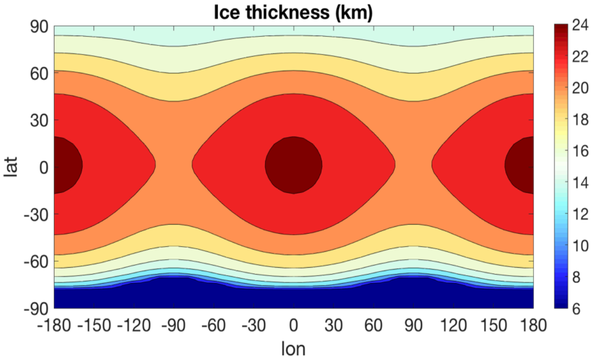

Figure 1. The equilibrium ice thickness profile given by the ice sheet evolution model, starting from an almost flat ice sheet.

Ocean salinity and heat partition [7]: To achieve the second goal, we configure MITgcm to simulate Enceladus' ocean over a range of assumed mean salinities (4, 7, 10, 15, 20, 25, 30, 35 and 40 psu). The ocean is imagined to be encased by an ice shell with the observed meridional thickness variation and forced by the freezing/melting rate which is demanded to maintain such an ice geometry. This is equivalent to assuming that the tidal heating generated in the ice shell can accommodate the heat needed to maintain the prescribed freezing/melting rate. The degree to which the heat budget is in balance informs us of the plausibility of the assumed salinity as follows. We diagnose the water-ice heat exchange from the model and infer the tidal dissipation rate in the ice shell required to close the heat budget, i.e., the sum of latent heating, tidal dissipation and heat input from the ocean which balances the heat loss to space by heat conduction through the ice. This inferred tidal dissipation rate can then be compared against that given by an ice shell tidal dissipation model.

The observed poleward-thinning of the ice shell [6] has two important consequences. First, the relatively thick ice near the equator creates high pressure and depresses the freezing point and hence the ocean is cold there. Secondly, to sustain the thickness variation from being smoothed out by the down-gradient ice flow acting over geological timescales, the equatorial ice must freeze over time, increasing the local salinity. The opposite occurs in polar regions where ice is melting.

Therefore, just beneath the ice, water in low latitudes is colder and saltier than that near the poles, regardless of the mean salinity of the ocean

What we find is that the vertical overturning circulation of the ocean, driven from above by the melting and freezing and the temperature dependence of the freezing point of water on pressure, has opposing signs at very low and very high salinities. In the fresh limit, density variation is mostly temperature-induced, and the anomalous expansion of water makes polar water denser than the equator. Contrarily, in the salty limit, density variation is dominated by salinity gradient, and the salty equatorial water is therefore heavier. In both cases, heat and freshwater converges toward the equator, where the ice is thick, acting to homogenize thickness variations. In order to maintain observed ice thickness variations, ocean heat convergence ocean heat convergence should not overwhelm heat loss rates through the equatorial ice sheet. This can only happen when the ocean's salinity has intermediate values, order 20 psu. In this case polar-sinking driven by meridional temperature variations is largely canceled by equatorial-sinking circulation driven by salinity variations and a consistent ocean circulation, ice shell geometry and tidal heating rate can be achieved.

Shown in Fig. 2 is the equatorial heat convergence as a function of ocean salinity and equator-to-pole ice thickness variation, predicted by a conceptual model constructed to reproduce the MITgcm solutions. Enceladus parameters are used to obtain panel (a). Since the equatorial ice sheet can loss no more than around 50 mW/m^2 of heat, ocean salinity needs to be between 10 to 22 psu in order to sustain the observed over 50% equator-to-pole ice thickness variation (the parameter regime corresponding to lower thickness variation is masked by a red shading).

For Enceladus, we can infer the less well constrained ocean salinity from the better constrained ice geometry [6], while for Europa we can do the opposite. Magnetic induction measurement suggests that Europa has a very salty ocean (likely greater than 50 psu) [8]. Water that salty would not have anomalous expansion and

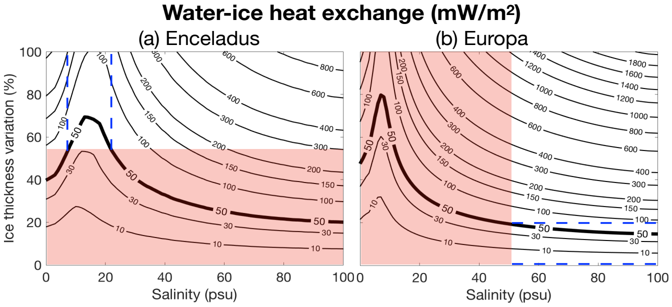

Figure 2. The amount of heat convergence toward the equatorial regions, or equivalently the heat divergence over the polar regions predicted by a conceptual model, which is made to reproduce the MITgcm solutions.

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