EUROPA'S ICY STRUCTURE: STATISTICAL MODELING AS A BRIDGE TO PHYSICAL MODELING.

S. M. Howell[1] (samuel.m.howell@jpl.nasa.gov) and H. Hay[1], [1]NASA Jet Propulsion Laboratory, California Institute of Technology

Introduction: Understanding Europa's icy shell and the role of geologic mixing is of critical importance to its habitability [1, 2]. However, the thickness of the icy shell [3,4] and therefore the potential for geologic material exchange are unknown [5]. While the thickness of Europa's ice shell is underconstrained by the current knowledge of the body, it is not unconstrained. That is, while there are many possible ice shell thicknesses, not all ice shell thicknesses are equally plausible. Howell (2021) [3] used statistical modeling (**Figure 1**) to develop a probability density distribution for the likely thickness of Europa's icy shell based on a simple heat balance and the uncertainty of dozens of underlaying parameters. That study estimated a current best estimate (CBE) icy thickness of $24.3^{+22.8}_{-1.5}$ km (**Figure 2**).

In addition to icy thickness, Howell (2021) [3] also derives distributions for numerous physical parameters, including conductive and convective layer thicknesses, heat flux from various sources as well as an average value, interior temperature structure, and icy viscosities, among many others.

The present study provides a basis for the understanding that not all predictions of icy shell thickness are equally likely. We estimate a probability distribution for Europa's present-day mean equatorial icy shell thickness by solving a heat flux balance across the iron-rich core, rocky interior, ocean, and icy shell. The resulting probability density distribution describes the relative likelihood of a particular thickness occurring given the underlying uncertainties in our knowledge of Europa.

This study assumes no significant present-day changes in icy shell thickness, which would introduce unbounded latent heat lost or gained through the changing phase of water. For simplicity, this study does not consider the effect of latitude or longitude on tidal heat dissipation, which may result in regional variations in icy shell thickness

We overview the further development of this probabilistic model for Europa to provide insight into the thermal and mechanical structure of the body, as well as estimate physical body parameters such as the Moment of Inertia (MoI) factor and tidal Love Numbers.

Statistical Method: We adopt the Monte Carlo method of Howell (2021) [3] (**Figure 1**). We begin by assuming an ice shell in thermodynamic equilibrium, always including an upper conductive layer and sometimes including an isothermal convecting ductile layer. We assume the heat flux out of the icy lithosphere radiated to space is equal to the heat flux into the base of the lithosphere from the silicate interior plus the internal heat generated by tidal dissipation within a ductile convecting asthenosphere, integrated over the depth of the asthenosphere.

The first step in our Monte Carlo process is to sample an interior heat flux at random from a distribution. Next, we bound the thickness of the conductive layer. We determine a maximum thickness

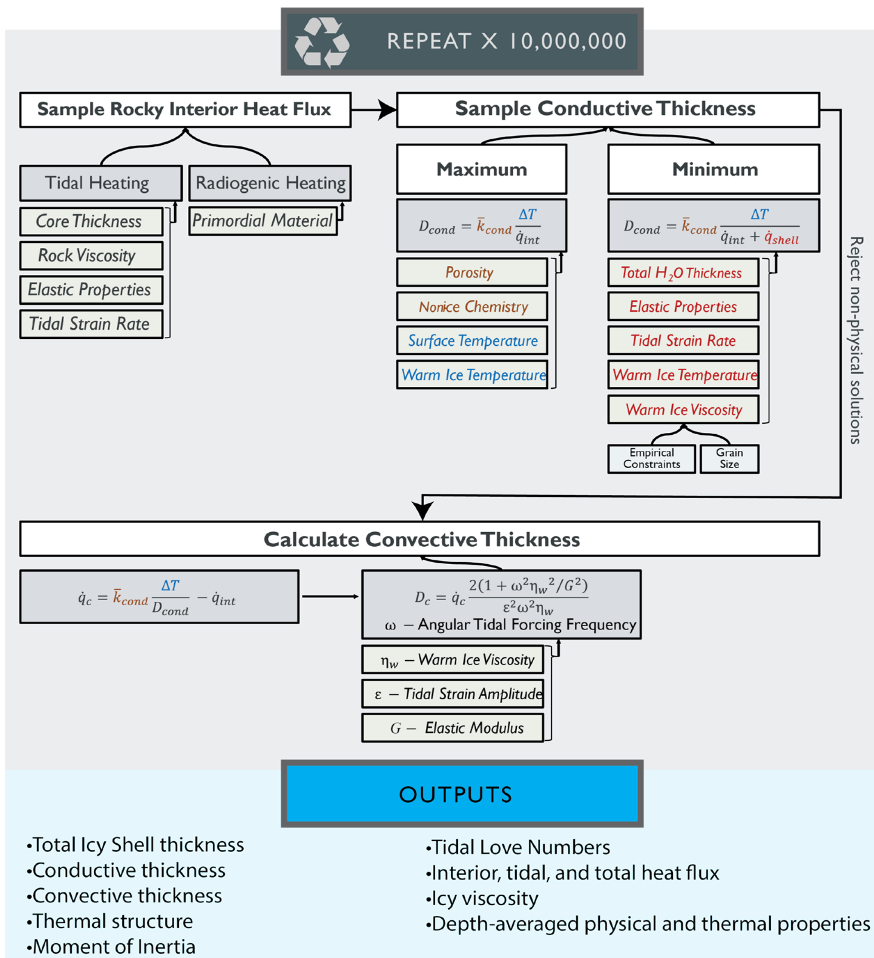

Figure 1 | *Statistical Model Schematic.* *(Top) Flowchart highlighting some parameters of interest and the step that they are introduced into the statistical model. (Bottom)Example model outputs.*

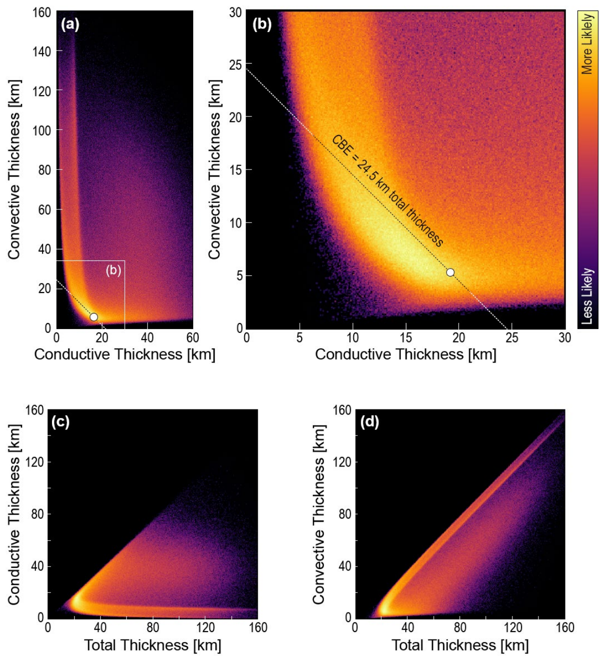

Figure 2 | *Two-dimensional joint-probability density distributions for icy shell and layer thicknesses.* *(a) Joint-probability distribution for layer thicknesses. The white box highlights the location of inset (b). In (a), (b), the current best estimate (CBE) total thickness is shown by a dashed line. The CBE icy shell is marked with a white circle. In (c) and (d), conditional probability distributions show how conductive and convective thicknesses vary with the total icy shell thickness.*

by sampling the distribution for silicate heat flux, as well as considering the critical thickness at which a conductive layer would begin convecting. We estimate a minimum thickness by sampling the interior viscosity and considering the maximum amount of tidal heat that could be generated in a convecting layer equal to the full H_2O thickness. We then select a conductive thickness from the allowed range using a uniform distribution, and calculate the corresponding convective thickness. This process is repeated 10^7 times, and a small number of non-physical configurations stemming from initial assumptions are discarded.

For each resulting model, we obtain the structure of Europa from core to surface, including layer densities and depths. From this information we are able to produce estimations for each Europa of full-body parameters, including MoI and tidal Love Numbers.

Results: Current best estimate (CBE) values and uncertainties for ∼20 key parameters are propagated through this steady-state heat flux balance to construct ∼10^7 independent simulations. We estimate present-day values for the icy shell layer thicknesses, the rocky interior and icy heat fluxes, icy shell thermal properties, and convective ice viscosity (**Figure 3**). This result is highly skewed; icy shells many tens of kilometers thick are much more probable than icy shells <10 km thick. The resulting distributions have key implications for future spaceborne, landed, and subsurface exploration of Europa, as well as studies of icy shell processes, thermal and mechanical state, and habitability across the icy ocean worlds.

Further, we show the utility of this modeling method in producing body parameters that may guide future studies to understand the deformation response of the body to orbital and tidal forcing. Predicting these distributions permits the refinement of our model in light of any future observations of Europa's shape, interior structure, thermal, and mechanical state.

Perspectives: We demonstrate the utility of a probabilistic approach to interior structure estimation in incorporating a wide range of spacecraft and laboratory measurements, theoretical behavior, and observations. In this study, we demonstrate that future observations of Europa's icy shell can offer constraints on the total shell thickness, as well as layer thicknesses, thermal, and mechanical properties.

Acknowledgments: This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References: [1] K. P. Hand et al. (2009) *Europa,* 589-629. [2] S. K. Trumbo et al. (2019) *Astron. J., 158/3*. [3] S. M. Howell (2021) *PSJ*, 2(4), 129 [4] S. E. Billings and S. A. Kattenhorn (2005) *Icarus, 177,* 397–412. [5] S. M. Howell and R. T. Pappalardo (2019) *Icarus, 322,* 69–79.

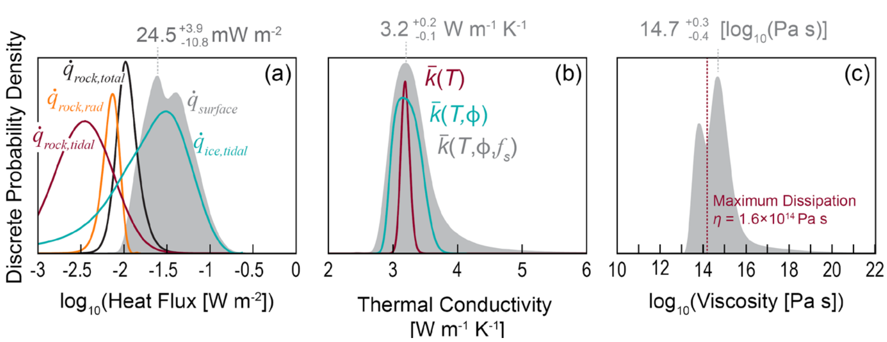

Figure 3 | *Derived discrete probability distributions.* *The most likely values are labeled as current best estimates.*