INVESTIGATING THE THERMODYNAMICS AND SEISMIC PROFILE OF THE EUROPAN HYDROSPHERE THROUGH PURE-WATER MODELING AND SALTWATER EXPERIMENTS. S. L. Rosenfeld[1] and H. C. Watson[1], [1]Union College Department of Physics and Astronomy (807 Union St., Schenectady, NY 12308, rosenfes@union.edu).

Introduction: The search for life beyond Earth has never ceased since we discovered objects beyond our home planet. The icy moons of Jupiter and Saturn, such as Ganymede, Europa, Callisto, Titan, and Enceladus are the prime candidates for the search for life beyond Earth because of their theorized subsurface liquid water oceans. For our study, we are interested in Europa particularly due to the high possibility of its ocean being the next habitable entity outside of Earth.

Europa is believed to be fully differentiated with an H_2O shell, a silicate mantle, and an iron-rich core. Europa's surface, as studied by *Galileo*, proves to be relatively young in age due to some critical surface features; it contains a very small number of impact craters, which suggests that it has gone through recent resurfacing due to either tectonic or cryovolcanic processes, or both [1]. Remaining surface features such as chaos terrain have been extensively studied, where most theories about its origin have concluded that there must be both strong tidal forces and a thick subsurface liquid layer present in order for the chaos terrain to have formed, which alludes to the existence of its subsurface liquid water ocean [2].

While there exists very strong evidence for the existence of Europa's subsurface ocean, it still remains unconfirmed. NASA's Europa Clipper mission will conduct a detailed survey of the moon to answer this question among many others concerning its habitability [3]. However, since it will be some time before the Europa Clipper can make its way to the Jovian system, we look to studying Europa's interior through performing a computational analysis of a pure-water Europan hydrosphere and experimentally investigating the phase diagram of different saltwater concentrations. We then compare the results from the computational and experimental processes in an effort to understand the thermodynamics and seismic properties of the ice shell and ocean layer with respect to depth.

Methods: *Ice Layer Modeling.* For our analysis of the ice shell, we used a Python program called SeaFreeze, which is a programming framework that provides an environment in which to study the equilibrium thermodynamic properties of water, including, but not limited to density, p- and s-wave velocities, Gibbs free energy, shear modulus, and bulk sound speed. It can calculate these properties for each of the more commonly-occurring phases of pure water such as liquid water, Ice Ih, Ice II, Ice III, Ice V, and Ice VI [4]. We used the estimated range for surface temperature (50K to 140K) and ice shell thickness (3km to >30km) given by Soderlund et al. (2020) to create four possible models of the ice shell [5]. Applying these boundary conditions to SeaFreeze, we focused on calculating the density and seismic wave velocities as functions of depth for each of the models.

Saltwater Freezing Point Experiments. To look into the phase diagram of different types of saltwater, we determine the freezing-melting points of varying saltwater concentrations by frequently measuring the temperature of the saltwater sample as we cool it at different pressures. The samples are each a solution of distilled water and a high-purity solute (NaCl, for this particular study) with a concentration of 5%, 10%, or 20% by weight. We use a high-precision pressure-pump system to accurately set the pressure within a range of 0MPa to 80MPa in order to collect the freezing points of the samples at varying high pressures.

Results: In our computational analysis of the thermodynamic properties of pure water-ice under Europan conditions, we find trends of density, p-wave velocity, and s-wave velocity as functions of depth for each model. Figure 1a shows the density trend for one model, which assumes a linear temperature gradient from 50K to 271K and a pressure range from 0MPa to 36.15MPa. Figure 1b shows the density trend for a second model that only differs from the model in Figure 1a by having a surface temperature of 140K instead of 50K.

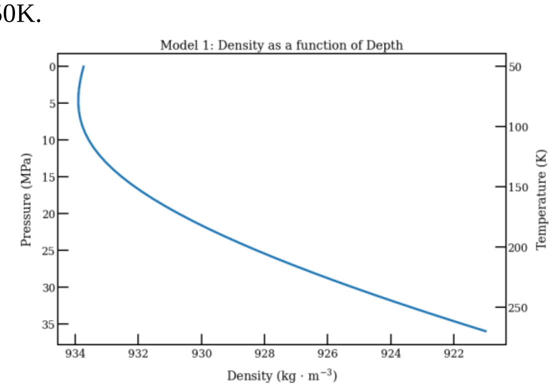

Figure 1a. Density of Ice Ih as a function of depth for a temperature range of 50K-273K and pressure range of 0MPa-36MPa.

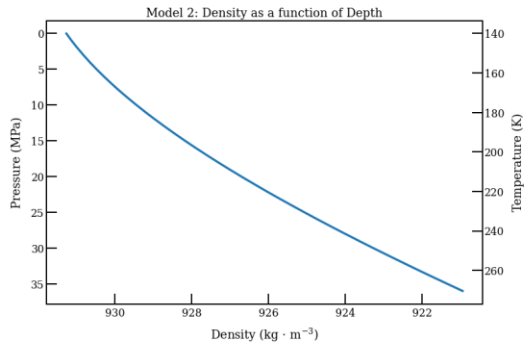

Figure 1b. Density of Ice Ih as a function of depth for a temperature range of 140K-273K and pressure range of 0MPa-36MPa.

For the saltwater experiments, we take the average of all the trials done within each type of concentration and pressure setting. Figure 2 shows the final freezing points found from all of the NaCl trials (for 5%, 10%, and 20% concentration by weight) at varying high pressures.

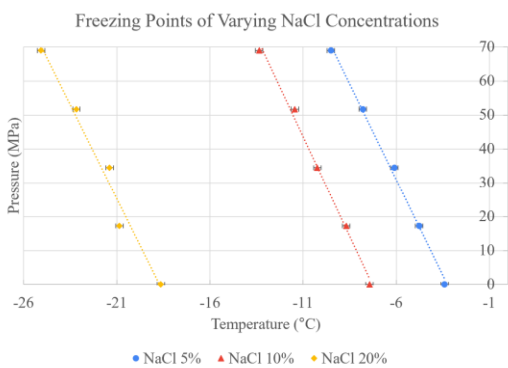

Figure 2. Final freezing points for all NaCl trials at varying pressures. The blue circles correspond to a 5% NaCl concentration, the red triangles to a 10% NaCl concentration, and the yellow diamonds to a 20% NaCl concentration.

Discussion: Our models for pure-water Ice Ih placed under a range of similar conditions for the ice shell on Europa show relatively linear trends. The density of the model in Figure 1a shows an inversion curve near the surface, which is only introduced in the models that assume a colder surface temperature of 50K. The models that use a surface temperature of 140K are more consistently linear, as shown in Figure 1b. Thus, we find that the pressure in the ice layer does not drastically influence the density or seismic wave velocities as much as the change in temperature. Something to note is that these models analyze pure-water, not saltwater, which requires further analysis to look into how their trends would differ with the addition of salt.

The results of the saltwater experiments show that as the pressure increases, and the concentration of NaCl increases, the melting-freezing point of the solution decreases. This result is consistent throughout our experiments, as visualized by Figure 2. Thus, comparing our results to the pure-water Ice Ih models of Europa's ice shell, we find that if the models contained some concentration of NaCl, they would require lower temperatures at the ice-water boundary, and thus slightly flatten the slopes of the linear trends we found for the models of density and seismic wave velocities.

Future Work. The next steps for this study include further comparisons between the saltwater experiment results and the pure-water ice shell models. We are also continuing with the saltwater experiments, looking into varying concentrations of magnesium sulfate ($MgSO_4$) at high pressures. Additionally, we plan to begin analyzing the ocean layer computationally, using SeaFreeze to create pure-water models based on the predicted conditions of Europa's subsurface ocean given by literature. After making the pure-water ocean models, we will compare the resulting trends to the saltwater freezing data and make potential conclusions about Europa's hydrosphere.

Conclusion: Investigating the ice and ocean layers on Europa is a crucial step to determining whether the moon is habitable, based on our understanding of life on Earth. Since it may be some time before we can study Europa up-close, performing computational analyses and related ground-based experiments can enhance how we perceive its conditions and characteristics well before we send spacecrafts, and it can significantly help interpret the remote sensing data that will result from the Europa Clipper mission.

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References: [1] Hussmann, H., Sotin, C., & Lunine, J. I. (2015) *Treatise on Geophysics: Second Edition*, *10*, 605–635. [2] Lowell, R. & DuBose, M. (2005) *Geophysical Research Letters*, *32*, LO5202. [3] Pappalardo, R. et al. (2021) *BAAS*, *53*. [4] Journaux, B. et al. (2020) *Journal of Geophysical Research: Planets*, *125*(1). [5] Soderlund, K. M., et al. (2020) *Space Science Reviews*, *216*, 5, 1–57.