MICROSTRUCTURAL EVOLUTION OF SOLAR SYSTEM ICES THROUGH SINTERING. J. L. Molaro[1], G. Meirion-Griffith[2], C. B. Phillips[2], K. L. Mitchell[2], R. P. Hodyss[2], M. Choukroun[2]. [1]Planetary Science Institute (jmolaro@psi.edu), [2]Jet Propulsion Laboratory.

Introduction: Ice sintering is a form of frost metamorphism whereby adjacent grains adhere together and experience the diffusion of material into their contact regions. This causes growth of the "necks" between grains and densification of the aggregate over time, resulting in the evolution of the strength, thermal conductivity, and pore size and shape of the sintered ice. Recent focus on understanding ocean worlds, the planned exploration of Europa by NASA's Europa Clipper mission, and the possibility of future lander and orbiter missions to Europa, Enceladus, and Titan have driven keen interest in characterizing the surfaces of these bodies at small scales. Not only do their microstructural surface properties have critical implications for the interpretation of remote sensing data, *in-situ* exploration of these worlds requires knowledge of surface strength, roughness, and porosity in order to develop appropriate spacecraft landing systems. Understanding the sintering process is crucial to characterizing the microstructural properties of ice on planetary surfaces, and quantifying its contribution to landscape evolution.

Sintering has been studied extensively in terrestrial environments [e.g., 1-4], however most of this research focuses on *in-situ* characterization of snow and glacial ice. This makes the body of research challenging to apply in a planetary context, where ice has not been subjected to the same thermal and atmospheric conditions present on Earth. In spite of the cold temperatures, the limited work available on ice sintering on other bodies suggests that it is a sigificant process throughout the solar system. For example, modeling of nitrogen ice sintering on Triton found that non-porous ice slabs could form over seasonal timescales, consistent with telescope observations of absorption features [5]. Similar features were also explained by sintering on Mars and Pluto [6, 7]. Modeling studies of comets [8-10] paired with spacecraft data have found that sintering can significantly affect the strength and thermal conductivity of their surfaces, and another study suggests that neck growth from radiation-driven diffusion can explain the thermal anomalies observed on Mimas and Tethys [11]. Sintering rates on these bodies vary with surface temperature and grain size. Composition also plays a key role, as rates increase with homologous (absolute/melting) temperature, suggesting that, e.g., water and nitrogen ice evolve on very different timescales.

We model pressureless (no over-burden) ice sintering of aggregates of spherical water-ice grains of varying diameters and temperatures to obtain a first-order estimate of their sintering timescales. We will validate our results using laboratory measurements of sintering rates on Earth, and explore the implications for the surface evolution of Europa, Enceladus, Mars, and other planetary bodies.

Model: We will implement the model of Swinkels and Ashby (1981) [12] to estimate sintering timescales and densification rates on planetary surfaces. This model was developed to research sintering of metal powders, and has been well-validated in those applications [12, and references therein]. The same model was also used by [5-11] to quantify the sintering of ice, though it has never been validated experimentally for this material.

Modification of spherical grains within an aggregate is driven by surface, volume, and grain-boundary diffusion mechanisms (Fig 1) that contribute to either neck growth and/or densification (decrease in interparticle distance), with different mechanisms dominating at different stages of the process. The first stage is characterized by a period of rapid neck growth, which slows down as the pores become circular and the grains become indistinguishable. Some densification of the aggregate also occurs, but it is not dominant. This is followed by a densification stage, during which the aggregate resembles a solid slab of ice containing isolated spherical pores, which occurs over a much longer time period.

The rates of change of the neck size, interparticle distance, and aggregate density are proportional to the sum of the active diffusive currents at a given time. These are driven by differences in the surface curvature along the length of the neck, and the dominant mechanism varies with temperature, neck size, grain size, and environment. In our application, the vapor transport diffusion mechanism is dominant during most of the sintering process. We refer the reader to

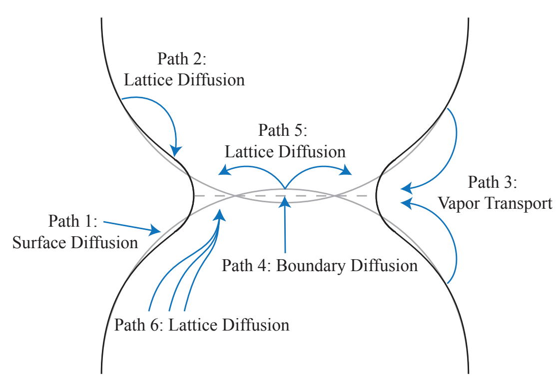

Figure 1. Diffusion mechanisms in sintering grains.

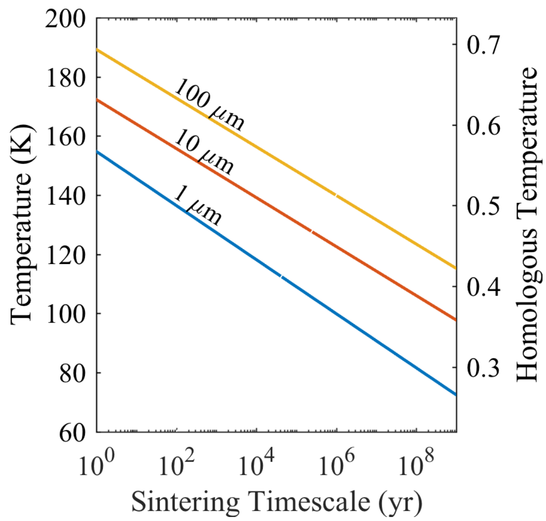

Figure 4. Timescale to complete the first stage (neck growth) of the sintering process with temperature and grain size.

Table 2 of [11] for a description of the rate equations. The key parameters are the temperature, and the surface (2.2×10^{-13} to 1.4×10^{-8} m^2/s) and volume (10^{-23} to 1.5×10^{-8} m^2/s) diffusion coefficients, which are not well constrained for ice. Errors due to diffusion coef cients are within one order of magnitude. Results are presented in terms of relative neck size (neck size/grain radius), relative density (density of aggregate/pure material), and homologous temperature (temperature/melting temperature).

Preliminary Results: Laboratory measurements of ice sintering in the literature are limited, which presents a challenge to determining how accurately this model may reflect its behavior. Moreover, the sintering rates reported by existing studies are inconsistent with each other. Comparing model simulations three studies [2-4], we find that it most closely matches the data from Hobbs and Mason (1964) [3]. However, it predicts neck growth to be significantly slower than Kingery and Berg (1955) [1] and significantly faster than Thomas et al. (1992) [2], in spite of the fact that both studies used comparable grain sizes at similar temperatures. Unfortunately, few details are offered that might indicate why their measurements were so different. Thus, while the model qualitatively reproduces neck growth behavior and is perhaps quantitatively accurate +/- an order of magnitude, this highlights our lack of understanding of ice sintering in general and emphasizes the need for more laboratory studies on this topic. While imperfect, this model can be used to obtain a first order approximation of sintering timescales throughout the solar system. Since sintering rates vary exponentially with homologous temperature and grain size, these timescales will vary significantly across planetary surfaces. Figure 2 shows the timescales to complete the neck growth stage of the process. For example, we estimate the lower limit time for 10 μm ice grains at Europa at 130 K, its warmest daytime temperature, to be <1 Myr. However, grains that are larger may only have partially sintered over its 30 Myr surface age. Further, our results predict that no substantial densification (not shown) will occur over 30 Myr, suggesting that ice regolith at Europa's surface may form a cohesive but porous crust. This is a significant finding, as the slow rate of densification relative to neck growth in ice contrasts strongly with the behavior of metals. A detailed exploration of the model's inner workings will reveal that the way the model handles the transition from the neck growth to densification dominated sintering stages relies on this assumption, suggesting it may underestimate total sintering timescales by several orders of magnitude.

The warmest times of day drive the majority of sintering, and thus surface ice will experience more time at higher temperatures than the layers beneath it. This suggests that decreasing sintering rates with depth may cause gradients in neck size, thermal conductivity, and other properties to develop in the near surface. Similar variations may exist at the surface due to topographic shadowing. Timescales will also vary with salt content, whos presence raises the homologous temperature of the ice. Other ices (e.g., N_2) will have similar timescales to water ice at a given homologous temperature, but will vary slightly with the values of their diffusion coefficients.

Future Work: Understanding the role that sintering plays in the microstructural evolution of ice is critical to characterizing planetary surfaces. We will use our model to estimate sintering timescales of ice on the surfaces of Europa, Enceladus, Mars, and other bodies throughout the solar system. We will quantify the effect of diurnal thermal cycling on neck growth and densification in the near-surface, and explore the implications for their surface properties.

References: [1] Blackford J. R. (2007) *J. of Physics D: Applied Physics 40.21*, R355. [2] Kingery W. D. (1960) *J. of Applied Physics 31.5*, 833-838. [3] Hobbs and Mason (1964) *Philosophical Magazine 9.98*, 181-197. [4] Thomas et al. (1994) *Advances in Space Research*, *14*(12), 207-216. [5] Eluszkiewicz J. (1991) *J. of Geophys. Res. Space Physics 96.S01*, 19217-19229. [6] Eluszkiewicz J. (1993) *Icarus 103.1*, 43-48. [7] Eluszkiewicz J. et al. (2003) *Icarus 166.2*, 375-384. [8] Kossacki K. J. et al. (2006) *Icarus 184*, 221-238. [9] Kossacki K. J. (2015) *Icarus 245*, 348-354. [10] Kossacki K. J. et al. (2015) *Icarus 260*, 464-474. [11] Schaible M. J. et al. *Icarus* (2016). [12] Swinkels F. B. and M. F. Ashby (1981) *Acta Metallurgica 29.2*, 259-281.