THERMAL CONDUCTIVITY OF WATER-ICE REGOLITH AND APPLICATION TO THE OUTER SOLAR SYSTEM.

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Introduction: The surfaces of icy moons, as with all of the solid planets, moons, and asteroids are coated with regolith, a layer of loose granular particles largely derived from "bedrock" [1]. This layer develops and evolves through various processes. When properly deciphered, the regolith reveals the geologic and geochemical history of the surface and subsurface. Additionally, the regolith is the landing pad for exploration, the first location for *in situ* scientific analysis, and may hold clues of habitable zones hidden beneath.

In this work, we simulate and examine water-ice regolith (appropriate to outer-solar-system bodies) in a laboratory setting and measure its thermal conductivity. Such data is useful for interpreting thermal-infrared remote-sensing data of the surfaces of icy moons and other icy bodies in the outer solar system.

Background: Within the inner solar system refractory silicate minerals, like those found in basalt, dominate the regolith. However, in the outer solar system the regolith is instead dominated by water ice [2]. As a result of low temperatures (typically << 200 K) this water ice plays the refractory role.

The ice regolith forms through the breakdown of "bedrock" ice into loose or weakly cemented particles depending on relative processes of impact fragmentation, sintering (welding and rounding), geyser eruption, frost deposition, and mass wasting. These processes each leave distinct structural fingerprints in grain size, shape, and angularity, as well as differences in ice phase, the effects of which on remote sensing are largely unknown.

At present, little is known about ice regolith in our solar system leaving many challenges to interpreting remote-sensing data and designing spacecraft to land, sample, and analyze these surfaces. Questions need to be addressed about the spectral, thermal, electrical (radar), and mechanical characteristics of ice regolith, and in particular the signatures of trace constituents of inert mineral salts and organic compounds, which may reveal the composition and habitability of the subsurface. Characterizing these signatures will play an important role in the analysis of remote sensing data, as well as *in situ* sampling. Characterizing the ice-regolith substrate is a first step toward understanding the broader complexities of these trace constituents.

Ice Regolith Simulant: We have developed a procedure for simulating ice regolith as it would form by micrometeorite impact fracture and fragmentation, and by some types of mass wasting. The thermal conductivity of laboratory-generated samples have been measured to shed light on interpretations of remote-sensing observations of icy bodies.

The main apparatus (Figure 1) consists of a rotary cutter (rasp) driven by a stepper motor, above which is a feed tube, into which a cylindrical bar of ice is placed. The ice is gravity fed into the cutter and grains fall freely onto a sample tray. A linear stage is used to move the sample under a Celestron digital microscope for analysis. The sample try can also be fitted with a heated-needle style thermal-conductivity probe. This apparatus fits into a bell jar vacuum chamber, which itself fits into a -40°C freezer.

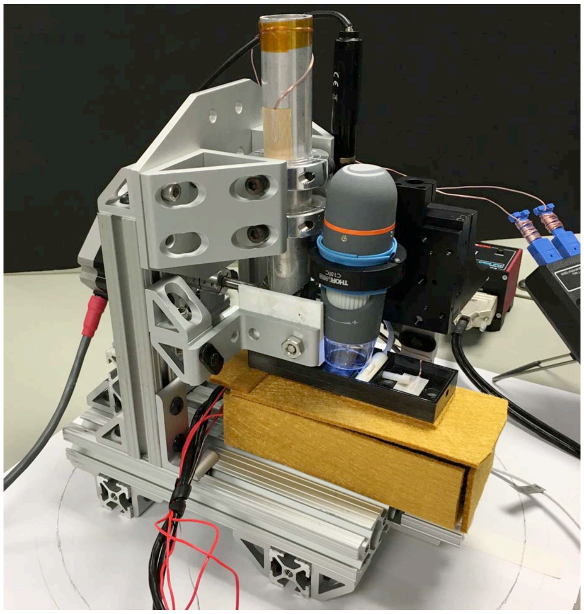

Figure 1. Apparatus to generate and characterize ice regolith samples. A stepper motor (far left) drives a rasp (center, obscured) to grind ice grains from an ice bar in the feed tube. A linear stage (heated and insulated) moves the sample to a microscope for analysis.

We examined the effects of temperature, cutting speed, load force, and rasp style on the generation of ice grains. Temperatures of -10°C, -20°C, and -40°C were tested. Rapid cutting can induce steady frictional heating, therefore we kept cutting speed below 10 rps, typically of order 1-2 rps.

Microscope images (example, Figure 2) show shards and grains are generated, mostly between a few microns and a couple hundred microns in size, with a concentration of grains tens of microns in size. Grains are angular to subangular in shape with an abundance of conchoidal fractured textures. At -10°C agglomerates of smaller grains were often observed, becoming less abundant at colder temperatures. At all temperatures, over time (minutes-to-hours) grains became more rounded and smaller grains were observed to shrink, suggesting sublimation and sintering processes play a role at these laboratory conditions.

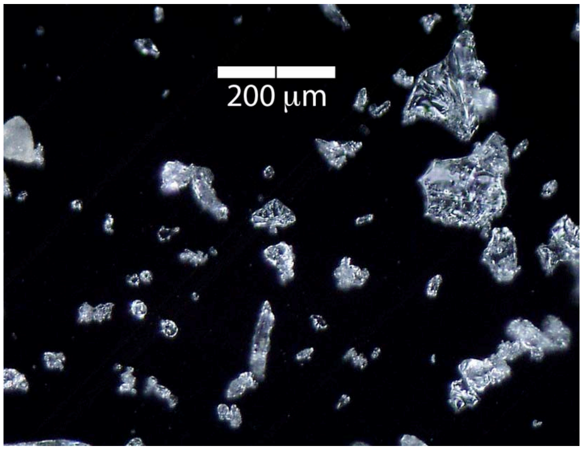

Figure 2. Ice-regolith grains generated at -20°C.

Thermal Conductivity: For measurements of thermal conductivity we employed a commercial Decagon Devices KD2-Pro thermal-conductivity probe, which employs a transient heated-needle method.

Thermal conductivity is a key component of the thermal inertia which is readily derived from thermal-infrared remote sensing [3]. These properties are highly dependent on the structure of regolith. For example, high thermal inertia and thermal conductivity is associated with bedrock exposure, while low values are associated with unconsolidated granular regolith. Thermal conductivity varies substantially with differences in: i) grain size and shape; ii) bulk density; iii) interstitial gas (if any); iv) the presence of cementation (or sintering); v) temperature; and vi) composition.

Because gas pressure can play a large role in the thermal conductivity of granular materials we measure it as a function of pressure, from ambient to vacuum. At -40°C the equilibrium partial pressure of water is ~0.13 mbar – evacuation to pressures near or below this limit induces substantial sublimation, thwarting efforts to obtain accurate conductivity measurements.

Outer-solar-system conditions are mostly much colder than -40°C (233K) and vapor pressures are orders of magnitude lower and can be virtually nonexistent. Measurements under those conditions are not possible with the current laboratory system; however, by characterizing thermal conductivity over a range of pressures, well-know theory [3] can be employed to extrapolate to outer solar system conditions, constrained by our laboratory data. To this end, we measure thermal conductivity over a range of pressures (example, Figure 3).

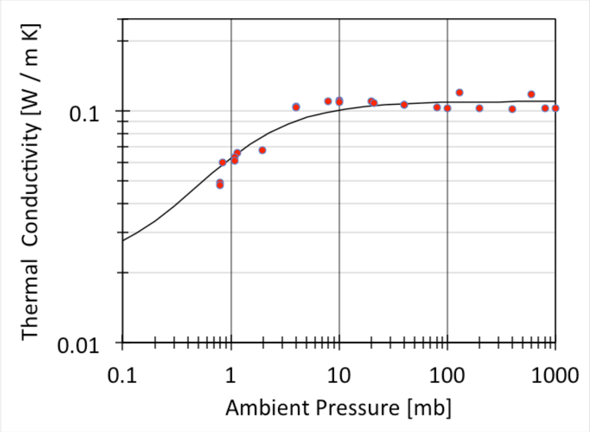

Figure 3. Thermal conductivity (dots) of simulated ice regolith grains at -40°C with a bulk density of 0.286 g/cc, as a function of ambient N_2 pressure. The line is an analytical fit following [3].

Discussion: Our simulated regolith represents fractured and fragmented ice grains as might form by the ongoing micrometeorite erosion of ice boulders and bedrock. This material differs in structure from terrestrial snow and firn, or from geyser/plume fallout.

At 1 bar N_2 pressure we find the thermal conductivity of ice regolith to be similar to that of terrestrial snow [4]. As the pressure decreases the thermal conductivity begins to fall off, as the mean free path of interstitial gas increases to that of the pore size [3]. This behavior with pressure is similar to that which is well documented in loose granular silicate materials [5,6,7]. The observed trend is similar to that specifically measured for glass beads ~2 mm in size [7]. Yet the observed grain sizes are predominantly 10's of um. This discrepancy may be explained by the presences of aggregation and adhesion between grains, creating an open high-porosity structure with large diameter pores relative to the actual grain size (unusual in uncemented silicate grains), consistent with the low bulk density. Further measurements are planned to characterize these dependencies.

References: [1] Ollier C. and Pain C., (1995) *Regolith, Soils, and Landforms,* Wiley, New York. [2] Moore J. M., et al. (2008) in *Europa,* U. Arizona Press, 329-349. [3] Mellon M. T. et al. (2008), in *The Martian Surface: Composition, Mineralogy, and Physical Properties,* Cambridge U. Press 399-427. [4] Sturm M. et al. (1997), *J Glaciology, 43,* 26-41. [5] Fountain J. A. and E. A. West, (1970) *J Geophys Res 75,* 4063–4069. [6] Presley M. A. and P. R. Christensen (1997) *J Geophys Res 102,* 6551–6566. [7] Mellon M. T. et al. (2015) *46th Lunar Planet. Sci. Conf.* Abstract 2837.