PROPERTIES OF PERMANENTLY SHADOWED REGOLITH. Joshua R. Neubert, Paul G. Lucey, G. Jeffrey Taylor, Hawaii Institute of Geophysics & Planetology, 1680 East-West Road, POST 602B, Univ. of Hawaii, Honolulu, HI 96822 (neubert@higp.hawaii.edu)

Introduction: Lunar polar regions are a source of much interest due to the possibility of sizeable quantities of water ice in the permanently shadowed regions. If present, the concentration and properties of the ice bearing regolith will have great implications for future exploration of the Moon and could be a rich scientific resource to help understand processes on other icy bodies such as comets and the Galilean satellites. The lunar poles harbor a microenvironment that possess conditions utterly unlike those of the lunar equator, where Apollo samples came from. These conditions may allow *in situ* production of organics on the Moon from indigenous inorganic material. If this is the case, the Moon may allow field testing of models of inorganic synthesis which have been invoked for many surfaces in the solar system, and even interstellar clouds.

It is important to fully understand the environment of the permanently shadowed regions to maximize the potential of future experiments and missions. We review what is known and speculated about the surface in the unique environment in permanently shadowed regions on the Moon. Mercury exhibits an even stronger signal of water ice at its poles, which raises other questions about the source of such water, and why it is so much larger than the lunar signal.

Cold Trap Modeling: The idea that polar craters could cold trap volatiles was introduced in the 1960s [1]. A temperature of ~110K was noted to be the upper limit for the stability of water ice deposits [2]. A more recent study modeled the temperatures of polar craters on both the Moon and Mercury. A number of craters on both bodies were found to have temperatures well under the 110K cap (as low as ~40K). The size of the craters modeled varies from 10 to 100 km with smaller craters having larger temperature cycles [3,4]. At these low temperatures H_2O condenses as amorphous ice. It can, however, recrystallize to cubic or hexagonal ice if heated above about 80 K, depending on structural details of the amorphous ice [5].

Observations of Shadowed Regions: The first observations of the lunar poles aimed at detection of water ice were from the Clementine radar experiment [6,7]. These data showed evidence for ice deposits at both poles but with a larger signal at the southern pole; however, a continuing controversy regarding details of data analysis has yielded no consensus on these results [8].

Other radar experiments aimed at both the Moon and Mercury were conducted by the Arecibo radio observatory [9]. Observations of Mercury showed strong signals indicative of water ice, in some large polar craters; Observations of craters of similar size and morphology on the Moon expected on the basis of modeling to achieve temperatures consistent with trapping water ice show no radar returns similar to those found on Mercury. However, only about 20% of the areas of permanent shade have been observed from Earth based radar, so Mercury-like deposits cannot be excluded. It should be noted that all potential large cold traps on Mercury exhibit radar anomalies, and thus far none on the Moon do so.

Unambiguous evidence for enhanced volatiles at the lunar poles was provided by the Lunar Prospector mission, which carried neutron detectors sensitive to the presence of hydrogen. This enhanced hydrogen concentration was attributed to water ice [10-12].

A few other relevant observations have been made. Analysis of the Galileo images show evidence for phyllosilicates in areas of the south pole, supporting the presence of water ice [13].

Potential Sources of Lunar Hydrogen: Cocks et al. state that small amounts of adsorbed water has been shown to be sufficient to explain a majority of the north polar hydrogen signal; however, it is not enough to account for the higher hydrogen signal in the larger southern craters. This may indicate the presence of more substantial ice layers or patches within the subsurface [14].

Hodges [15] looked at the degradation effects and transport methods for getting H_2O to the polar cold traps and argues that the concept of distinct bulk water ice at the poles is insupportable. Crider et al [16] proposed the solar wind as a source of the hydrogen. This source would both implant free hydrogen ions into the regolith as well as actively reducing iron oxides to produce water molecules. Duxbury et al [17] state that the hydrogen signature could also be from clathrate hydrates. These materials are stable at very shallow depths (millimeters to centimeters below the surface) in the shadowed craters.

Other sources of hydrogen or water molecules include hydrous meteorite and cometary impact. However, the ability of these impacts to deposit significant amounts of water molecules in the cold traps is debatable [15].

Shadowed Craters—Processes and Properties: The physical and chemical environment of any "wet" craters may be very complex due to the properties of the regolith in the ancient highlands, the number of potential stable phases for ice and how their properties vary with temperature, and potential reactions that may have taken place during the past few billion years.

Extreme bombardment might have pulverized the regolith in the most ancient highlands. The typical lunar regolith has a mean grain size of ~100 μm, with ~10% of the material smaller than 10 μm [18]. However, the polar regions are in the most ancient lunar highlands, which have been subjected to the most intense bombardment for more than 4 billion years. Hartmann [19] suggests that the upper hundreds of meters have been reworked so extensively that it resembles the typical lunar regolith. Since the heavy bombardment ceased about 3.8 billion years ago, the upper several meters of the Moon have been modified by micrometeorite impacts. That regolith may be much finer grained than typical regolith as it developed on hundreds of meters of fine-grained material., although continued production of agglutinates, which are constructional, would moderate the extent of decrease in grain size. Smaller particle sizes provide a larger surface area for the adsorption of water ice. This would also affect the porosity, shear strength, and other physical properties of the material within the craters

The shadowed craters in the north pole of the Moon are significantly smaller than those in the south. The temperature profile of these craters is suspected to be as low as 40K and up to 105K [4]. In the upper end of this range bulk ice layers would be converted to adsorbed layers over time if they ever existed. Temperature data and ice stability studies have shown that the stable form of any bulk layers in southern craters is amorphous ice [14].

A number of studies have been conducted on the chemical alteration of ices due to radiation from UV photons, the solar wind, and galactic cosmic rays [e.g., 20]. Many different chemical reactions could take place. If the solar wind is a large source of the hydrogen seen by Lunar Prospector, a significant amount of C, N, and H ions could be delivered as well. These ions provide the reactants necessary for even more complex reactions. Or, if cometary gases are deposited they will be trapped in amorphous ice [21]. If significant amounts of ice exist, the products of these reactions with the solar wind or cometary impact should exist as well, such as amorphous ice with relatively high concentrations of trapped gases [21]. If there are enough trapped gases from these reactions it could produce an explosive effect if a small amount of thermal energy were applied, such as that of a landed spacecraft or a small impact.

Conclusions: Permanently shadowed regions near the lunar poles must be characterized thoroughly to extract the scientific, technical, and economic benefits from this unique environment. Future missions to study the poles will benefit greatly from further laboratory study and data analysis.

References:

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