DARK MATERIAL AT THE SURFACE OF POLAR CRATER DEPOSITS ON MERCURY. Gregory A. Neumann[1], John F. Cavanaugh[1], Xiaoli Sun[1], Erwan Mazarico[2,1], David E. Smith[2], Maria T. Zuber[2], Sean C. Solomon[3] and David A. Paige[4], [1]Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA (Gregory.A.Neumann@nasa.gov); [2]Department of Earth, Atmospheric, and Planetary Sciences, MIT, Cambridge, MA 02139, USA; [3]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA; [4]Department of Earth and Space Sciences, UCLA, Los Angeles, CA 90095, USA.

Introduction: Earth-based radar measurements [1-3] have yielded images of radar-bright material at the poles of Mercury postulated to be near-surface water ice residing in cold traps on the permanently shadowed floors of polar impact craters. The Mercury Laser Altimeter (MLA) on board the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft has now mapped much of the north polar region of Mercury [4] (Fig. 1). Radar-bright zones lie within polar craters or along poleward-facing scarps lying mainly in shadow. Calculations of illumination with respect to solid-body motion [5] show that at least 0.5% of the surface area north of 75° N lies in permanent shadow, and that most such permanently shadowed regions (PSRs) coincide with radar-bright regions.

MLA transmits a 1064-nm-wavelength laser pulse at 8 Hz, timing the leading and trailing edges of the return pulse. MLA can in some cases infer energy and thereby surface reflectance at the laser wavelength from the returned pulses. Surficial exposures of water ice would be optically brighter than the surroundings, but persistent surface water ice would require temperatures over all seasons to remain extremely low (<110 K). Thermal models [6,7] incorporating direct and scattered radiation, Mercury's eccentric orbit, 3:2 spin-orbit resonance, and near-zero obliquity generally do not support such conditions in all permanently shadowed craters but suggest that water ice buried near the surface (<0.5 m depth) could survive for > 1 Gy.

We describe measurements of reflectivity derived from MLA pulse returns. These reflectivity data show that surface materials in the shadowed regions are darker than their surroundings, enough to strongly attenuate or extinguish laser returns. Such measurements appear to rule out widespread surface exposures of water ice. We consider explanations for the apparent low reflectivity of these regions involving other types of volatile deposit.

Determination of return energy: MLA has both high- and low-threshold detection channels. MLA times the weakest pulses at a single low threshold, but measures those of sufficient amplitude simultaneously at a higher threshold. Dual-return pulse widths may be inverted for total area under the pulse, and thereby for returned energy [8]. The ratio of return energy to outgoing pulse energy provides the bidirectional reflectance. The measurement of pulse widths is subject to slope and terrain effects as well as solar background noise, which renders problematic any estimation from the weakest pulse returns at long ranges and shallow incidence angles. Where the laser beam is locally near-normally incident to the surface and slant ranges are less than ~500 km, reflectance may be estimated within ± 25% (Fig. 2).

Observations of permanently shadowed regions: MLA normally ranges to nadir over the northern hemisphere and obtains dual returns near the pole. The 83.5° inclination of the MESSENGER orbit, with a ~200-400 km periapsis altitude at 60-70° N, does not permit coverage of the entire surface in nadir mode, so the spacecraft has maneuvered to measure ranges to the northernmost 6° degrees of latitude where most PSRs are found. Off-nadir slews have succeeded in obtaining return pulses on both channels from PSRs, although such oblique observations spread out the energy in the return pulse and decrease its height, reducing the energy that may be detected above the background noise level.

Reflectance observations: The north polar topographic map shows that nearly all of the surveyed radar-bright regions at latitudes south of 84° N lie within relatively fresh craters on the northern volcanic plains on poleward-facing slopes where high crater rims provide permanent shadow from the Sun. All of these PSRs have lower reflectance than the surrounding terrain, as shown in Figure 2. An adjacent track along the shadowed wall shows even more reflectance contrast, while a track crossing the illuminated portion of the crater floor shows no contrast. Coverage to date suggests that darker material covers and is more extensive than the radar-bright regions, and extends slightly southward of 70° N. At latitudes higher than 84° N, MLA signals are generally weaker, but so far all of the large craters hosting radar-bright deposits appear to be optically darker than the surroundings. A significant deficit of dual returns is consistent with a darker surface. We do not find any brighter-than-average deposits. The collocation of dark material with pole-facing crater walls and interior, and the lack of such darkening in most craters southward of 70° N, appear to rule out instrumental effects or observational geometry as a cause.

Interpretation and speculations: The fact that these polar deposits have dark surfaces means that the process that is forming them is occurring on Mercury today, and it is occurring faster than other processes that act to homogenize the surface reflectance, such as horizontal and vertical transport of the regolith by impact gardening. Were impact gardening dominant, then we would expect these deposits to have the same reflectance as the surrounding terrain.

Thermal models suggest that surface temperatures in the high-latitude craters MLA has observed so far are too warm to support persistent water ice at the surface, but subsurface temperatures are permissive of stable water ice beneath a ~10-cm-thick layer of thermally insulating regolith, a geometry fully consistent with the radar results.

Why is the regolith overlying these ice deposits optically dark? Thermal model calculations of annual maximum surface temperatures in the shadowed regions that have been mapped so far are as high as ~150K. We hypothesize that the surfaces in these cold traps are covered by another volatile species that is thermally stable at these temperatures and intrinsically dark. One candidate for this material is hydrocarbon compounds [6, 9], which are abundant in comets and meteorites, have lower volatility than water, and are very dark. Following impact, such materials can be cold-trapped at the poles along with water, forming a sublimation residue on the surface that provides thermal protection for ice-rich deposits below the surface, as well as protection from micrometeoroids, photons and energetic particles.

Visible volatile deposits may eventually be confirmed in similar conditions on the Moon by active [10] or passive [11] means. The Lunar Crater Observation and Sensing Satellite (LCROSS) experiments [12] have suggested that both water and hydrocarbons are cold-trapped in lunar polar craters, but temperatures as low as 37 K [13] undoubtedly lead to a different style of fractionation and sublimation of volatiles than on Mercury (see also [6]).

References: [1] Slade, M. A., B. J. Butler, and D. O. Muhleman (1992) *Science 258*, 635–640. [2] Paige, D. A., et al. (1992) *Science 258*, 643–646. [3] Harmon, J. K., et al. (2011) *Icarus 211*, 37-50. [4] Zuber M. T. et al. (2012) *Science,* submitted. [5] Mazarico, E., et al. (2010) *Icarus 211*, 1066-1081. [6] Paige, D. A., et al. (2012) *LPS 43*, this mtg. [7] Vasavada, A. R., et al. (1999) *Icarus 141*, 179-193. [8] Cavanaugh, J. F., et al. (2007) *Space Sci. Rev. 131*, 451-479. [9] Zhang, J.-A., and D. A. Paige (2009) *Geophys. Res. Lett.* 36, L16203, 10.1029/2009GL038614. [10] Zuber M. T., et al. (2011) *Nature,* submitted. [11] Gladstone, G. R., et al. (2012) *JGR 117*, 10.1029/2011JE003913. [12] Colaprete, A. et al. (2010) *Science 330*, 463-468. [13] Paige, D. A., et al. (2010) *Science 330*, 479-482.

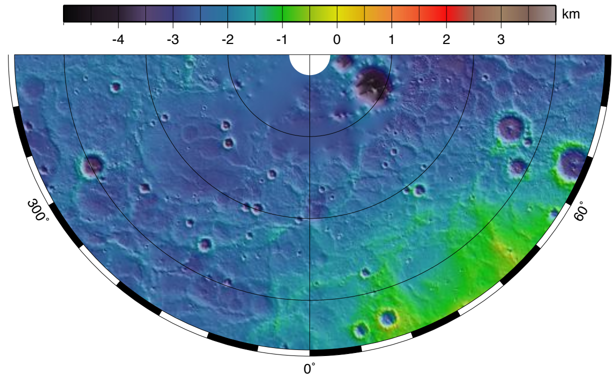

Figure 1. Topographic map of Mercury's north polar region in polar projection to 72° N (circle). The color bar denotes elevation relative to a sphere of radius 2440 km.

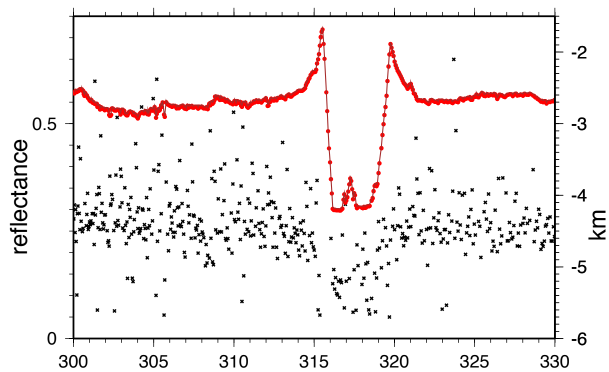

Figure 2. MLA topography (red) and preliminary reflectance (black) vs. longitude, from profile MLASCICDR1108140844 through the center of a 25-km-diameter crater at ~82.5° N in Goethe basin.

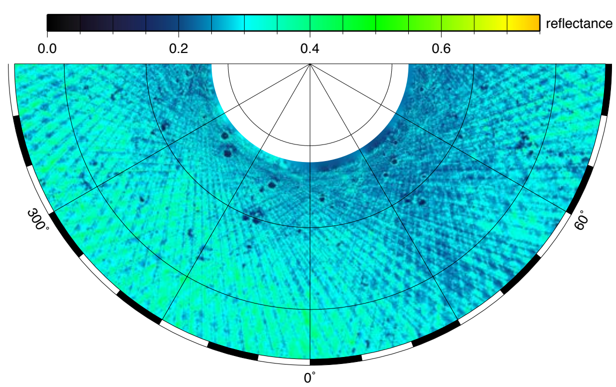

Figure 3. MLA reflectance at 1064 nm wavelength, interpolated between tracks, in polar projection to 72°N. Region north of 84° N is sparsely covered by dual returns and is therefore masked.