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How thick are Mercury's polar water ice deposits?

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ABSTRACT

An estimate is made of the thickness of the radar-bright deposits in craters near to Mercury's north pole. To construct an objective set of craters for this measurement, an automated crater finding algorithm is developed and applied to a digital elevation model based on data from the Mercury Laser Altimeter onboard the MESSENGER spacecraft. This produces a catalogue of 663 craters with diameters exceeding 4 km, northwards of latitude $+55^{\circ}$. A subset of 12 larger, well-sampled and fresh polar craters are selected to search for correlations between topography and radar same-sense backscatter cross-section. It is found that the typical excess height associated with the radar-bright regions within these fresh polar craters is (50 ± 35) m. This puts an approximate upper limit on the total polar water ice deposits on Mercury of $\sim 3 \times 10^{15}$ kg.

1. Introduction

The presence of water in the inner solar system is vital for the development of life. Violent collisions between planetary embryos are thought to have built the rocky planets (Morbidelli et al., 2012), and the associated high energies and temperatures would not have been conducive for volatile molecules such as water. The source of Earth's water is therefore of considerable interest. Measurements of deuterium/hydrogen ratios of solar system bodies (Hartogh et al., 2011; Alexander et al., 2012) combined with models of accretion onto the Earth (Morbidelli et al., 2000; O'Brien et al., 2014) appear consistent with exogenous sources.

Both the Moon and Mercury provide relatively unweathered surfaces in comparison with the Earth, so their near-surface volatile inventories provide additional constraints on models of water delivery to the inner solar system. Surface volatiles are not stable for significant periods unless placed into the low temperature "cold traps" provided by near-polar impact craters containing permanently shaded regions. In order to discriminate between the various possible sources of water (Moses et al., 1999; Crider and Killen, 2005), which often imply different amounts of water being delivered, one also needs to understand how efficiently it can migrate from the delivery location to the cold traps (Butler, 1997; Ong et al., 2010; Stewart et al., 2011). Such models can then inform the interpretation of actual measurements of the volatile inventories of these bodies.

Various neutron spectroscopy, circularly polarized radar, albedo (IR, visible and UV) and impact measurements have been made of the Moon and Mercury to investigate their cold traps. While the LCROSS experiment (Colaprete et al., 2010) found a few per cent by mass of the material in Cabeus crater on the Moon was water ice, which is at a level consistent with neutron spectroscopy results (Eke et al., 2015), there is evidence for substantially purer water ice deposits near Mercury's poles.

A remarkable increase in the same sense circular polarized radar backscatter cross-section was detected at wavelengths of 3.5 cm (Slade et al., 1992; Butler et al., 1993), 12.6 cm (Harmon and Slade, 1992; Harmon et al., 1994; 2001) and 70 cm (Black et al., 2010) from Mercurian polar cold traps. One explanation for these radar returns was that there was multiple scattering occurring within a low-loss medium such as water ice (Hapke, 1990; Hagfors et al., 1997). The high radar backscatter regions correlated spatially with areas that have modelled surface or near-subsurface temperatures that remain below $\sim 100-150$ K (Paige et al., 1992; Ingersoll et al., 1992; Vasavada et al., 1999). This provided extra circumstantial evidence to motivate the interpretation of the anomalous radar measurements as indicating the presence of volatile molecules.

Instruments onboard the MESSENGER spacecraft (Solomon et al., 2007) have considerably increased the information available about the polar cold traps. The deficit in neutron flux observed over the poles is consistent with a localised hydrogen-rich layer

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extending down for tens of centimeters beneath a 10–20 cm thick layer that is less rich in hydrogen (Lawrence et al., 2013). These observations suggest that nearly pure water ice, and not an alternative volatile such as sulphur (Sprague et al., 1995), is responsible for the radar features. MESSENGER's Mercury Dual Imaging System (MDIS) has allowed an improved determination of the locations of the permanently shaded regions, increasing the confidence with which they can be associated with the high radar backscatter regions (Chabot et al., 2012; 2013). Albedo measurements from the Mercury Laser Altimeter (MLA, Cavanaugh et al., 2007) at 1064 nm showed either bright or dark surfaces coincident with these polar cold traps (Neumann et al., 2013). The distinction matched temperature model predictions for either thermally stable water ice at the surface (high albedo) or under a ∼ 10 cm thick organic lag deposit (low albedo) as noted by Paige et al. (2013).

More recently, the sensitivity of MDIS images has allowed the imaging of permanently shaded regions using scattered light (Chabot et al., 2014). The results are similar to the MLA albedo measurements, albeit at visible wavelengths, with anomalous reflectance regions largely coincident with radar-bright ones. Of the surveyed areas, only Prokofiev crater has a high albedo in MDIS images, with the other radar-bright regions appearing anomalously dark. The imaging in Prokofiev crater shows a ∼ 3 km-wide zone that is still in permanent shade with high radar reflectivity, but lies outside the high MDIS reflectance area. One possible reason for this could be the presence of a stable subsurface ice deposit that does not affect the surface reflectance. Chabot et al. (2014) further note that the imaged, high-reflectance region displays a similar texture to that in the sunlit region of Prokofiev, suggesting a relatively recent ice deposition onto a previously cratered surface. Deutsch et al. (2016) used a combination of MLA-derived topography and MDIS imagery to show that radar-bright features colocate with regions of both permanent (from MLA) and persistent (from MDIS) shadow. Furthermore, they demonstrated that many regions of persistent or permanent shadow do not host radar-bright deposits, and that insolation was not the determining factor. Possible reasons for the lack of radar-bright deposits in such apparently conducive situations were mooted to be: a lack of radar coverage, unusually thick lag deposits hiding water ice from the radar, and an actual lack of water ice deposits.

These various lines of evidence collectively point to the presence of many reasonably pure water ice deposits in Mercury's polar cold traps. Estimating the area covered by these deposits, either from radar measurements or maps of permanent shadow if the radar misses some (Deutsch et al., 2016), the remaining observational challenge in determining their volume is to measure their depth. While the neutron measurements suggest that the hydrogen-rich layer needs to be at least half a metre deep, for the radar results to arise due to volume scattering requires ice at least several wavelengths thick (Black et al., 2001; Harmon, 2007). Given the results of Black et al. (2010) at 70 cm, this interpretation implies a layer of ice at least a few metres deep.

To place an upper limit on the thickness of possible water ice deposits in the Mercurian polar cold traps, a few different studies have considered the depth-diameter relations of craters. Barlow et al. (1999) anticipated that subsurface ice might lead to a softening of the terrain, as was seen on Mars (Cintala and Mouginis-Mark, 1980; Squyres and Carr, 1986). However, they found no unequivocal evidence of such an effect on Mercury's craters, when split as a function of latitude. Vilas et al. (2005) extended this analysis, using the better resolution of the Harmon et al. (2001) radar results to focus on individual craters. With Mariner 10 imagery to determine crater depths and diameters, Vilas et al. (2005) found radar bright craters to have significantly lower depth-to-diameter ratios than radar dark ones, to an extent that could be explained by the presence of ∼ 900 m of infilling material. Talpe et al. (2012) used the MLA data to study depth-to-diameter ratios in a sample of 537 craters poleward of 48°N. In contrast to Vilas et al. (2005), they found no evidence for different depths, slopes or surface roughnesses for radar-bright craters compared with their radar-dark counterparts. Ascribing the different results to having altimetry-derived measurements, Talpe et al. (2012) placed an upper limit on the depth of ice in a 10 km-diameter crater of ∼ 300 m.

There are two orders of magnitude separating current lower and upper limits on the depth of the ice deposits in Mercury's polar cold traps. This paper aims to determine how the existing MLA Gridded Data Record Digital Elevation Model (GDR DEM) can be used to improve the constraint on the depth of these deposits in craters near the north pole. The specific question being addressed is: are the radar-bright regions of polar crater interiors systematically elevated relative to otherwise similar radar-dark parts of the surface?

Section 2 describes the data being used in this study. The methods for constructing the crater sample and measuring the change in height associated with the radar-bright regions are detailed in both Section 3 and Appendix A. Section 4 contains the results of the analysis, and the implications are summarised in Section 5.

2. Data

This section contains descriptions of the topography and radar backscatter cross-section data sets used to study the Mercurian north polar craters. The topographical data were also used to define the crater populations within which the dependence of height with radar backscatter cross-section was studied.

2.1. Topographical data

Data from the 11th and 15th data releases (DR11 and DR15 hereafter) of the MLA GDR DEM, available from the Geosciences Node of NASA's Planetary Data System (PDS[1]), have been used. While DR11 contained a GDR at a spatial resolution of 500 m per pixel in a north polar stereographic projection, DR15 included both 250 m and 500 m resolution DEMs. All of these data sets were investigated in this study, to determine the best approach for constraining the thickness of Mercury's polar deposits.

The MLA has absolute range uncertainties on individual altitude measurements of better than 1m and an accuracy relative to the centre of mass of Mercury of better than 20 m (Sun and Neumann, 2015; Zuber et al., 2012). Glitches are evident in the DR15 GDR, where the DEM height differs systematically along particular orbital tracks by of order ± 100 m relative to surrounding pixels. Thus, despite the improved sampling relative to the DR11 GDR, these glitches make the DR15 GDR unsuitable for this study and the DR11 500 m resolution option will be the default choice for the rest of this paper. A square region in the polar stereographic projection out to ± 1536 km from the north pole in both directions will be considered. This reaches a latitude $+55^\circ$ along the coordinate axes. The pixelated DEM has altitudes in the range $-6 < a/\mathrm{km} < 2.5$, and the mean number of observations per pixel is ∼ 0.11. This sampling rate increases toward higher latitudes, peaking at ∼ 0.5 observations per pixel at $+84^\circ$. The MLA GDR DEM includes interpolated altitudes for unobserved pixels.

2.2. Radar data

The Arecibo S-band (12.6 cm) radar data from Harmon et al. (2011)[2] were used to determine the radar properties of the sur-

[1] http://pds-geosciences.wustl.edu .

[2] available at http://www.naic.edu/~radarusr/Mercpole/ .