Morphometry and Temperature of Simple Craters in Mercury’s Northern Hemisphere: Implications for Stability of Water Ice

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Abstract

Multiple lines of evidence support the hypothesis that Mercury’s polar regions host deposits of water ice in permanently shadowed regions, often within the interiors of craters. Pre-MERcury, Surface, Space, ENvironment, GEochemistry, and Ranging (MESSENGER) thermal modeling of the temperature of idealized simple craters found that the interiors of these craters were too hot to host near-surface ice on geologic timescales unless within 2° of the poles. However, results from the Arecibo Observatory and the MESSENGER mission identified many small, <10 km diameter, simple craters that host radar-bright deposits located considerably farther than 2° from the pole. Here we investigate the location and morphometry of north polar craters with diameters of 5–10 km and find that the craters were, on average, 30% shallower than the idealized simple crater morphometry assumed in previous thermal studies. The craters that host radar-bright deposits have an asymmetric longitudinal distribution that cannot be fully explained by the thermal environment and may be related to the original water ice deposition. We also investigate the maximum and average temperatures of the shadowed regions in these craters and find that many of them possess temperatures that allow water ice to be stable under a thermally insulating layer on geologic timescales outside of 2° from the pole. Thus, while the presence of radar-bright deposits in 5–10 km craters is not necessarily a constraint on the stability of the deposits, it provides additional information on the distribution and deposition of the water ice.

Unified Astronomy Thesaurus concepts: Mercury (planet) (1024); Planetary polar regions (1251); Impact phenomena (779)

1. Introduction

Earth-based radar images of Mercury’s polar regions revealed bright features, which led to the hypothesis that water ice is present at the poles in regions of permanent shadow (Harmon & Slade 1992; Slade et al. 1992; Butler et al. 1993). Comparisons of the locations of the radar-bright areas with Mariner 10 images confirmed that these deposits are located within high-latitude impact craters (Harmon et al. 2001, 1994). Thermal models indicated that the temperature within many regions of permanent shadow would permit water ice to be stable at the surface and under an insulating layer on geologic timescales (Paige et al. 1992).

Observations by the MERcy, Surface, Space, ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft provided several additional independent lines of evidence in support of the hypothesis that Mercury’s polar deposits consist primarily of water ice. Orbital images from MESSENGER’s Mercury Dual Imaging System (MDIS) indicate that all radar-bright deposits within craters >10 km in diameter collocate with regions of permanent shadow (Chabot et al. 2012, 2013, 2018b; Deutsch et al. 2016). Neutron spectrometer measurements confirm a hydrogen enrichment at the north pole (Lawrence et al. 2013) that is quantitatively consistent with the presence of water ice in the radar-bright deposits, as long as most of the deposits are buried under a decimeters-thick, hydrogen-poor layer. Mercury Laser Altimeter (MLA) reflectivity measurements at a wavelength of 1064 nm reveal anomalously high- and low-reflectance areas that generally match the locations of the radar-bright deposits (Neumann et al. 2013), and more recent work has found extensive evidence for water ice deposits outside the largest craters, potentially doubling the estimates of water ice volume (Deutsch et al. 2017). Detailed thermal models incorporating MLA topography (Paige et al. 2013) show that the high-reflectance regions lie in areas where surface ice is predicted to be stable over geologic timescales, and low-reflectance regions lie in areas where water ice is stable over geologic timescales, when protected, only decimeters beneath an insulating surface layer. The modeled temperatures of these low-reflectance regions are consistent with the idea that the surface layer consists mostly of volatile complex organic material (Hamill et al. 2020). Images of permanently shadowed craters in Mercury’s north polar region have revealed areas of anomalously low and high albedo (Chabot et al. 2014, 2016) consistent with those observed by MLA (Neumann et al. 2013; Deutsch et al. 2017).

Pre-MESSENGER thermal models suggested that long-lived water ice would not be stable in idealized bowl-shaped simple craters (with a depth/diameter rate of 0.2) located more than 2° from the poles (Vasavada & Paige 1999), even if buried beneath an insulating layer. Later studies identified radar-bright deposits in many simple craters with diameters less than 10 km (Harmon et al. 2001, 2011; Chabot et al. 2012, 2013). Deutsch et al. (2016) surveyed all radar-bright craters with diameters down to 6 km within 10° from Mercury’s north pole and found that 25%–35% of sub–10 km craters that contain permanently shadowed regions host radar-bright deposits. If the assumed, idealized bowl shape of these craters is correct, the presence of radar-bright deposits within many polar sub–10 km diameter
craters could indicate that the water ice on Mercury was emplaced relatively recently, and the ice in these craters has not yet been lost to thermal processes (e.g., Deutsch et al. 2016). However, if these craters are shallower than assumed in the earlier calculations, their interior thermal environments could be more favorable to the retention of water ice over geologic timescales. In this study, we investigate the morphometry and previously modeled temperatures of sub–10 km north polar craters to investigate their potential to host water ice deposits over geologic timescales. In the following sections, we describe the methodology used to identify radar-bright 5–10 km craters, measure crater morphometry, and investigate the modeled temperatures within these craters. We present the depth/diameter ratio and the average and maximum temperatures within the permanently shadowed regions of each crater. Finally, we discuss the implications of our results for water ice deposits in sub–10 km craters.

2. Methodology

2.1. Identifying Craters that Host Radar-bright Deposits

We identified 273 craters between 5 and 10 km in diameter using a monochrome, 250 m pixel$^{-1}$ MDIS base map within our study region of 75°N to 85°N (Figure 1). The latitude range’s lower limit was based on the locations of radar-bright deposits (the majority of north polar deposits are located >75°N), and the upper limit was constrained by the density of MLA coverage. We used the radar maps from Harmon et al. (2011), with a scale of 1.5 km pixel$^{-1}$, to identify whether these craters do or do not host radar-bright deposits and which do not host such deposits.

2.2. Measuring the Morphometry of Small Craters

The morphometry of craters is an important factor in the expected thermal environment within regions of permanent shadow and thus the stability of water ice on geologic timescales. We used two data sets to measure the morphometry of 5–10 km diameter craters: individual MLA tracks and gridded topography from the entire MLA data set (Philips et al. 2018). The use of individual MLA tracks allows the MLA data to be evaluated in more detail and avoids track mismatch and potential interpolation issues (Zuber et al. 2012; Susorney et al. 2016); the use of the gridded data set allows a direct comparison to the temperature calculations (Paige et al. 2013; Chabot et al. 2018a).

We restricted our measurements of crater morphometry to craters that do not appear to be subsequently modified after emplacement (e.g., subsequent impact craters, volcanic activity), as that would bias our crater measurements toward lower depth/diameter ratios. We focused on measuring craters within Mercury’s smooth plains (Denevi et al. 2018). The smooth plains have fewer variations in topography (Kreslavsky et al. 2014; Fa et al. 2016; Susorney et al. 2017); thus, crater depth measurements are more accurate. Measurements using individual MLA tracks were limited to 99 craters that were bisected by multiple MLA tracks. An additional 102 craters were measured from the gridded MLA topography. To check the validity of the gridded topography measurements, 54 of the 99 craters measured by MLA tracks were also measured by the gridded topography (156 craters total measured using the gridded topography; Figure 2).

The diameter of each crater was measured by selecting three points on the crater rim and fitting a circle. This step was repeated three times, and the reported diameter is the average of three measurements, with the error bars being one standard deviation of the three measurements. To measure the crater depth from individual MLA tracks, an MLA track that bisected the crater was mapped onto the 250 m pixel$^{-1}$ base map, and the crater depth was calculated as the difference between the MLA point on the highest portion of the rim and the average depth of three MLA points on the crater floor. This step was repeated for three different tracks that bisected the crater, and the error bars represent one standard deviation of the depth measurements of the three tracks. For the gridded topography measurements, the depth was calculated between the average rim height for three cross sections that bisected the crater and the deepest point in the crater floor, excluding superimposed impact craters, and the error bars represent one standard deviation of the three measurements.

2.3. Estimating the Temperature and Depth to Ice of Small Craters

Models of the biannual average surface temperature, biannual maximum surface temperature, and depth below the surface where ice would be stable, hereafter called depth to ice, calculated by Paige et al. (2013), were updated to use the entire MLA data set from the full MESSENGER mission in Chabot et al. (2018a). The depth to ice was calculated at the depth at which water ice would be lost to sublimation at a rate of less than 1 mm per billion years (Paige et al. 2013;
We use the updated models from Chabot et al. (2018a) that have a spatial scale of 1 km pixel$^{-1}$. The maps were combined with the mapped regions of permanent shadows produced by Deutsch et al. (2016) at a scale of 500 m pixel$^{-1}$ and used to determine the temperature and depth to ice within the areas of permanent shadow for the 156 craters measured by gridded topography. The 1 km pixel$^{-1}$ scale of the thermal maps results in only 5 pixels across the smallest craters, which could lead to overestimates of the thermal conditions, as the thermal maps may not pick up small variations in topography that might create pockets of variable temperatures. However, as our study is focused on whether favorable thermal conditions exist, overestimating thermal conditions in some craters will not affect our main results. We measured the mean, minimum, and maximum temperature values for each permanently shadowed region from the previously produced biannual average and maximum surface temperature maps. In addition, the mean depth to ice was extracted using the regions of the Chabot et al. (2018a) maps that overlapped with areas with permanent shadows. In many craters, particularly in the biannual maximum surface temperature map, there were 1 or more pixels on the rim of the shadowed area that were several deviations higher in temperature than the next greatest pixel. Due to the spatial limitations of the permanent shadow and thermal maps, these pixels were attributed to being a mixture of permanently shadowed and dimly sunlit locations and were therefore eliminated from the calculations.

3. Results

3.1. Radar-bright Deposits

Deutsch et al. (2016) surveyed radar-bright craters with diameters down to 6 km within 10° of Mercury’s north pole and identified an increase in the percentage of radar-bright deposits at longitudes between 0°E and 90°E, which was also observed earlier by Harmon et al. (2001). We also observe a large increase in the percentage of radar-bright craters in the same longitudes centered around 60°E (Figures 1 and 3). The longitude enhancement is consistent with the presence of the large crater Prokofiev (112 km in diameter, 86°N, 64°E) and is near one of Mercury’s cold poles at 90°E. The enhancement centered at 60°E is not at the cold pole itself, consistent with the conclusions of Deutsch et al. (2016). In addition, there is also a slight increase (much smaller than the 60° E one) from −60°E to −140°E, but we do not observe a similar magnitude increase in radar-bright craters at Mercury’s other cold pole (−90°E). Showing the distribution of radar-bright craters by latitude, Figure 4 is also consistent with previous observations by Deutsch et al. (2016), where we observe a general increase in the percentage of craters that are radar-bright with latitude.

3.2. Crater Morphometry

To assess whether the gridded topography provides robust morphometry measurements, we compared the measured depth/diameter ratios of 54 craters measured by both the
gridded topography technique and the individual MLA tracks (Figure 5). We found the mean difference in depth/diameter ratios estimated by the two techniques for the same craters to be 0.002. Therefore, we use all 102 craters measured by gridded topography and the 99 craters measured by MLA in our results and discussion. The mean depth/diameter ratio of these cumulative 201 craters is 0.13 ± 0.03, which is less than the idealized ratio of 0.2 (Figure 6) used in early thermal studies to model small crater morphology (Vasavada & Paige 1999). For radar-bright craters, the mean depth/diameter ratio was 0.12 ± 0.04, and for non-radar-bright craters, the depth/diameter ratio was 0.14 ± 0.03.

The mean depth/diameter is below the idealized 0.2 ratio for all longitudes and latitudes (Figure 7), and the mean depth/diameter ratios of radar-bright craters and non-radar-bright craters overlap at the one standard deviation error bars. No statistically meaningful change is observed in the depth/diameter ratio with latitude (Figure 7), but we do observe a general decrease of the mean depth/diameter ratio between 30°E and 110°E, although the one standard deviation error bars continue to overlap.

3.3. Temperature within Permanent Shadows

The calculated mean values for the biannual maximum surface temperatures in the permanently shadowed regions for the craters in this study are higher than 110 K, the threshold for ice stability (Vasavada & Paige 1999; Figures 8(a)–(b)). However, many craters have biannual average surface temperatures, a proxy for the temperature below an insulating layer, below 110 K (Figures 8(c)–(d)). Therefore, while no craters would have the entire permanently shadowed region covered in a surface layer of water ice, the permanently shadowed regions for many of these small simple craters could host water ice under an insulating layer. The depth to ice, originally modeled by Paige et al. (2013) with an update included in Chabot et al. (2018a), shows that for many craters, the depth to ice is less than 50 cm (Figure 8(e)).

All of the results discussed above are based upon a mean temperature value for an entire given permanently shadowed region, but the temperature can vary within the shadowed region. We also measured the minimum temperature value from the biannual maximum surface temperature map for each permanently shadowed region (lowest maximum temperature; Figure 8(f)). The results showed only that three craters had locations within their permanently shadowed regions where the biannual maximum surface temperature was below 110 K, suggesting water ice potentially could be stable at the surface in small geographic regions of some of these 5–10 km craters. However, the 1 km spatial scale of the thermal models used in this study limits investigations and interpretations of small-scale features.

4. Discussion

Previous studies have noted a nonuniform distribution in small radar-bright craters (Harmon et al. 2001; Deutsch et al. 2016), which we have confirmed in this study as well. We found a large increase in the percentage of radar-bright craters from 0°E to 120°E. While this concentration is near one of Mercury’s cold poles (centered at 90°E), the radar-bright craters are centered at 60°E, and Mercury’s other cold pole (centered at 270°E) is not associated with a similar magnitude increase in the percentage of radar-bright craters. The increase in the percentage of radar-bright craters is also spatially correlated with the presence of secondary craters originating from the large, 112 km crater Prokofiev (located at 86°N, 64°E). Secondary craters are typically shallower than primary craters (e.g., Susorney et al. 2016), and we found that craters located between 30°E and 110°E are slightly shallower than other 5–10 km craters that we analyzed, although the one standard deviation error bars overlap. However, this regional shallowing does not appear to be limited to Prokofiev’s definitive secondaries. After identifying clear secondaries of Prokofiev (linear chains of craters emanating from the crater), we found that the depth/diameter ratios of Prokofiev’s definitive secondaries are not noticeably shallower than the depth/diameter ratios of other 5–10 km craters in this region (Figure 9). The lack of difference between definitive
secondaries and other craters may be due to the inability to clearly identify all of Prokofiev’s secondary craters. Previous studies of the regions that are in permanent shadow at the north and south poles but do not host radar-bright deposits also show an uneven longitudinal distribution (Chabot et al. 2018b; Deutsch et al. 2016), which could be due to a relatively recent source of water ice, such as a large impact (e.g., Ernst et al. 2018). In addition, some studies have also raised the question of uneven radar coverage being the source of longitudinal variations (Harmon et al. 2001; Deutsch et al. 2016); see Deutsch et al. (2016) for a review of this issue. Overall, our results show that the different depth/diameter ratios of the craters cannot account for the distinct longitudinal distribution of small radar-bright craters.

The morphometry of a crater, particularly its depth/diameter ratio, has an important control on its thermal regime. Previous thermal models of polar craters on Mercury used an idealized morphometry with a depth/diameter ratio of 0.2 and found that water ice would not be stable within bowl-shaped craters with diameters under 10 km that are located more than 2° from the pole (Vasavada & Paige 1999). The presence of radar-bright materials in smaller craters located equatorward of 88° has been proposed to help to constrain the timing of ice delivery, given that water ice was not predicted to be stable in these craters on geologic timescales (e.g., Deutsch et al. 2016; Chabot et al. 2018a). In this study, we find that the majority of north polar 5–10 km diameter craters on Mercury are shallower than the idealized 0.2 depth/diameter ratio used in the pre-MESSENGER modeling efforts of Vasavada & Paige (1999). Therefore, the presence of radar-bright signatures within these craters is not necessarily a constraint on the age of water ice deposits, as we find from our study that the temperatures within these craters could be cold enough to allow water ice to be stable on geologic timescales.

The timing and age of the deposits on Mercury is still an area of active research. Evidence from microcold traps (Rubanenko et al. 2018), regolith gardening (Crider & Killen 2005; Costello et al. 2020), images of the sharp boundaries of ice deposits (Chabot et al. 2014), surface modification models (Lawrence et al. 2013), crater density statistics (Deutsch et al. 2019), and a potential impactor source (Ernst et al. 2018) all point toward geologically young deposits. Our results do not contradict a geologically young age of water ice on Mercury; instead, our results show that the presence of water ice itself in these young craters is not a constraint on water ice timing.

Figure 7. Mean depth/diameter ratio of craters in this study vs. latitude measured over 2° latitudinal bins for craters measured by individual MLA tracks (a) and gridded topography (c). The error bars are one standard deviation of the depth/diameter ratio within each latitude bin. Also shown is the mean depth/diameter ratio of craters vs. longitude over 30° bins every 15° for craters measured by individual MLA tracks (b) and gridded topography (d). The longitude range is restricted from −30°E to 120°E, where the smooth plains are present and the majority of craters were measured.
Since the Vasavada & Paige (1999) study, the MESSENGER mission has gathered topography of sufficient resolution to calculate temperature within many of the north pole’s permanently shadowed regions (Paige et al. 2013; Chabot et al. 2018a). The temperature results from sub–10 km craters show that many of these craters could host stable water ice under an insulating layer. The temperature maps are limited by the original MLA topography data set and thus may not include small-scale variations in topography that could produce local cold traps where additional water ice could be present on the surface. Therefore, the lack of a clear match between radar-bright craters and craters with modeled temperatures where water ice would be stable is not unexpected. In addition, Deutsch et al. (2017) showed low-reflectance deposits in 6 km craters above 75°N, providing additional evidence that water ice could be stable both under an insulating layer and on the surface in small craters.

Results from previously modeled maps of depth to ice show that for many of the high-latitude craters, water ice would be stable around 50 cm below the surface (Figure 8(e)). The range in insulating layer thickness is from 0 to 1.7 m, but this is averaged over the entire shadowed region, and local variations would be possible due to local thermal conditions. While the maps used in this study to calculate depth to ice are less accurate than more complex calculations, such as those of Schorghofer & Taylor (2007), the depth to ice results provide additional evidence of the stability of water ice in small polar craters. Future thermal studies of Mercury’s polar craters that

Figure 8. Mean maximum and average temperature for all of the pixels in the shadowed region of each crater vs. the crater’s latitude (panels (a) and (c)) and longitude (panels (b) and (d)). The mean depth to ice of each crater vs. the crater’s latitude is shown in panel (e), and the lowest maximum temperature within the shadowed region vs. latitude is shown in panel (f). The dotted line in panels (a)-(d) and (f) is the temperature at which water ice is stable on Mercury, 110 K.

It is not clear whether the water ice would be stable in the craters with modeled temperatures where water ice would be stable.
than the one standard deviation error bars overlapping our individual measurements. A study of nonpolar craters on Mercury found that the mean depth which may be due to natural variations in crater morphology. A bright craters in our study is also less than the mean ratio of non-radar-diameter ratio results with Rubanenko et al. 2019

We measured the morphometry of 5–10 km diameter craters from 75°N to 85°N and found that they are 30% shallower than the idealized 0.2 depth/diameter ratio, with an average depth/diameter ratio of 0.13. Previously modeled temperatures inside the permanently shadowed regions of these craters show that the temperatures are sufficiently low in many craters for water ice to be stable under a thermally insulating deposit over geologic timescales. In a few craters, the modeled temperatures show that water ice could be stable on the surface in small cold traps. The results of this study show that water ice could be stable in sub–10 km craters outside of 2° from the north pole, and the presence of radar-bright deposits within these craters is unlikely to be a constraint on the age of these deposits.

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applied such models could provide new insight into the depth to ice on Mercury in these cold trap locations.

A previous study of the morphometry of north polar craters on Mercury found a decrease of the crater depth/diameter ratio toward the pole and attributed it to the presence of tens of meters of ice within the craters, reducing the crater depth (Rubanenko et al. 2019). Similar changes in the depth/diameter ratio have been attributed to the presence of water ice in other craters on Mercury (Eke et al. 2017; Deutsch et al. 2018). We compared our depth/diameter ratio results with Rubanenko et al. (2019) and found a similar fitted linear trend toward Mercury’s pole (Figure 10), but there is a large amount of scatter in the individual measured depth/diameter ratios. The mean depth/diameter ratio of radar-bright craters in our study is also less than the mean ratio of non-radar-bright craters (0.14 versus 0.12); however, the difference is less than the one standard deviation error bars (0.03). Like Rubanenko et al. (2019), we observe a large spread in the depth/diameter ratio, which may be due to natural variations in crater morphology. A study of nonpolar craters on Mercury found that the mean depth/diameter ratio of sub–10 km craters is 0.17 ± 0.03, with the error bars overlapping our individual measurements (Susorney et al. 2016). As the depth/diameter ratio of craters on Mercury varies outside the poles and the difference between the mean depth/diameter ratios of radar-bright and non-radar-bright craters in our study is less than their associated error bars, we cannot confidently attribute the latitudinal difference in the mean depth/diameter ratio to ice infill.

5. Conclusion

The radar-bright deposits have been proposed to be unstable on geologic timescales in sub–10 km craters more than 2° from the poles when modeled with an idealized depth/diameter ratio of 0.2 (Vasavada & Paige 1999). Later observations by the Arecibo Observatory and the MESSENGER mission identified radar-bright deposits in many sub–10 km craters (Harmon et al. 2001, 2011; Chabot et al. 2012, 2013; Deutsch et al. 2016). We measured the morphometry of 5–10 km diameter craters from 75°N to 85°N and found that they are 30% shallower than the idealized 0.2 depth/diameter ratio, with an average depth/diameter ratio of 0.13. Previously modeled temperatures inside the permanently shadowed regions of these craters show that the temperatures are sufficiently low in many craters for water ice to be stable under a thermally insulating deposit over geologic timescales. In a few craters, the modeled temperatures show that water ice could be stable on the surface in small cold traps. The results of this study show that water ice could be stable in sub–10 km craters outside of 2° from the north pole, and the presence of radar-bright deposits within these craters is unlikely to be a constraint on the age of these deposits.

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