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Comparison of areas in shadow from imaging and altimetry in the north polar region of Mercury and implications for polar ice deposits

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ABSTRACT

Earth-based radar observations and results from the MESSENGER mission have provided strong evidence that permanently shadowed regions near Mercury's poles host deposits of water ice. MESSENGER's complete orbital image and topographic datasets enable Mercury's surface to be observed and modeled under an extensive range of illumination conditions. The shadowed regions of Mercury's north polar region from 65°N to 90°N were mapped by analyzing Mercury Dual Imaging System (MDIS) images and by modeling illumination with Mercury Laser Altimeter (MLA) topographic data. The two independent methods produced strong agreement in identifying shadowed areas. All large radar-bright deposits, those hosted within impact craters ≥6 km in diameter, collocate with regions of shadow identified by both methods. However, only ~46% of the persistently shadowed areas determined from images and ~43% of the permanently shadowed areas derived from altimetry host radar-bright materials. Some sizable regions of shadow that do not host radar-bright deposits experience thermal conditions similar to those that do. The shadowed craters that lack radar-bright materials show a relation with longitude that is not related to the thermal environment, suggesting that the Earth-based radar observations of these locations may have been limited by viewing geometry, but it is also possible that water ice in these locations is insulated by anomalously thick lag deposits or that these shadowed regions do not host water ice.

1. Introduction

More than two decades ago, Earth-based radar images of Mercury first revealed an area of high radar backscatter near the planet's north pole (Slade et al., 1992; Butler et al., 1993). Observations made at the Arecibo Observatory confirmed the presence of radar-bright materials at Mercury's north pole and indicated similar materials near the planet's south pole (Harmon and Slade, 1992). Because the radar characteristics of Mercury's polar deposits are similar to those of water ice at the martian polar caps and the icy outer Solar System satellites, and because the locations of the deposits coincided with impact craters in Mariner 10 images of polar regions where available (Harmon et al., 1994, 2001, 2011; Harmon 2007), these materials have been interpreted as water-ice deposits on the shadowed portions of crater floors. Early thermal models constructed for idealized flat-floored crater shapes indicated that the permanently shadowed regions near Mercury's poles provide thermal environments capable of hosting stable water-ice deposits on geologic timescales (Paige et al., 1992).

More recently, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft returned a broad range of evidence confirming that these radar-bright materials are predominantly water ice. The spacecraft's Neutron Spectrometer (NS) documented enhanced concentrations of hydrogen in Mercury's north polar region, quantitatively consistent with models in which all radar-bright polar deposits consist primarily of water ice (Lawrence et al., 2013). Maps of shadowed regions derived from images captured by the Mercury Dual Imaging System (MDIS) (Hawkins et al., 2007) showed that all major radar-bright deposits collocate with regions of permanent shadow in the south polar region (Chabot et al., 2012) and with areas of persistent shadow – i.e., shadowed in all images acquired – in the north polar region (Chabot et al., 2013). Mercury Laser Altimeter (MLA) (Cavanaugh et al., 2007) measurements of reflectance at 1064 nm wavelength (Neumann et al., 2013) and MDIS imaging (Chabot et al., 2014) of

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the radar-bright deposits in the shadowed north polar craters revealed low-reflectance surfaces that extend to the edges of shadowed areas and terminate with sharp boundaries. On the basis of thermal models, these low-reflectance surfaces are interpreted to consist of a surficial layer of volatile organic-rich materials, formed as lag deposits, which insulate water ice beneath them (Paige et al., 2013). Thermal models also indicate that the floors of some higher-latitude craters near the north pole can support long-lived water ice exposed at the surface without the need for an insulating layer (Paige et al., 2013). MLA reflectance (Neumann et al., 2013) and MDIS imaging observations (Chabot et al., 2014) revealed a high-reflectance surface on a radar-bright polar deposit on the floor of one such crater, Prokofiev, suggesting that water ice is exposed at the surface in this crater.

Earlier mapping of shadowed areas in Mercury's north polar region (Chabot et al., 2013) was from images acquired during the first Earth year of MESSENGER's orbital mission. After its first year of operations, MESSENGER had not yet achieved full coverage of Mercury, and, in particular, there were substantial gaps in the north polar region because of MESSENGER's non-polar orbit inclination (Solomon et al., 2007). This incomplete image coverage limited mapping of persistently shadowed regions from MDIS images and left a gap from ~86°N to 90°N (Chabot et al., 2013). Previously unmapped regions include craters with large radar-bright deposits (>10 km in horizontal extent), an unresolved radar-bright "diffuse patch," and craters predicted by thermal models as able to host surface water-ice deposits (Paige et al., 2013). Additionally, the previous measurements of persistent shadow were made from a limited MDIS dataset of ~6500 images with which the majority of the polar surface had been imaged approximately 10–20 times (Chabot et al., 2013). This dataset allowed for the identification of only those persistently shadowed craters ≥10 km in diameter. Similarly, incomplete MLA coverage of this region after MESSENGER's first year of operations required interpolated measurements to model the topography north of 84°N, limiting the resolution and accuracy of thermal models in the northernmost area (Paige et al., 2013).

The full image dataset now available provides more than 16,000 images useful for mapping shadows in Mercury's north polar region from 65°N poleward, and every point on Mercury's surface in this latitude range was imaged. Furthermore, with these images we are able to identify small craters (<10 km in diameter) with simple bowl-shaped morphologies as persistently shadowed. Moreover, MESSENGER acquired just over four years of MLA data from orbit before impacting Mercury's surface on 30 April 2015. This complete orbital dataset offers the opportunity to map topography and shadows in Mercury's north polar region to a level of detail that was not previously possible.

Here we map regions of shadow in Mercury's north polar region with two independent methods. With MDIS images, we map persistent shadow following the methods of Chabot et al. (2013), but with a more robust dataset that covers the entire north polar region and under an extensive range of illumination conditions. Regions of persistent shadow are again defined as those that remain in shadow in all orbital images. We also model regions of permanent shadow in Mercury's north polar region from MLA topographic data, with a method similar to that used to identify permanently shadowed regions on the Moon (Mazarico et al., 2011). Regions of permanent shadow are defined as those that are modeled to be in shadow by illumination models derived from topography. With shadows in Mercury's north polar region from 65°N to 90°N determined from full orbital datasets by both methodologies, we compare the strengths and limitations of each shadow map. We also compare the spatial distribution of regions of shadow with that of deposits identified from Earth-based radar observations, and we discuss the implications for water ice on Mercury.

2. Methods

2.1. Mapping shadows from MDIS imagery

During just over four years of orbital operations, MDIS imaged Mercury's north polar region with repeated imaging campaigns. In particular, the MDIS wide-angle camera (WAC) provided images of Mercury's surface under a range of illumination conditions that revealed the planet in different degrees of shadow. MDIS was also equipped with a narrow-angle camera (NAC), but the NAC footprint, with a 1.5° field of view, was considerably smaller than that from the 10.5° field of view of the WAC and provided negligible coverage compared with the WAC dataset. Our mapping from MDIS uses all available WAC views of the north polar region to identify areas that are in shadow whenever imaged.

The majority of WAC images were acquired as part of MESSENGER's global mapping campaigns to create multiple monochrome and color base maps of the planet. Images were captured either as color sets or as individual monochrome images. The color sets were comprised of 3–11 images acquired with the narrow-band filters on the WAC filter wheel. Each individual image in a given color set was acquired 1–4 s after the previous one in the set, resulting in negligible changes in illumination and viewing conditions among images within a color set. To map regions of shadow, we used images taken with the 750-nm filter (5.1-nm bandwidth), which was used in all of the global monochrome and color mapping campaigns. Since the other narrow-band WAC filters were always used in conjunction with the 750-nm filter, the images acquired with these other filters contain no information not captured by the 750-nm filter imaging. These 750-nm filter images capture the full range of illumination conditions available in the narrow-band WAC MDIS dataset. In total, 15,626 750-nm filter images centered at or poleward of 65°N were taken during MESSENGER's orbital operations.

In contrast, the MDIS 700-nm broadband filter (600-nm bandwidth) was utilized in a separate campaign to image within the shadowed regions near Mercury's north pole by scattered sunlight (Chabot et al., 2014). This WAC broadband filter was used to image the floors of north polar craters in an effort to observe the radar-bright deposits directly. This campaign resulted in a wide range of exposure times, given the trial-and-error approach of imaging the surfaces in permanent shadow. Although there are 3270 WAC broadband filter images that fall within the area from 65°N to 90°N, the majority of these images by design contain substantial saturation, which leaked into shadowed portions of the image as an artifact of the goals of the campaign. Thus, for the WAC broadband images, we limited our dataset to the images with exposure times ≤2 ms that have fewer than 50 saturated pixels, resulting in 581 images.

In total, 16,207 WAC images taken with the narrow-band 750-nm filter and the broadband 700-nm filter were used to map areas of persistent shadow from 65°N to the pole (Fig. 1). The coverage is greater than that used in the previous study to map shadow in this area after one year of MESSENGER operations (Chabot et al., 2013). With this complete dataset, each surface point in the region, mapped at 200 m/pixel, was imaged on average 50 times. The most sampled locations were observed in over 220 images. The locations that were sampled the least, at the lowest latitudes and at some regions north of 85°N, have coverage from at least 9 images. The narrow low-count edges on Fig. 1 are an artifact of our image selection process, namely that only images with a central latitude of 65°N or greater were considered.

Each of the 16,207 WAC images was map-projected at a pixel scale of 200 m in a polar stereographic projection, using an MLA-produced digital elevation model (DEM) for orthorectification. A photometric correction (Domingue et al., 2015) was applied to the