Age constraints of Mercury's polar deposits suggest recent delivery of ice

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ABSTRACT

Surface ice at the poles of Mercury appears as several-m-thick deposits that are composed of nearly pure water. We provide new age estimates of the surfaces of Mercury's polar deposits from combined analyses of Poisson statistics and direct observations of crater densities within permanently shadowed, radar-bright regions imaged by the MESSENGER spacecraft. These age estimates conservatively suggest that ice was delivered to Mercury within the last ∼330 Myr. The geologically young ages suggest that the surfaces have been recently refreshed, and this may be accomplished by the delivery of ice in a young impactor or impactors. A single, recent impactor is more consistent with the relative purity of the ice, as suggested by the Earth-based radar observations. In contrast to ice on Mercury, observations of the lunar poles are suggestive of a highly patchy distribution of surface frost. The patchiness of lunar polar deposits is consistent with long exposure times to the space weathering environment. Given enough time, the polar deposits on Mercury may age into a more heterogeneous spatial distribution, similar to that on the Moon.

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1. Introduction

The polar terrains of Mercury are characterized by permanently shadowed regions (PSRs) that are thermally stable environments for water ice on geologic timescales (Vasavada et al., 1999; Paige et al., 2013). Observations from both Earth-based radar and the MESSENGER Surface, Space ENVironment, GEOchemistry, and Ranging (MESSENGER) spacecraft have demonstrated that water-ice deposits occupy such PSRs (Fig. 1) (Deutsch et al., 2016; Chabot et al., 2018). For example, radar observations of Mercury's poles are suggestive of ice deposits that are at least several meters thick (Harmon, 2007; Black et al., 2010), and modeling of the radar data suggests that these deposits are composed of ∼95% pure water ice (Butler et al., 1993). Neutron data acquired by the MESSENGER spacecraft of the north polar region of Mercury is also consistent with a near pure water-ice composition (Lawrence et al., 2013). While some ice deposits closest to the pole are exposed at the surface (Neumann et al., 2013; Chabot et al., 2014; Deutsch et al., 2017), the majority of ice deposits on Mercury are insulated by 10–30 cm (Lawrence et al., 2013) of low-reflectance materials that are interpreted to be a sublimation lag composed of carbon-rich material (e.g., Zhang and Paige, 2010; Paige et al., 2013). Finally, images (Chabot et al., 2014; 2016) and reflectance measurements (Neumann et al., 2013; Deutsch et al., 2017) of Mercury's PSRs reveal spatially coherent ice deposits with distinct albedos and sharp reflectance boundaries that align with boundaries of permanent shadow.

Understanding the ages of Mercury's polar deposits is important when considering the possible source(s) and evolution of the ice. An early pre-MESSENGER analysis used regolith gardening models to constrain the age of Mercury's polar ice (Crider and Killen, 2005). Because Earth-based radar observations suggest that the radar-bright ice deposits on Mercury's surface have <5% volume fraction of silicates (Butler et al., 1993), it is likely that the ice deposits were emplaced relatively recently in order to maintain this high degree of purity through time (Butler et al., 1993; Crider and Killen, 2005). The regolith gardening models suggest that the ice deposits are <50 Myr in age, given that 20 cm of regolith is expected to cover the deposits in this timeframe, which is not observed (Crider and Killen, 2005). Similarly, Lawrence et al. (2013) used the average thickness of the upper layer of ice inferred from neutron spectrometry and models of surface modification to predict that ice was delivered to the poles in the last 18 to 70 Myr.

Data acquired by the MESSENGER Surface, Space ENVironment, GEOchemistry, and Ranging (MESSENGER) spacecraft support the
hypothesis that the ice on Mercury may be relatively young. For example, images of the north polar region show that the ice deposits are not buried by regolith (Chabot et al., 2014; 2016). Furthermore, images (Chabot et al., 2014; 2016) and reflectance measurements (Neumann et al., 2013) reveal sharp reflectance boundaries delineating coherent deposits, suggesting that volatiles were delivered relatively recently or are actively restored.

Here we estimate the surface ages of specific ice deposits on Mercury using crater-counting methods and Poisson statistical analyses and discuss possible sources for ice on Mercury. We conclude by discussing the differences between ice at the poles of Mercury and the Moon, and suggest that differences in ages of the ice may be an important factor contributing to the stark differences in surface characteristics between ice on these two airless bodies.

2. Methods

2.1. Surface age estimates for polar deposits on Mercury

During MESSENGER’s low-altitude campaign, high-resolution images (pixel resolution \( \leq 100 \) m) were acquired of 35 host craters at the north polar region of Mercury (Chabot et al., 2016). These broadband Wide-Angle Camera (WAC) images use sunlight scattered from nearby illuminated peaks to image within PSRs. The permanently shadowed floors where radar-bright ice deposits are located can be resolved in these images, and the images sometimes reveal central crater structures or small impact craters superposing the host crater. Identified superposing impact craters are all \(<100 \) km in diameter, but are typically much smaller, between 100 and 300 m. While the majority of small craters \((<100 \) km in diameter) observed in the PSRs may have formed before the deposition of the ice (Chabot et al., 2016; Deutsch et al., 2018), some anomalous small impact craters are associated with high-reflectance rings, suggestive of excavated material (Fig. 2). If these anomalous craters associated with high-reflectance material are superposing the ice, then they can be used to estimate the ages of the ice surfaces.

Each of the analyzed craters is located below \( \sim 86^\circ \)N and has a low-reflectance layer of materials within its PSR. Low-reflectance layers are found exclusively within Mercury’s PSRs, specifically in regions where biannual average surface temperatures are \( >110 \) K (the temperature at which water ice is stable) but still \( <210 \) K, suggesting that the distribution of these low-reflectance materials is thermally controlled and that the composition of these materials is volatile (Paige et al., 2013). Materials with a lower volatility than water can form as sublimation lags and help insulate water-ice deposits beneath (Paige et al., 2013), and the reflectance properties of Mercury’s low-reflectance materials are consistent with organic-rich compounds such as those present in comets and primitive meteorites (e.g., Zhang and Paige, 2010; Paige et al., 2013). After the initial emplacement of ice, it is possible that any disturbance to the ice (e.g., bombardment) would result in the formation of new lag deposits, restoring the ice to a stable configuration.

We analyze all high-resolution MDIS images of the 35 host craters at the north polar region of Mercury that were acquired during MESSENGER’s low-altitude campaign (Chabot et al., 2016). The PSRs of each crater (Deutsch et al., 2016) are visually inspected for the presence of any impact craters that are associated with high-reflectance rings suggestive of excavated material. Larger-scale brightness variations in polar craters correlate with variations in modeled maximum surface temperature, suggesting that multiple volatile species are contained within the surficial lag deposits that insulate the majority of polar deposits on Mercury (Chabot et al., 2016). The brightness variations associated with the craters selected for this study are smaller in size than the brightness variations that are suggestive of different volatiles, and they are also not correlated with any predicted temperature variations (Chabot et al., 2016). However, the thermal models presented by Chabot et al. (2016) have a spatial scale of 1 km, and therefore cannot predict variations at the spatial scale of these high-reflectance rings associated with small craters (between 100 m and 300 m in diameter).

If small craters associated with high-reflectance rings are identified in \( \geq 2 \) images, then we interpret these small craters as superposing the ice deposit and we interpret the high-reflectance rings as crater ejecta. Thus, even if high-reflectance rings associated with small craters appear to be present in an image, if the remaining images are unclear due to poor lighting conditions or non-ideal viewing geometries, then we do not use the host craters in our analysis. For the majority of host craters analyzed (29 of 35 craters), the available images do not adequately resolve the permanently shadowed floors such that the presence or absence of high-reflectance rings can be confidently identified in association with small craters. If small craters associated with high-reflectance rings are not identified in any images (and \( \geq 2 \) images) that clearly
resolve the host crater floor, then we interpret the host crater as having no small craters that superpose the ice deposit.

We identify 3 north polar craters that host small impact craters (∼100–300 m) associated with high-reflectance ejecta rings: Ensor, Laxness, and Bechet (Fig. 1; Table 1). The images used to identify high-reflectance material for these 3 craters were acquired at phase angles between 77.2° and 118.3°, incidence angles between 82.8° and 84.7°, and emission angles between 0.3° and 34.0°. For each of these 3 craters, count areas for crater statistics are measured for the regions of the crater floors that could be resolved in all of the images. All small impact craters >100 m that are associated with high-reflectance rings are identified.

Using CraterStatsII (Michael and Neukum, 2010), crater size-frequency distributions (CSFDs) are derived for the ice surfaces by fitting models of the crater-derived retention ages to the chronology and production curves for Mercury (Le Feuvre and Wieczorek, 2011). We estimate surface ages for each ice deposit from the CraterStatsII output age model.

We also describe the relative likelihoods of possible ages of the ice surfaces using Poisson statistics, which do not require data binning or curve fitting techniques (Michel et al., 2016). In contrast to fitting best-fit model isochrons to some crater population, which results in an approximate evaluation of the crater chronology model prediction, this approach yields an exact evaluation of a crater chronology model using Poisson statistics and Bayesian inference (Michael et al., 2016). It is exact given that it does not rely on approximation in evaluating the predictions of the crater chronology model (although uncertainties inherent to the model itself remain). Poisson statistics determine the time-resolved probability of a given observation within the chronology model, where uncertainties stem from the predictions of the chronology model (Michael et al., 2016). With this technique, order-of-magnitude ages can even be estimated for surfaces that show no craters. The likelihood function for the set of observed craters, D, as divided into n bins for any given time, t, is expressed by Michael et al. (2016) in their Eq. (8):
that we analyze are similarly small and located in crater interiors, away from steep slopes or warmer topographies. Furthermore, analysis of flow conditions within permanently shadowed craters on Mercury suggests that the extremely cold conditions and limited thickness of the ice prevent substantial flow (Fastook et al., 2019).

The crater counts are completed for individual ice deposits, which have limited count areas (Williams et al., 2018). CSFDs can vary across a putative uniform geologic unit when count areas become small (Warner et al., 2015); however, small count areas down to 4 km² have been shown to be consistent with model ages derived from larger (100 km²) count areas, although with lower accuracy (Pascart et al., 2015). The count areas analyzed here are between 79 and 109 km², and thus we consider errors due to limited count areas negligible.

Finally, chronology and production curves for Mercury are derived for impact craters in regolith (Le Fèvre and Wieczorek, 2011). Given that the AMAs estimated here are derived from impact craters assumed to be in ice, we estimate AMAs after scaling the superposed impact craters to estimate the sizes of these craters as if they were in regolith. Impact experiments suggest that craters in ice are found to have final diameters 2 to 3 times larger than craters in competent rocky materials (e.g., Croft et al., 1979; Koschny and Grün, 2001). Thus, we estimate ages of the ice surfaces from crater populations that are 1 (unscaled), 1/2, and 1/3 times the size of the measured crater diameters.

2.3. Stability of ejected high-reflectance material in Mercury’s PSRs

We use crater scaling laws (Eq. (2)) (Croft, 1981) to estimate the depth of material excavated by impacts into Enson, Laxness, and Bechet, the three craters that are identified as hosting small impact craters that are located within PSRs and are associated with high-reflectance ejecta rings (Fig. 2). The identified small craters used in our crater-counting analysis range in size from 100 to 300 m in diameter, and the average diameter for all superposed craters is 211 m. We estimate the depth from which material is excavated (d_{excavation}) from the measured final crater diameter (D_{final}):

\[ d_{excavation} = \frac{1}{10} (D_{final}) \]  (2)

We estimate that impactors resulting in craters with diameters between 100 m and 300 m would have excavated material from depths of 10 m and 30 m.

We also estimate the depth of material excavated by impacts after scaling the impacts in order to account for target properties. As discussed above, the crater scaling laws (Eq. (2)) are derived for impacts into silicate material. Here we scale the diameters of the identified craters by a factor of 1/3 in order to estimate the minimum final crater diameters for equivalent impacts into regolith. This endmember scaling scenario results in a range of crater diameters from 33 m to 100 m and an average scaled diameter of 70 m. From Eq. (2), we estimate that small impact craters between 100 m and 300 m in diameter (scaled to new diameters between 33 m and 100 m) superposing a pure ice deposit would have excavated between ~3 m and ~8 m below the ice surface, respectively, with an average excavation depth of ~6 m expected for all identified craters.

The thickness of water-ice deposits on Mercury is estimated to be several m (Harmon, 2007; Black et al., 2010; Talpe et al., 2012), although possibly extending deeper with maximum thicknesses estimated of tens of m (Eke et al., 2017; Deutsch et al., 2018; Susorney et al., 2019). Most recently, an analysis of the changes in topography across radar-bright and non-radar-bright deposits resulted in an upper limit thickness of 15 m for Mercury’s water-ice deposits (Susorney et al., 2019). Assuming a water-ice thickness of several (~5) m (Harmon, 2007; Black et al., 2010), then all small impactors resulting in craters >180 m (scaled regolith diameter of 60 m) may have excavated both ice as well as underlying regolith. If the sizes of the impact craters superposing Mercury’s polar deposits do not differ substantially in size from impact craters in Mercury’s regolith (given that the ice deposits may be only several m thick), then it is possible that all impactors resulting in the craters identified here have excavated both ice and regolith.

Exposed surface water ice and typical mercurian regolith are factors of 4 and 2 brighter, respectively, than the average reflectance of low-reflectance lag deposits that insulate the majority of ice deposits on Mercury, including all of the 35 ice deposits analyzed here (Neumann et al., 2013). Therefore, both water ice and excavated regolith would appear as anomalously bright ejecta superposing the ice deposits. Pure water ice may sublimate away on top of the low-reflectance lag deposit, but the rate of sublimation is relatively slow in comparison to the ages of the ice that we estimate (Sec. 4): 1 m of water ice sublimates in 1 Gyr at 110 K (Vasavada et al., 1999). Importantly, any ejected regolith would of course not sublimate away. While the morphologies of craters impacting into pure ice differ from the morphologies of craters that impact through ice into underlying regolith (e.g., Bramson et al., 2015), the spatial resolution of the images analyzed here is too low in order to observe the morphologies of any of the small craters (100–300 m in diameter). From the estimates of excavation depths above, all impact craters that superpose the ice deposits and have a preserved final diameter >180 m should be associated with high-reflectance materials, assuming an average ice deposit thickness of 5 m and that the preserved final diameters are 1/3 the size of craters from similar impacts into regolith.

3. Results: surface age estimates for Mercury’s ice deposits

Here, we suggest that brightness variations associated with small impact craters (100–300 m in diameter) that appear bright in multiple images of different viewing geometries are indicative of excavated material. Under this assumption, we estimate the surface ages of specific ice deposits on Mercury using impact craters that superpose individual ice deposits (Fig. 2). Although high-resolution images of 35 north polar ice deposits have been acquired, only three individual ice deposits, hosted by Enson, Laxness, and Bechet craters (Table 1, Supplementary Materials), show clear evidence for high-reflectance material associated with individual small craters (Fig. 2). The remaining ice deposits either show no small craters associated with high-reflectance ejecta rings using the aforementioned criteria (3 craters), or there are not multiple clear images for these craters that allow the PSRs to be resolved (29 craters).
Despréz, Fuller, and V2 craters host the three ice deposits in which no high-reflectance materials are identified in association with small craters (Fig. 3). These three north polar ice deposits were imaged multiple times (Table S1, Supplementary Materials) during MESSENGER’s low-altitude imaging campaign. In none of the images do we identify high-reflectance material in association with impact craters (Fig. 3). Given that (1) ice is not expected to sublimate away quickly within these PSRs and (2) impact craters are expected to have excavated both ice and regolith (Sec. 2), the lack of high-reflectance ejecta materials suggests that the craters observed in these PSRs formed before the ice was emplaced (e.g., Deutsch et al., 2018). Furthermore, the lack of high-reflectance ejecta materials suggests that these polar ice deposits are very young, and that no impacts that can be observed at the spatial scale of these images have occurred since ice deposition. It is also possible that the top ice layer has been recently restored, thus erasing any visible brightness variations on the surface, and this scenario would also favor a very young age of the surface ice. Finally, it is possible that unfavorable viewing conditions have impeded our ability to identify bright ejecta, however we note that the images of these three craters (Despréz, Fuller, and V2) were acquired under viewing conditions similar to those of the three craters in which bright materials are identified (Ensor, Laxness, and Bechet). Specifically, the images of Despréz, Fuller, and V2 that were analyzed were acquired at phase angles between 74.4° and 129.2°, incidence angles between 80.5° and 87.0°, and emission angles between 1.6° and 42.2°, in comparison to the images of Ensor, Laxness, and Bechet, which were acquired at phase angles between 77.2° and 118.3°, incidence angles between 82.8° and 84.7°, and emission angles between 0.3° and 34.0°.

Absolute model ages (AMAs) (Le Feuvre and Wieczorek, 2011) derived from superposed impact craters on Ensor, Laxness, and Bechet (Table 1) suggest that the surficial layers of the ice deposits are geologically young (Fig. 4a), and were delivered in the most recent Kuiperian period. The specific AMAs estimated for the surface ice in Ensor, Laxness, and Bechet are 210 ± 60 Ma, 29 ± 10 Ma, and 47 ± 20 Ma before scaling the impact craters. There is overlap in the estimated surface ages between ice hosted by Laxness and Bechet when doubing the reported error to consider a 2-σ deviation. When the impact craters are scaled by 1/2 to represent craters impacting into pure ice, the estimated ages of all three craters overlap within a 2-σ deviation of the mean. Finally, when the impact craters are scaled by 1/3, then the estimated ages of ice surfaces within Ensor and Bechet overlap within a 2-σ deviation of the mean, and the estimated ages of ice surfaces within Bechet and Laxness overlap as well. The reported errors for crater counting statistics are from counting statistics alone (Michael and Neukum, 2010), and as discussed in detail in Sec. 2.2, a variety of other statistics and observational biases may affect crater counting on Mercury’s ice deposits. Thus, the errors reported here are considered to be a minimum.

Poisson analyses are used to describe the relative likelihoods of possible ages of the surface ice deposits (Michael et al., 2016). These analyses suggest that surface ice deposits hosted by Ensor, Laxness, and Bechet craters are 137 ± 15 Myr, 100 ± 18 Myr, and 81 ± 19 Myr, respectively, and that any ice deposits that lack superposing impact craters are likely to be <10 ± 1 Myr (Fig. 4b). Considering a 2-σ deviation of the mean, the ice surfaces in Ensor, Laxness, and Bechet overlap in age.

Relatively young ages for the ice deposits are consistent with stratigraphic relationships of host craters and contained polar ice. Global mapping of craters ≥40 km in diameter reveals that craters from the Munsurian period (280 Ma–1.7 Ga) are located within both the north and south polar regions (Prockter et al., 2016) and these craters host radar-bright materials indicative of water ice, placing an upper bound on the delivery of surface water ice (Deutsch et al., 2016; Chabot et al., 2018). Large Kuiperian craters (280 Ma–today) have not been mapped in the north polar region, and the only two Kuiperian craters mapped in the south polar region have not been well-imaged by Earth-based radio observations (Harmon et al., 2011; Chabot et al., 2018).

In conclusion, ages derived from both crater-counting statistics and Poisson statistics suggest that the surfaces of the individual ice deposits analyzed here are very geologically young. Even the most conservative crater-counting estimates (in which craters are not scaled for impacting into ice, and given a 2-σ uncertainty) suggest that the surface ice was delivered within the last ~330 Myr.

4. Discussion

4.1. Implications of geologically young ice surfaces

Importantly, the age estimates presented here, derived both from crater-counting statistics as well as Poisson statistics, give constraints on the surface ages of the ice. If ice deposits accumulated from a single event, then the age of the surface is representative of the age of the whole deposit. Alternatively, if ice deposits have accumulated over time, then the surface age does not reflect the deposit age. It is not possible to determine which is the case from the current orbital data, however the high purity of the radar observations is suggestive of delivery in a single event.
of the Earth-based radar data indicated that the ice deposits must be extremely pure, with less than \( \sim 5\% \) silicates by volume (Butler et al., 1993). This high degree of purity is consistent with the ice being delivered in a relatively short period of time (Butler et al., 1993), and is difficult to explain by a more continuous process in which ice accumulates over time. As discussed earlier, regolith gardening models suggested that all of the ice deposits are \(< 50 \) Myr in age because 20 cm of regolith is predicted to cover the ice in this timeframe, which is not observed (Crider and Kallen, 2005). An independent analysis of surface modification models also concluded that all of the ice deposits are relatively young (18–70 Myr old) using constraints on the average thickness of the upper layer of ice deduced from MESSENGER's neutron data (Lawrence et al., 2013). In line with these previous studies, we favor the hypothesis that all of the several-m thick ice deposits imaged by MESSENGER are young and may have been emplaced during a single event. However, it is certainly possible that there is additional older ice hidden beneath the visible ice deposits, garnered deep in the subsurface, and we discuss this in detail in Sec. 4.2. If all of the ice was emplaced in a single event, then the ages derived for the surface ice presented here are representative of the entire ice deposits. Alternatively, if the ice has accumulated over time in more than one event, then the ages we derived for the surface ice represent an age of the most recent emplacement episode.

A single event that led to the emplacement of surface ice in each of the analyzed craters is not favored if the error statistics reported here for crater counting are precise and thus the ages of all of the individual ice deposits do not overlap. In such a case, the surfaces of these individual ice deposits must have been emplaced by recent and discrete delivery mechanisms, such as individual, young impacts. However, given the fact that reported errors for crater counting are from counting statistics alone, and also given the overlap in estimated AMAs between two or three of the craters in all cases, we also find it worthwhile to consider the possibility that the ice analyzed here was emplaced at the same time. In such a case, we may consider an average AMA for polar ice on the basis of these three specific host craters: the average AMA is 95 Ma \( \pm 33 \) Ma before scaling the impact craters and 4.2 Ma \( \pm 1.2 \) Ma after scaling the impact craters by 1/3, where the reported uncertainties are 1–\( \sigma \) standard errors derived from counting statistics alone (Table 1).

Overall, a relatively recent delivery or deliveries may explain why ice deposits on Mercury have sharp reflectance boundaries, coherent surfaces (Neumann et al., 2013; Chabot et al., 2014, 2016), and high radar backscatter (Butler et al., 1993; Harmon et al., 2011). If the ice deposits have accumulated over time via multiple events, the delivery rate must exceed the regolith overturn rate given the sharp reflectance boundaries observed for all ice deposits on Mercury (Neumann et al., 2013; Chabot et al., 2014, 2016). Relatively young surface ages of the ice are inconsistent with volcanic outgassing delivering volatile species to Mercury's poles given that the bulk of volcanic activity on Mercury ceased \( > 3.5 \) Ga (Byrne et al., 2016), and recent, localized pyroclastic eruptions (Jozwiak et al., 2018) are not expected to have produced 3.45 \( \times 10^{17} \) g of water, which is the mass of ice calculated for Mercury (Susorney et al., 2019).

4.2. Comparison to lunar polar ice

Mercury and the Moon show distinct differences in the abundance and purity of ice cold-trapped at their poles, despite both bodies having PSRs that are thermally stable environments for water ice on geologic timescales (Vasavada et al., 1999) due to the small axial tilt of each body. While both Earth-based (Harmon et al., 2011) and orbital (Lawrence et al., 2013; Neumann et al., 2013; Paige et al., 2013; Chabot et al., 2014; Deutsch et al., 2016, 2017) observations indicate that there are extensive water-ice deposits within Mercury's PSRs (Fig. 1), data suggest that water-ice deposits on the Moon (Lawrence et al., 2006; Colaprete et al., 2010; Campbell et al., 2006; Spudis et al., 2010; Thomson et al., 2012; Haruyama et al., 2008; Zubere et al., 2012; Hayne et al., 2015; Fisher et al., 2017; Li et al., 2018) are smaller in extent and less concentrated than those on Mercury.

For example, neutron spectrometer data of the lunar polar regions are suggestive of concentrations of only \( \sim 1.5\% \) water ice by mass in the upper \( \sim 1 \) m of the lunar regolith (Lawrence et al., 2006). Furthermore, Lunar CRater Observation and Sensing Satellite detected only \( \sim 6 \) wt.% water ice in the ejecta plume resulting from an impact into Cabeus crater (Colaprete et al., 2010). Earth-based radar observations do not show evidence for concentrated water ice on the Moon (e.g., Campbell et al., 2006) and spacecraft radar observations are suggestive of only patches of ice (e.g., Thomson et al., 2012). Finally, imaging (Haruyama et al., 2008) and reflectance (Zubere et al., 2012; Hayne et al., 2015; Fisher et al., 2017; Li et al., 2018) campaigns of the lunar poles have not revealed thick, coherent ice deposits, but instead are suggestive of a spatially heterogeneous, or patchy, distribution of water frost. Thus, ice on Mercury appears to be purer and more extensive than any ice on the Moon. The cause for the differences between ice on Mercury and the Moon is not understood. One possibility is that differences in delivery time may explain the stark differences between surface ice on these two airless bodies.

Impact gardening can produce spatial heterogeneities in ice distribution due to the loss and redistribution of volatiles through time (e.g., Hurley et al., 2012). Impacts introduce heterogeneity into the system because they remove volatiles via vaporization, and also preserve volatiles through the emplacement of ejecta, with a net effect of breaking up and burying the ice through time (e.g., Hurley et al., 2012). Because these processes take time, heterogeneity is inherently related to the age of the ice.

Hurley et al. (2012) present Monte Carlo simulations of the evolution of ice in PSRs on the Moon. They find that, statistically, individual locations on the Moon experience more burial events than excavation events and they estimate an average burial rate of 1 mm/Myr. Using this average burial rate, we extrapolate backwards in time from the present day (0 Myr) into the past (4500 Myr), starting with a present-day ice thickness of 1 mm. If an initial ice layer on the Moon was ever similar in thickness to the ice deposits observed at the poles of Mercury (and thus at least several meters thick (Harmon, 2007; Black et al., 2010)), then the ice observed at the surface of the Moon today must have been delivered very early on in lunar history. For example, in order for regolith gardening processes to rework a 4 m-thick layer of ice into a present-day 1-mm thickness on the surface, then the 4 m of ice should have been accumulated by \( \sim 4 \) Ga. Interestingly, the average burial rate of 1 mm/Myr (Hurley et al., 2012) cannot account for an initial thickness of ice in the lunar PSRs that exceeds, on average, 4.5 m, which may be thinner than what is observed on Mercury today; lower estimates for the thickness of Mercury's polar ice deposits are at least several meters (Harmon, 2007; Black et al., 2010; Talpe et al., 2012; Susorney et al., 2019), while maximum estimates approach \( \sim 50 \) m (Eke et al., 2017; Deutsch et al., 2018). Thus, the regolith gardening simulations presented by Hurley et al. (2012) suggest that the ice on the Moon is relatively ancient, that less ice has been delivered to the Moon than has been delivered to Mercury through time, or that additional loss processes are very efficient on the Moon.

5. Conclusion

Unlike surface water ice on the Moon, surface water ice on Mercury appears as coherent deposits whose distinct reflectance
boundaries align directly with regions of permanent shadow (Chabot et al., 2014, 2016, 2018; Deutsch et al., 2016). If ice deposits on Mercury are relatively young, then they have not been exposed to extensive space weathering processes that would break up, destroy, or bury the ice. A relatively young age, as estimated here from both superposed impact craters on the ice surfaces and Poisson analyses, is consistent with (1) regolith gardening models that suggest the ice deposits were emplaced <50 Ma (Crider and Killen, 2005), (2) analyses of high-resolution images of the polar deposits that uniformly reveal sharp reflectance boundaries and spatial coherence within PSRs (Chabot et al., 2014; 2016), and (3) the presence of ice in micro-cold traps (Rubanenko et al., 2018). If the ages and error statistics presented here are precise and not all individual ice surfaces overlap in age, then the surface ice must have been delivered by a multitude of young, discrete emplacement events. However, if the errors do overlap, it is possible that the surface ice was delivered by a single, young impact (e.g., Chabot et al., 2016; Rubanenko et al., 2018; Ernst et al., 2018). Recently, an analysis of Mercury’s Hokusai (a 97-km Kuiperian crater) estimated that the Hokusai impact event could account for the entire ice inventory on the planet, strengthening the viability of a single-impact delivery scenario (Ernst et al., 2018).

To date, it is not clear why polar ice on the Moon is relatively less pure and extensive than polar ice on Mercury, which has a water-ice cold-trapping efficiency of only 50% of the Moon (Schönhofen et al., 2016). It is possible that these differences may be related to the age of the ice. Surface ice on the Moon is characterized by a substantial degree of spatial heterogeneity within and between PSRs (Hayne et al., 2015). If the ice observed at the lunar poles today was delivered early on during the Moon’s history, it has undergone substantial impact bombardment, leading to a spatially heterogeneous surface distribution (e.g., Hurley et al., 2012). The ice deposits that show the greatest spatial heterogeneity on the surface may have substantial vertical heterogeneity as well, with additional ice buried in the subsurface (e.g., Hurley et al., 2012).

The same impact bombardment and space weathering processes operate on Mercury and the Moon, and Mercury’s regolith may be overturned even more frequently than the lunar regolith (e.g., Domingue et al., 2014) due to higher impact rates and speeds (e.g., Borin et al., 2009). Thus, it is possible that relatively ancient, degraded ice deposits exist below the extensive, pure deposits observed on Mercury’s surface today. The lunar polar deposits therefore provide an interesting opportunity to inform us about the ultimate fate of mercúrian polar deposits, as well as ices on other airless bodies.

This work has provided new surface age estimates of Mercury’s polar ice deposits, which provide critical insight into the possible delivery mechanism(s) for the ice. We find that individual ice surfaces on Mercury are all <330 Ma, and possibly as young as only a few Ma. These young ages are suggestive of recent comet impacts, or a single impact if larger errors on the estimated ages are considered. As BepiColombo prepares to enter its orbit around Mercury, this work will serve as an important test as the first high-resolution images of the south polar PSRs are acquired.

Author contributions

A.N.D. developed the methods, performed the computations, and authored the manuscript with support from J.W.H. and C.A.N. J.W.H. and C.A.N. verified the analytical methods and contributed to the interpretation of the results.

Declaration of Competing Interest

The authors declare no competing financial interests.

Data availability

Imaging data analyzed in this paper are available at the NASA Planetary Data Systems archives (http://pds-geosciences.wustl.edu/missions/messenger/). The individual images analyzed here are included as supplementary files.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2019.05.027.

References


