MESSENGER Into Darkness

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One of the oddest juxtapositions in the solar system can be found near the poles of Mercury. On a planet with daytime temperatures regularly exceeding the boiling point of water, there is ice at the bottom of polar impact craters. This unusual pairing is made possible because of Mercury's rigidly upright posture in its orbit around the Sun. With an axial tilt of nearly zero, large regions of permanent shadow are found in depressions near the poles. Without direct sunlight to warm their surfaces, the crater floors remain at temperatures low enough to retain water ice—Mercury's own built-in freezer.

The first evidence for ice deposits came more than two decades ago, from observations by ground-based radar observatories (Slade et al., 1992; Harmon and Slade, 1992; Butler et al., 1993). Water ice has unusually high radar reflectivity, and the poles stood out brightly against the surrounding rocky surface in radar images of Mercury. The image resolution improved over time, and many of the radar-bright features were observed to lie within impact craters imaged by Mariner 10 (Harmon et al., 2011). However, many more features could not be mapped in this way, because Mariner 10 imaged only half of the planet during its three encounters with Mercury in 1974 and 1975. In March 2011, NASA's MESSENGER spacecraft became the first to orbit Mercury, providing the first full view of Mercury's poles. The Mercury Dual Imaging System (MDIS) on this spacecraft collected countless images of Mercury's north and south poles. These images allowed for the identification of regions of persistent shadow, which correlate remarkably well with the radar-bright deposits (Chabot et al., 2012, 2013). Indeed, within 10° of Mercury's north pole, nearly every crater with a diameter larger than 10 km hosts a radar-bright deposit.

Still, there remained some doubt that the material shining so brightly within Mercury's shadowed craters was in fact water ice, and not some more exotic volatile such as sulfur (Sprague et al., 1995). Additional instruments on MESSENGER confirmed their icy nature. Measurements by the Neutron Spectrometer showed a decrease in the flux of epithermal and fast neutrons near the north pole, consistent with the presence of water ice (Lawrence et al., 2013). The radar-bright deposits also have an infrared reflectance consistent with water ice (Neumann et al., 2013) in areas where water ice is predicted based on thermal models to be stable at the surface (Paige et al., 2013). In other regions, where water ice is predicted to be stable only in the near subsurface, the infrared reflectance is lower. It's likely that this dark material is a sublimation lag deposit, possibly composed of an organic-rich material.

The total volume of water on Mercury is estimated to rival that of Lake Ontario (North America; Lawrence et al., 2013), a relatively substantial volume for an otherwise "dry" world, begging the question of where it all came from. Water could have been brought to Mercury through one or more mechanisms: delivered by comets and asteroids, formed through reactions between Mercury's regolith and the solar wind, or outgassed from Mercury's interior over long time scales. Water can migrate through ballistic trajectories, with eventual capture in the permanently shadowed regions near the poles (Arnold, 1979). However, other mechanisms can disrupt the formation of ice deposits over relatively short time scales. Crider and Killen (2005) modeled the burial of ice on Mercury through 'impact gardening' (the process by which impacts disrupt the surface of a planet or moon, turning rock into regolith), and found burial rates of ~0.4 cm/m.y. Erosion through photo-dissociation can also limit the lifetime of exposed ice (Morgan and Shemansky, 1991), and bombardment by galactic cosmic rays may darken the ice on time scales of tens of millions of years (Crites et al., 2013). The morphology of Mercury's polar ice deposits could tell us their relative age, and the importance of different water delivery and loss processes.

Despite the success of the MESSENGER mission, it remained unclear whether we would ever see these extraterrestrial "skating rinks" up close. They are cloaked in permanent shadow, safe from the view of any curious onlooker. Or are they? Although the permanently shadowed regions receive no direct sunlight, low levels of light arrive at the crater floors by scattering off the illuminated walls, and MESSENGER's MDIS instrument is sensitive enough to see inside these shadows. A paper in this issue of *Geology*, by Chabot et al. (2014, p. 1051), presents the first high-resolution views of the surface of Mercury's polar ice deposits, providing important constraints on the origin and emplacement of the deposits.

As reported by Chabot et al., Mercury's polar deposits are morphologically similar to nearby sunlit surfaces, covered with many small craters. Where they stand out is in their reflectance properties. Like the infrared observations obtained by the Mercury Laser Altimeter (MLA), the permanently shadowed region in Prokofiev crater (at 86°N) has a uniformly higher reflectance, whereas craters south of ~86°N have lower-reflectance surfaces. Several lines of evidence suggest that both high- and low-reflectance deposits are geologically young. First, the uniform reflectance of the surface, without obvious ejecta from the superimposed craters, indicates that the material was emplaced after the craters were formed. Second, the dark regions have extremely sharp boundaries, indicating there has been very little lateral mixing by impacts. Thus, Chabot et al. (2014) conclude that the deposits are either being actively restored at the surface through an ongoing process, or were delivered to the surface of Mercury very recently.

This conclusion is consistent with the observed distribution of Mercury's polar deposits. As noted earlier by Chabot et al. (2013), there are craters at low latitudes (as far south as 66°N) correlated with radar-bright deposits. Thermal models of Mercury's polar craters suggest that the temperatures within such regions are too high to maintain water ice over geologic time scales, even if the ice is insulated by a thin layer of regolith (Vasavada et al., 1999). The presence of ice within such craters suggests that it was emplaced relatively recently.

These observations provide an interesting contrast to observations of the poles of the Moon. Like Mercury, the Moon has a small obliquity, so that large regions of permanent shadow persist in craters near the poles. Some of these craters exhibit enhanced radar reflectivities (Spudis et al., 2010), but not to the same extent as observed on Mercury, and many more craters show no enhancement (Campbell et al., 2006; Neish et al., 2011; Thomson et al., 2012). However, permanently shadowed regions on the Moon, like those on Mercury, often have higher infrared reflectance than nearby illuminated regions (Lucey et al., 2014), and show a decrease in neutrons indicative of the presence of water ice (Feldman et al., 1998). Indeed, the presence of ice was confirmed by the NASA LCROSS (Lunar Crater Observation and Sensing Satellite) spacecraft, which observed absorptions characteristic of water vapor and ice particles in the ejecta plume produced by the impact of a rocket stage into a permanently shadowed region of Cabeus crater (Colaprete et al., 2010). Still, observations suggest that the ice present near the lunar poles is not as widespread or as pure as that on Mercury. Counterintuitively, this might be related to the lower temperatures inside the permanently shadowed regions on the

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Moon (Paige et al., 2010). The lower temperatures may inhibit the migration of ice through regolith, making the ice more vulnerable to changes in orbital obliquity (Seigler et al., 2011, 2013). Alternatively, it is possible that Mercury just got "lucky," and happened to have a cometary impact replenish its polar reserves in the recent past. Additional missions to study the polar environments of both Mercury and the Moon are needed to fully understand their different histories.

MESSENGER will shortly run out of fuel, and is scheduled to crash into Mercury in March 2015. However, the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) already have plans to send probes to the innermost planet. The joint BepiColombo mission is presently scheduled to launch in July 2016 (Benkhoff and Futjimoto, 2014). It will bring with it the Mercury Planetary Orbiter, equipped with 11 instruments, and the Mercury Magnetospheric Orbiter, equipped with five instruments. One of these instruments—MERTIS, a thermal imager—will be able to measure temperatures in the permanently shadowed regions, providing observational tests of the thermal models of Mercury's poles (i.e., Paige et al., 2013). There are plans for further exploration of the lunar poles as well. NASA and the Canadian Space Agency (CSA) are developing a landed mission to characterize the distribution of water ice in lunar polar surface materials, for use in the future manned exploration of the Moon (Colaprete et al., 2013). In addition, the Lunar Flashlight mission was recently selected by NASA's Advanced Exploration Systems to fly as a secondary payload on the first test flight of the Space Launch System. This first CubeSat mission to the Moon would use its large solar sail as a mirror to direct sunlight into permanently shadowed cold traps and look for spectral lines indicative of water ice (Hayne et al., 2013). These future missions will continue to shed light on the nature of Mercury's polar ice, illuminating the origins of these unusual deposits.

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