Mercury's Polar Radar Anomalies: Ice and/or Cold Rock?

S. J. Weidenschilling, Planetary Science Institute

Radar observations of Mercury revealed regions near its poles with anomalous radar properties: high reflectivity relative to the rest of the planet's surface, and high polarization ratios (1,2). These properties are similar to those of the martian residual south polar cap and the icy Galilean satellites, and were immediately interpreted as indicating the presence of ice.

The diagnosis of ice as the cause of the radar anomalies invokes the phenomenon of coherent backscatter; if a weakly absorbing medium contains inhomogeneities (voids or inclusions) with separations greater than the wavelength, multiple scattering can enhance the intensity of the backscattered radiation (3). For an incident wave with a single sense of circular polarization, as used in radar astronomy, the returned radiation contains components with both senses; coherent backscatter can yield a higher ratio of "same sense" to "opposite sense" polarization in the returned signal than results from simple reflection from irregular surfaces. While other mechanisms, such as multiple reflections from an extremely rough surface, can in principle produce high circular polarization ratio (CPR), values greater than unity are rarely seen even for the roughest terrestrial lava flows (4). Most rocky bodies in the solar system show CPRs about 0.1, while the martian south polar cap and Galilean satellites have values of about 1.2 to 2.0. Thus, CPRs >1 are generally taken as diagnostic of ice. However, coherent backscatter depends on structure (inhomogeneities of the proper scale); composition is important only in that ice is very transparent to microwaves. For reasons that are not known, the martian north polar cap does not show a distinctive radar signature (5). Mercury's polar regions show areas with CPRs in the range 1.0-1.7; their radar albedos are also significantly higher than the rest of the planet (6).

The conclusion that ice accounts for Mercury's polar anomalies was strengthened by thermal modeling that demonstrated that in permanently shadowed regions near Mercury's poles, temperatures would be low enough for water ice to be stable for billions of years (7). Higher-resolution radar mapping showed that most of the anomalies coincide with near-polar craters seen in Mariner 10 images, with their bottoms in shadow (6). The source of the water is presumed to be exogenic, as most cosmogonical models imply a high-temperature origin and refractory composition for the planet. Water could be supplied as hydrated minerals in meteorites, and ice within active and inactive comet nuclei, with ballistic migration of water molecules to polar cold traps. Estimates of the impact flux, water content of impactors, and retention of projectile material all are uncertain, but plausibly allow buildup of ice deposits with thickness of meters at the poles over the age of the solar system (8, 9).

Although the case for ice is strong, a few paradoxes remain: Interpretation of the radar reflectivity and polarization characteristics seems to indicate that the ice layer must be at least a few meters thick, buried no more than about a meter below the surface. It must also be clean, mixed with no more than about 5% of silicates by volume (8). Such a deposit could not plausibly be the product of billions of years of gradual deposition in a regolith subject to impact gardening; Butler *et al.* (8) suggested that it was produced by the impact of a single very large comet. An ice layer deposited in this manner is subject to later impact gardening by smaller projectiles. The rate of gardening on Mercury is unknown, but is unlikely to be much less than on the Moon; the greater distance from the asteroid belt is compensated by higher impact velocities and gravitational focusing in the Sun's gravity well. The lunar maria have been thoroughly gardened to a depth of several meters in some 4 Gy; thus, the hypothesized large impact must have occurred relatively recently.

Recent results from radar observations of the Moon may suggest an alternative explanation. Stacy *et al.* (10) observed the lunar polar regions using the Arecibo radar in search of ice. They found a number of small features with CPRs ranging from 1.2 to 2.6, and moderately high radar albedos. The CPR values are comparable to those of Mercury's polar anomalies, although the latter have somewhat higher radar albedos (6) and much larger sizes. Most of the lunar anomalies could be identified with locations of small (<1 km) craters. More than a third of these were in sunlit areas, in which ice would have a short lifetime. Stacy *et al.* concluded that the anomalous radar properties of these areas were due to unusually high surface roughness on the scale of the wavelength (12.6 cm), although the precise mechanism for producing the observed CPRs is not clear. Apparently, some (possibly pathological) structure associated with fresh impacts can mimic the radar appearance of ice.

If this interpretation of the lunar radar anomalies is correct, then Mercury's could have a similar origin. However, any attempt to explain them as textural rather than compositional must address the question of why the unusual surface structure is more extensive than the very limited features seen on the Moon, yet confined to the permanently shadowed polar regions. These areas have a unique thermal environment, and contain the coldest surfaces of igneous silicates in the solar system that are exposed to meteoroid bombardment. Temperatures in permanent shadow may be as low as 30 K (5, 7), well below values in the outer asteroid belt. Due to Mercury's slow rotation, nightside surface temperatures on the rest of the planet fall as low as 90 K, but the insulating regolith keeps subsurface temperatures near the diurnal average at depths of order of one meter (11). Thus, on most of the surface any crater larger than a few meters diameter excavates "warm" rock. In contrast, permanently shadowed regions have been in "cold soak" on a timescale of Gy, and cryogenic temperatures extend below the base of the regolith. It is plausible that mature regoliths developed under such different thermal conditions would differ significantly in such properties as mean size and shape of fragments, abundances of agglutinates and impact melts, etc.; such properties may result in detectable differences in radar reflectivity and CPR. If not the entire cause of Mercury's polar anomalies, it may be a contributing factor, decreasing the amount of ice required to explain them, or allowing a more plausible "dirty" ice layer. It will not be possible to quantify this suggestion until more experimental data are attained for hypervelocity impacts on silicate targets at extreme temperatures.

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