The Possibility of Ice on the Moon

N. J. S. Stacy et al. (1) have dealt a blow to the hypothesis that ice deposits may exist in permanently shadowed regions at the lunar poles. Their ground-based radar observations detected several areas with high backscatter cross sections and circular polarization ratios consistent with ice, but in locations that are at least occasionally illuminated by sunlight. These features are associated with walls and rims of small craters; the most likely explanation for their occurrence is high surface roughness at the scale of the radar wavelength. Mercury has regions with similarly anomalous radar properties located near its poles, in permanently shadowed floors of large craters (2). These anomalies have been interpreted as resulting from ices accumulated by cometary and meteoritic bombardment (3). The results of Stacy et al. imply an alternative explanation: They may be a result of a difference in texture rather than composition. Such a difference could be caused by their thermal environment.

The sunlit and permanently shadowed regions of Mercury are, respectively, the hottest and coldest surfaces in the solar system that have silicate composition and are subject to meteoroid bombardment. Their responses to impacts should differ accordingly. Hot target material will yield a higher proportion of impact melt, while cold material should have a greater tendency toward brittle fracture, producing fragments that are more angular. Thus, one may expect mature regoliths developed at such different temperatures to have different radar scattering properties, with the colder surface having higher roughness and radar albedo. It is not clear whether this effect would suffice to account for the magnitude of the radar anomalies observed on Mercury, but this hypothesis could be experimentally tested by hypervelocity impacts into silicate targets at extreme temperatures.

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We would like to clarify our understanding of events associated with the 1992 Arecibo observations of the lunar south pole (1) and the Clementine bistatic radar experiment (2). The Clementine team was fully aware of the Arecibo observations before conducting the bistatic radar experiment. Although interpretation of the Arecibo observations was inconclusive, it had been suggested that areas showing high circular polarization ratios (CPRs), observed below the sun line inside the crater containing the south pole, could be underlain by ice (3). Surface roughness was an alternative explanation for the observed high CPR. The Clementine bistatic radar experiment was designed to resolve this ambiguity. Observations over a range of bistatic (phase) angle, , can distinguish diffuse scattering caused by wavelength-scale roughness from the highly directional coherent backscatter opposition effect (CBOE), indicative of low-loss targets (for example, ice). This measurement cannot be made from ground-based telescopes. The rationale for bistatic observations is well documented (4).

Clementine observed a CPR peak around near the south pole, consistent with the presence of ice at the surface. This peak was not observed anywhere else on the lunar surface and was isolated to an area within 60 km of the south pole. The radar footprint was fairly broad, and included areas outside of permanent shadow; thus, only a tiny fraction of this area could be underlain by ice. The method used (2) to estimate the area of putative ice deposits is similar to that applied to the polar deposits on Mercury (5). An upper limit on the area of ice deposits of 80 to 135 km² was estimated, assuming contributions to the scattered signal from the total observed area of 43,000 km². If the estimate is made strictly from the surface area that can contribute to the observed CPR peak (that is, the area over which the range of ), the area of possible ice deposits is reduced to 7 to 10 km². Given uncertainties in the properties of the putative ice deposits, this estimate can be reconciled with areas showing high CPR in the Arecibo images. We should have been clearer in our presentation in order to avoid misleading interpretation. The high spatial resolution of the Arecibo images show that any possible ice is small and patchy, as we suggested (2). Stacy et al. suggest that Clementine and Arecibo measurements are in disagreement (1), but meaningful comparisons can be made only for regions observed at similar incidence and , normalized to the same area.

A result reported by us (2) for a specific area (80° to 82° south latitude), angle of incidence 84°, 0.36 ± 0.01, is in agreement (3 σ) with the Arecibo near south pole (CPR 0.43 ± ?) values, given that no error was stated (1). This correct Clementine near south pole CPR value was not used by Stacy et al. (1).
The Arecibo and Clementine north pole values reported (1, 2) show disagreement. Because Arecibo cannot measure CPR as a function of $\beta$, direct comparisons between the data sets must be done carefully. The Clementine north and south pole values internally agree (3 $\sigma$), as do the reported Arecibo measurements, although no error is reported (1) except for $\beta = 18^\circ$ at the south pole. The Clementine values used (1) were not compared in a consistent manner. The actual Clementine $\beta = 0$ areas are an order of magnitude smaller than the reported (1) Arecibo areas, and in two cases the Clementine median CPR (over $82^\circ$ to $90^\circ$ angle of incidence) was compared instead of the appropriate values of $\beta$, incidence angle, and area (1). The Arecibo and Clementine data are fundamentally different measurements with different error sources, one made with a spacecraft transmitter near the moon with rapidly changing geometry (incidence angle, $\beta$, illuminated surface area) and one ground-based over a range of incidence angles at $\beta = 0$. Given these inconsistencies and differences in data analysis, the conclusion that the Clementine and Arecibo data sets do not agree is probably incorrect.

Surface roughness was postulated to be responsible for areas of local high CPR observed from Arecibo, because these areas are associated with impact craters (1). But the interiors of impact craters near the poles are also the areas most likely to be permanently shadowed. Ice, if present, must be associated with impact craters. A majority of the high CPR patches observed from Arecibo within 60 km of the lunar south pole are likely to be in permanent shadow. One of the areas with highest CPR found from Arecibo is in the deepest part of a small pole crater observable from Earth. From the combination of Clementine and Arecibo observations, it can be shown that this part of the crater is in permanent shadow. Ice can occur wherever it is thermodynamically stable, on a crater wall or on the floor. We suggest that the lower part of the south pole crater wall is a principal source of the CPR peak observed by Clementine. There is no a priori geological reason for the south pole crater to be any rougher than its neighbors. Roughness will produce diffuse scattering and a general CPR enhancement over a range of $\beta$ at many surface locations. Clementine observed a CPR and SS peak centered at $\beta = 0$ localized to the south pole. A comparison of the Clementine data with physically based computations of coherent backscattering suggests that the peak measured by Clementine is consistent with CBOE produced by grazing incidence scattering in an area where the scatterers only cover a fraction of the surface (6). Perhaps the strongest evidence in this regard is the lack of a CPR peak in the

Clementine bistatic measurements of regions not in permanent shadow. These terrains contain geological units comparable to the south polar region, being rugged highlands, including several 20-km diameter craters. Only the south polar pass (orbit 234) shows the CPR enhancement at $\beta = 0$. This strongly suggests a controlling factor related to shadowing. Surface roughness does not so qualify.

On Mercury, radar bright features are observed well off the pole, but they are not assumed to be produced by the same scattering mechanism as the polar deposits (5). This situation illustrates the difficulty in correctly interpreting combined space- and ground-based data sets. Ground-based radar observations of Venus revealed radar bright regions (for example, Maxwell Montes) that were initially attributed to roughness (7, 8). Low-resolution space-based observations by Pioneer Venus suggested that some of these areas were bright as a result of intrinsic chemical differences, not roughness (9); finally, high-resolution bistatic observations by Magellan showed this to be the case (10). The main weakness in the Clementine result is that the CPR peak was only observed on one orbit, albeit the only orbit with correct geometry for detecting CBOE at the south pole. The existence of ice will await confirmation by another independent spacecraft (Lunar Prospector). If confirmed, we believe that it will have been discovered by Clementine.

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