Icarus 241 (2014) 66–78

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

# Lunar polar craters – Icy, rough or just sloping?

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A R T I C L E   I N F O

*Article history:*
Received 6 January 2014
Revised 16 June 2014
Accepted 16 June 2014
Available online 30 June 2014

*Keywords:*
Moon, surface
Radar observations
Ices

A B S T R A C T

Circular Polarisation Ratio (CPR) mosaics from Mini-SAR on Chandrayaan-1 and Mini-RF on LRO are used to study craters near to the lunar north pole. The look direction of the detectors strongly affects the appearance of the crater CPR maps. Rectifying the mosaics to account for parallax also significantly changes the CPR maps of the crater interiors. It is shown that the CPRs of crater interiors in unrectified maps are biased to larger values than crater exteriors, because of a combination of the effects of parallax and incidence angle. Using the LOLA Digital Elevation Map (DEM), the variation of CPR with angle of incidence has been studied. For fresh craters, CPR ~0.7 with only a weak dependence on angle of incidence or position interior or just exterior to the crater, consistent with dihedral scattering from blocky surface roughness. For anomalous craters, the CPR interior to the crater increases with both incidence angle and distance from the crater centre. Central crater CPRs are similar to those in the crater exteriors. CPR does not appear to correlate with temperature within craters. Furthermore, the anomalous polar craters have diameter-to-depth ratios that are lower than those of typical polar craters. These results strongly suggest that the high CPR values in anomalous polar craters are not providing evidence of significant volumes of water ice. Rather, anomalous craters are of intermediate age, and maintain sufficiently steep sides that sufficient regolith does not cover all rough surfaces.



## 1. Introduction

Knowing the quantity of water ice that is squirreled away in permanently shaded lunar polar cold traps will constrain models of volatile molecule delivery and retention. It is also of interest as a potential resource for future explorers. The seminal work of Watson et al. (1961) introduced the possibility of water ice accumulations in regions so cold, beneath ~110 K, that ice would be stable against sublimation for billions of years. Using the Lunar Prospector Neutron Spectrometer (LPNS), Feldman et al. (1998) showed that there were concentrations of hydrogen at polar latitudes to the 70 cm depths probed by the neutrons. Eke et al. (2009) showed, with a pixon image reconstruction algorithm that sharpened the LPNS hydrogen map, that the excess polar hydrogen was preferentially concentrated into the permanently shaded regions. However, while suggestive, the level of ~1 wt% Water Equivalent Hydrogen (WEH), inferred from the models of Lawrence et al. (2006), was still not sufficiently high to prove that the hydrogen needed to be present as water ice. Only with the LCROSS impactor (Colaprete et al., 2010) did it become clear that water ice did indeed exist, in a small region within Cabeus, at a level of a few per cent by mass within the top metre or two of regolith. The hydrogen maps produced from the LPNS by Teodoro et al. (2010) implied that there may well be significant heterogeneity between permanently shaded polar craters, so the LCROSS result should not be assumed to apply to all of these cold traps.

Infra-red spectroscopy of the sunlit lunar surface has shown not only absorption by surficial water and hydroxyl (Pieters et al., 2009; Clark, 2009), but also that these molecules are mobile across the surface depending upon the time of lunar day (Sunshine et al., 2009). This supports the idea of a lunar "water cycle" of the sort envisaged by Butler (1997) and Crider and Vondrak (2000), but major uncertainties remain in our understanding of the efficiency with which cold traps protect the volatiles that they receive (Crider and Vondrak, 2003).

The Lyman Alpha Mapping Project (LAMP) instrument on LRO has shown, using radiation resulting from distant stars or scattering of the Sun's Ly $\alpha$ from interplanetary hydrogen atoms, that permanently shaded polar craters typically have a low far-UV albedo (Gladstone et al., 2012). These results are consistent with 1–2% water frost in the upper micron of the regolith of the permanently shaded regions, with the observed heterogeneity between different

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http://dx.doi.org/10.1016/j.icarus.2014.06.021
0019-1035/

craters perhaps implying a sensitivity to local temperatures. nowing how heterogeneous the water ice abundance is would provide insight into which physical processes are most relevant for determining volatile retention.

Another widely-used remote sensing technique with the potential to provide information about both the composition and structure of near-surface material is radar (Campbell, 2002). This often involves sensing the polarisation state of the reflected radiation when circularly polarised radio waves are transmitted towards a surface. The dielectric properties of the materials present, surface roughness, including rocks and boulders, composition and size of any buried materials within the regolith and the depth of regolith above bedrock could all affect the returned signal. For 13 cm radiation, the dielectric properties of regolith are such that the upper few metres of the surface can be probed by radar measurements. Given the complex nature of the scattering problem, it can be difficult to know what to infer from radar data without additional insights into the likely surface composition or structure. The most frequently used way of characterising the returned signal is to take the ratio of powers in the same sense (as transmitted) to the opposite sense of circular polarisation, namely the circular polarisation ratio, or CPR. A CPR of zero would be expected for specular reflection from a medium with higher refractive index, whereas higher CPR values can result from multiple scattering, which may imply the presence of a low-loss medium such as water ice making up the regolith.

Radar observations of Europa, Ganymede and Callisto showed surprisingly high CPR values of $\sim$1.5 (Campbell et al., 1978; Ostro et al., 1992). The low densities of these satellites were indicative of them having icy compositions. The temptation to associate high CPR values with ice increased when observations of the polar regions of Mercury showed that high CPR regions were associated with permanently shaded craters, within which temperatures could be low enough for water ice to be stable against sublimation (Harmon et al., 1994). Recent results from MESSENGER's neutron spectrometer (Lawrence et al., 2013) support this conclusion.

It is less clear what should be inferred from radar observations of the Moon about the presence of water ice in permanently shaded craters. The Clementine mission transmitted circularly polarised radio waves into the lunar polar regions, with the reflected flux measured on Earth. An increase in same-sense polarised power at zero phase angle was interpreted by Nozette et al. (1996) as possible evidence for constructive interference from waves taking reversed routes involving multiple scattering within an icy regolith. This coherent backscatter opposition effect (CBOE Hapke, 1990) is one physical process that would produce high CPR values. However, Stacy et al. (1997), Simpson and Tyler (1999) and Campbell et al. (2006) showed that high CPR could also result from surfaces that were rough on scales within an order of magnitude in size of the 13 cm radar wavelength, which would help to explain why at least some of the high CPR regions occurred in clearly sunlit locations where water ice would not exist in significant amounts.

In parallel with the acquisition of remote sensing radar data, various models have been constructed to help to interpret the CPR measurements. Descriptions of the scattering mechanisms relevant to the problem are given by Campbell (2002, 2012). An empirical two-component model was developed by Thompson et al. (2011) with a view to decoding CPR data from the Mini-SAR and Mini-RF instruments on Chandrayaan-1 and LRO respectively. The most physically motivated modelling to date was carried out by Fa et al. (2011) who used vector radiative transfer theory to follow the polarisation state of the input electromagnetic radiation. While their model did not include multiple scattering, so had no CBOE, it did predict the impact of incidence angle, regolith thickness, buried rocks and surface roughness on the returned signal. They found that the similarity in dielectric permittivity between ice and a silicate regolith would make it difficult to identify ice mixed into such a regolith.

The wealth of recent information returned from lunar missions provides the possibility of discriminating between the different reasons for high CPR regions on the lunar surface. Spudis et al. (2010) used the north pole CPR mosaic from the Mini-SAR instrument on Chandrayaan-1 to show how fresh craters showed high CPR both inside and out, whereas a set of 'anomalous' polar craters had high interior CPRs without any corresponding enhancement just outside their rims. If meteorite bombardment removed roughness at a similar rate inside and outside these craters then this is suggestive that something other than roughness was responsible for the anomalously high CPRs inside these craters. That something could be water ice. Using Mini-RF data from LRO, Spudis et al. (2013) argued that the abundance of anomalous craters was much greater near to the lunar poles than at lower latitudes, with the implication that temperature might be an important variable in determining the CPR in these craters.

More recently, Fa and Cai (2013) studied examples of both polar and non-polar fresh and anomalous craters using data from the Mini-RF Synthetic Aperture Radar instrument on board LRO, finding polar and non-polar anomalous craters to have indistinguishable distributions of pixel CPR. Given that water ice is not the reason for the non-polar crater interiors having anomalously high pixel CPR values, why should it be necessary for the high pixel CPR values in anomalous polar craters? Furthermore, Fa and Cai (2013) used LROC images to see boulders within, and not outside, the non-polar anomalous crater. Despite the mismatch in scales between the >1–2 m-sized rocks and the 13 cm radar wavelength, the model of Fa and Cai (2013) shows that dihedral scattering from such rocks can still significantly increase the CPR. This provides a potential reason for the anomalous crater CPR distributions and evidence for some differential weathering from the crater interior to its exterior. Unfortunately, the lack of illumination into the floors of the polar craters precluded such a detailed investigation of rockiness being carried out in these locations. In their detailed study of Shackleton crater, Thomson et al. (2012) found that "Mini-RF observations indicate a patchy, heterogeneous enhancement in CPR on the crater walls whose strength decreases with depth toward the crater floor." While placing an upper limit of $\sim$5–10 wt% $H_2O$ ice in the uppermost metre of regolith, they conclude that the result "...is most consistent with a roughness effect due to less mature regolith present on the crater wall slopes."

In this paper, the polar craters studied by Spudis et al. (2010) will be investigated using a combination of topography, radar and temperature data sets, with a view to determining what is responsible for the anomalous polar craters, and is anything special about their cold floors. Section 2 contains descriptions of the various data sets that will be employed and the set of polar craters to be studied. Results concerning the variation of CPR with incidence angle and position within the crater, as well as a simple model showing the impact of parallax in the range measurement, are contained in Section 3. What these CPR measurements imply about the presence of polar water ice are discussed in Section 4, and conclusions drawn in Section 5.

## 2. Data

A number of different lunar data sets, available from the Geosciences Node of NASA's Planetary Data System (PDS,[1]) will be used. This section describes them briefly, as well as providing details of the set of north polar craters to be studied.

[1] http://pds-geosciences.wustl.edu.