

# Direct evidence of surface exposed water ice in the lunar polar regions

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Edited by Jonathan I. Lunine, Cornell University, Ithaca, NY, and approved July 20, 2018 (received for review February 8, 2018)

**Water ice may be allowed to accumulate in permanently shaded regions on airless bodies in the inner solar system such as Mercury, the Moon, and Ceres [Watson K, et al. (1961) *J Geophys Res* 66:3033–3045]. Unlike Mercury and Ceres, direct evidence for water ice exposed at the lunar surface has remained elusive. We utilize indirect lighting in regions of permanent shadow to report the detection of diagnostic near-infrared absorption features of water ice in reflectance spectra acquired by the Moon Mineralogy Mapper [M (3)] instrument. Several thousand M (3) pixels (~280 × 280 m) with signatures of water ice at the optical surface (depth of less than a few millimeters) are identified within 20° latitude of both poles, including locations where independent measurements have suggested that water ice may be present. Most ice locations detected in M (3) data also exhibit lunar orbiter laser altimeter reflectance values and Lyman Alpha Mapping Project instrument UV ratio values consistent with the presence of water ice and also exhibit annual maximum temperatures below 110 K. However, only ~3.5% of cold traps exhibit ice exposures. Spectral modeling shows that some ice-bearing pixels may contain ~30 wt % ice that is intimately mixed with dry regolith. The patchy distribution and low abundance of lunar surface-exposed water ice might be associated with the true polar wander and impact gardening. The observation of spectral features of H<sub>2</sub>O confirms that water ice is trapped and accumulates in permanently shadowed regions of the Moon, and in some locations, it is exposed at the modern optical surface.**

lunar polar regions | permanently shaded regions | lunar water ice | near-infrared spectroscopy | Moon mineralogy mapper

The small tilt of the rotation axes of Mercury, the Moon, and Ceres with respect to the ecliptic causes topographic depressions in their polar regions, such as impact craters, to be permanently shadowed from sunlight (1). As a consequence, surface temperatures in these regions are extremely low (i.e., less than 110 K) (1–3) and are limited only by heat flow from the interior and sunlight reflected from adjacent topography (4–6). These areas are predicted to act as cold traps that are capable of accumulating volatile compounds over time, supported by observations of water ice at the optical surface of polar shadowed locations on Mercury (7–9) and Ceres (10, 11). There are a number of strong indications of the presence of water ice in similar cold traps at the lunar poles (12–14), but none are unambiguously diagnostic of surface-exposed water ice, and inferred locations of water ice from different methods are not always correlated. Epithermal neutron counts, for instance, can be used to estimate hydrogen in the upper tens of centimeters of the lunar regolith, but such data cannot isolate the uppermost (e.g., optical) surface and cannot discriminate between H<sub>2</sub>O, OH, or H (14). Ratios of reflected UV radiation measured by the Lyman Alpha Mapping Project (LAMP) instrument onboard the Lunar Reconnaissance Orbiter (LRO) have been interpreted to indicate the presence of H<sub>2</sub>O near the lunar south pole (13), but the observed signatures may not be uniquely attributable to

water ice because OH may exhibit similar characteristics at UV wavelengths (15). High reflectance values at 1,064-nm wavelength have also been observed near the lunar poles by the Lunar Orbiter Laser Altimeter (LOLA) and may be consistent with water ice, but fine particles and lunar regolith with lower degrees of space weathering may also give rise to higher reflectivity at this wavelength, making this interpretation nonunique (12, 16).

An advantage of near-infrared (NIR) reflectance spectroscopy is that it provides a direct measurement of molecular vibrations and can thus be used to discriminate H<sub>2</sub>O ice from OH and H<sub>2</sub>O in other forms (e.g., liquid, surface adsorbed, or bound in minerals). NIR reflectance data acquired by the Moon Mineralogy Mapper [M (3)] instrument on the Chandrayaan-1 spacecraft provide the highest spatial and spectral resolution NIR data currently available at a global scale, including the polar regions. The wavelength range of M (3) (0.46–2.98 μm) is too limited to properly discriminate OH/H<sub>2</sub>O species using fundamental vibration modes in the 3-μm region (17, 18), and in this study we focus on the detection of diagnostic overtone and combination mode vibrations for H<sub>2</sub>O ice that occur near 1.3, 1.5, and 2.0 μm. Numerical modeling results suggest NIR spectra representing as little as 5 wt % (intimate mixing) or 2 vol % (linear areal mixing) water ice are expected to exhibit all three of these absorptions (*Methods* and *SI Appendix, Fig. S1*), although actual detection limits in the M (3) data are dependent on instrumental response and signal-to-noise ratios (SNR).

The cooccurrence of all three absorptions would be evidence for water ice, and M (3) data (optical period 2C) at high latitudes were searched for pixels in shadow whose spectra exhibited these features (*Methods* and *SI Appendix, Table S1*). The resulting subset of pixels (spectra) was then analyzed using the spectral

## Significance

**We found direct and definitive evidence for surface-exposed water ice in the lunar polar regions. The abundance and distribution of ice on the Moon are distinct from those on other airless bodies in the inner solar system such as Mercury and Ceres, which may be associated with the unique formation and evolution process of our Moon. These ice deposits might be utilized as an in situ resource in future exploration of the Moon.**

Author contributions: S.L. designed research; S.L. performed research; S.L. contributed new reagents/analytic tools; S.L., P.G.L., R.E.M., P.O.H., E.F., J.-P.W., D.M.H., and R.C.E. analyzed data; and S.L., P.G.L., and R.E.M. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1802345115/-DCSupplemental](https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1802345115/-DCSupplemental).



are not observed in an example spectrum that did not pass the ice detection criteria (Fig. 1).

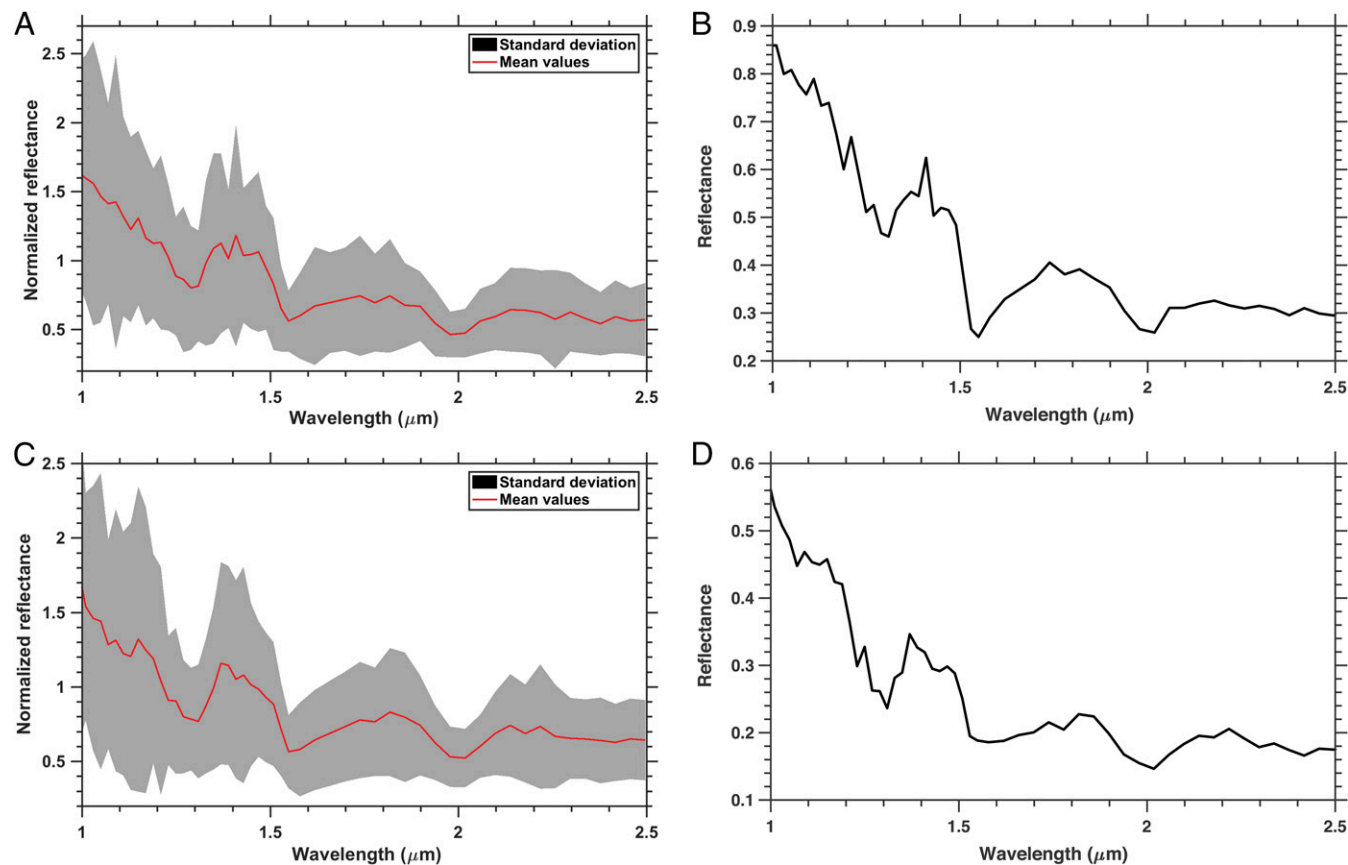
The spectra of all ice-bearing pixels were averaged and plotted for the northern (Fig. 2 *A* and *B*) and the southern (Fig. 2 *C* and *D*) polar regions to further reduce noise. The 1.5- $\mu\text{m}$  absorption appears broader and more asymmetric in the average spectrum for the south compared with that from the north (Fig. 2), which is suggestive of larger grain sizes in the former (20). Spectral mixing model results suggest that the weak absorption near 1.1  $\mu\text{m}$  and the blue slope of the M (3) spectra (Fig. 2) may be indicative of 30 wt % ice or higher if it is mixed intimately with regolith, or over 20 vol % if ice occurs as patches within otherwise ice-free regolith (*Methods* and *SI Appendix*, Fig. S1).

The absorption minima near 1.5  $\mu\text{m}$  of the M (3) spectra of ice-bearing pixels appear to be shifted  $\sim 0.05$   $\mu\text{m}$  to longer wavelengths compared with those of pure ice frost (Figs. 1 and 2). Such band shifts may reflect the increase of hydrogen bond strength due to water being bound with minerals (21). However, there was no apparent shift of the absorption near 1.5  $\mu\text{m}$  observed for olivine (1%) and water-ice (99%) mixtures (22), which may not represent the lunar case where the ice abundance may not be higher than 30%. Although there is no independent evidence to support such band shifts are due to molecular water bound to the surfaces of minerals that typify the lunar surface, such as pyroxene, plagioclase, olivine, ilmenite, and agglutinate, we cannot rule out the possibility that the apparent 0.05- $\mu\text{m}$  shift of the 1.5- $\mu\text{m}$  absorption represents water associated with certain hydrous minerals as some hydrous salts exhibit water bands close to  $\sim 1.55$   $\mu\text{m}$ . However, such minerals have not been observed in

returned lunar samples and most hydrous salts are unlikely to be stable under the vacuum and low-humidity conditions of the lunar surface.

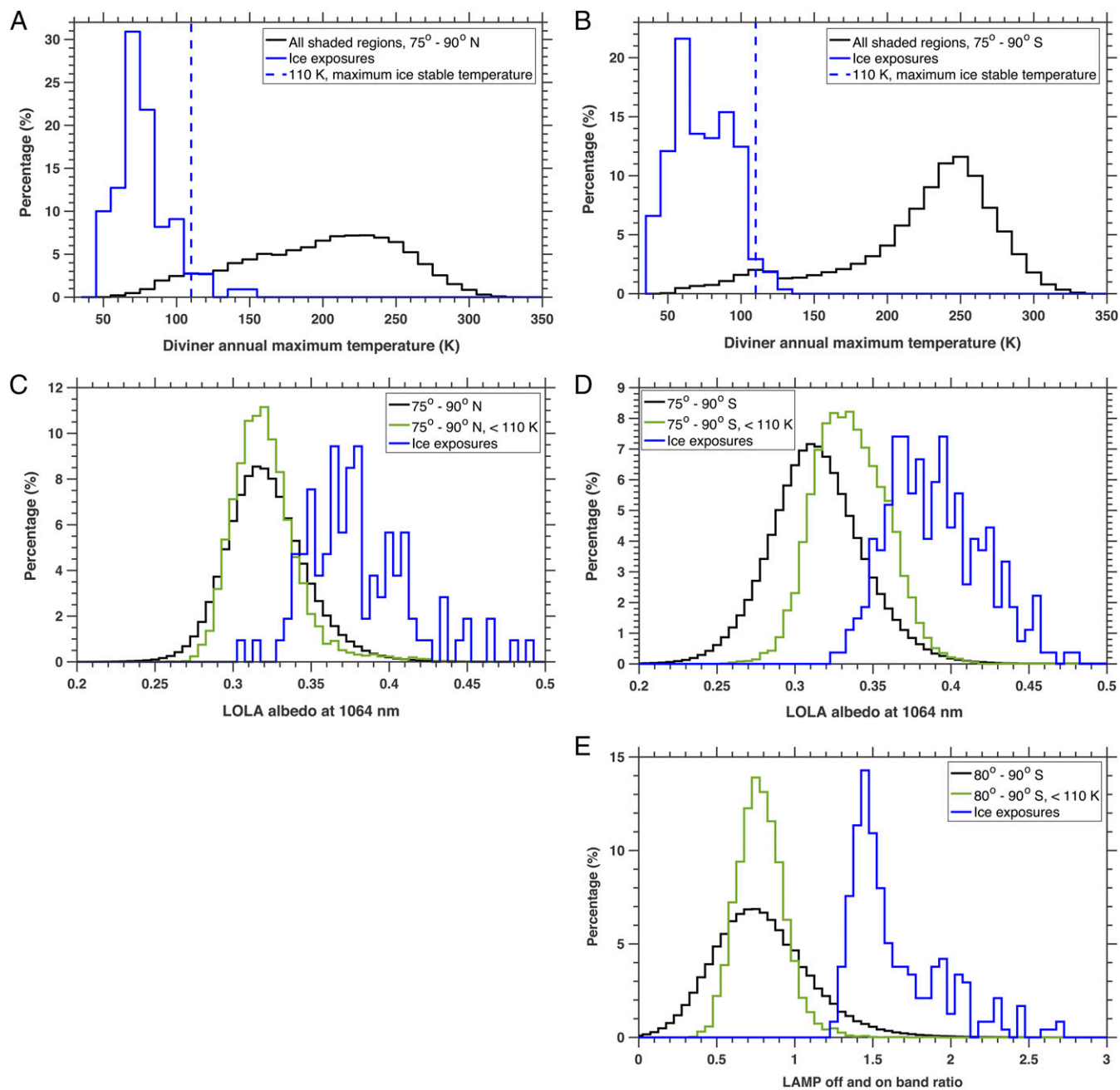
Alternatively, previous studies found that the OH fundamental stretching vibration shifted from  $\sim 2.94$   $\mu\text{m}$  ( $\sim 3,400$   $\text{cm}^{-1}$ ) for high-density ice to  $\sim 3.09$   $\mu\text{m}$  ( $\sim 3,230$   $\text{cm}^{-1}$ ) for low-density ice that was condensed from a vapor phase (23). The overtone absorption in the case of the low-density ice would be expected to occur near  $\sim 1.55$   $\mu\text{m}$ . The apparent 0.05- $\mu\text{m}$  shift of  $\text{H}_2\text{O}$  absorptions in the M (3) spectra could thus be consistent with the presence of low-density ice condensed from a vapor phase, a process that would be consistent with water delivered by volatile-rich impactors or migration of water molecules through the lunar exosphere toward cold traps. However, we cannot fully rule out the possibility that the 0.05- $\mu\text{m}$  shift [a range of two M (3) spectral bands] of the 1.5- $\mu\text{m}$  absorptions is due to the low SNR of the M (3) data.

Potential ice-bearing regions identified in the M (3) data were compared with LOLA reflectance (12), LAMP UV ratio (13), and Diviner maximum annual temperature values (24) to provide an independent check on whether or not these locations are consistent with the presence of water ice at the optical surface. We found that 93.2% of the M-(3)-derived ice locations also exhibited extreme LOLA reflectance and UV ratio values consistent with the presence of water ice, as well as annual maximum surface temperatures below 110 K (Fig. 3). The small number of candidate locations with slightly higher surface temperatures (110–160 K) or lower LOLA reflectance values (0.3–0.32, where 0.32 is the mean value near both poles from  $75^\circ$  to  $90^\circ$ ) may be



**Fig. 2.** Average spectra and SDs of ice-bearing pixels in the (*A* and *B*) northern and (*C* and *D*) southern polar regions from  $75^\circ$  to  $90^\circ$  latitude. In *A* and *C* we normalized each M (3) spectrum by its mean reflectance for each ice-bearing pixel to accommodate the variation of the intensity of light scattered onto different pixels, which helps to plot the SD of the whole polar region, whereas the average spectra without normalization are shown in *B* and *D*.





**Fig. 3.** (A) Histogram of maximum surface temperatures for ice-bearing pixels (blue) and all shaded pixels from 75° to 90° latitude (black) in the northern polar region and (B) southern polar region. (C) Histogram of LOLA reflectance values for ice-bearing pixels (blue), surfaces with maximum temperature < 110 K (green), and all shaded pixels from 75° to 90° (black) in the northern and (D) southern polar regions (E) LAMP "off" and "on" band ratios for ice-bearing pixels (blue), surfaces with maximum temperature < 110 K (green), and all shaded pixels (black); only south polar region LAMP data are available. Each dataset is normalized by the total number of pixels in that dataset.

false detections due to noise in M (3) data. The agreement between these four data sets constitutes a robust detection of water ice at the optical surface in these locations.

The distribution of surface-exposed water ice exhibits strong spatial coherence with temperatures less than 110 K (*SI Appendix, Fig. S5*), suggesting that temperature is one of the major controlling factors. However, not all regions less than 110 K (cold traps) show ice exposures, such as cold traps in craters Amundsen, Hedervari, Idel'son L, and Wiechert near the south pole; the cold trap in Bosch crater and most micro cold traps near 330° longitude between 80° and 85° N near the north pole

(*SI Appendix, Fig. S5*). No bias of M (3) data acquisition occurred at these regions that lack a detection of water ice (*SI Appendix, Fig. S6*). We find that the ice stability depth at these locations is coincidentally greater than zero when the Moon is hypothesized to be on its paleoaxis (*SI Appendix, Fig. S7*) (25), which indicates that surface ice may only be retained at long-timescale cold traps associated with the polar wander, similar to what has been proposed for the dwarf planet Ceres (11).

The patchy distribution and low abundance of surface-exposed water ice in lunar cold traps may reflect a low rate of water supply and a fast rate of regolith gardening process. The Moon is



scattered,  $\alpha$  is the amount of light scattered into the shaded region which depends on the local topography and phase angle and varies from pixel to pixel. The variation of  $\alpha$  will not introduce any absorptions and is only important for quantitative analysis of ice abundance. In this study,  $\alpha$  is set to 1 because we emphasize the global and qualitative assessment of water ice in the lunar polar regions. We assumed  $R$  to be the average reflectance spectra of illuminated regions near the poles (75° N/S–90° N/S) (SI Appendix, Fig. S8). The local solar incidence angle ( $i$ ) was applied as the criterion for determining whether a pixel was shaded ( $i \geq 90^\circ$ ) or illuminated ( $i < 90^\circ$ ). The  $M$  (3) solar incidence angles were derived using a ray-tracing model in conjunction with the LOLA topography data (30) and could be applied to determine shaded or illuminated  $M$  (3) pixels. Shaded pixels identified by this method were also verified by visually checking the  $M$  (3) images.

Radiative transfer modeling results (32) suggest that four diagnostic water-ice absorptions at 1.1, 1.3, 1.5, and 2.0  $\mu\text{m}$  may be detectable in NIR reflectance spectra of intimately mixed ice–regolith mixtures that contain  $>30$  wt % ice, whereas the three longer wavelength (and stronger) absorptions should be observed for ice contents  $>5$  wt % (SI Appendix, Fig. S1). If ice–regolith distribution is spatially heterogeneous and more akin to an areal (checkerboard) mixture at the subpixel scale, then spectral mixing may exhibit linear behavior. In this scenario, linear mixing results indicate that spectra for surfaces with  $>5$  vol % ice should exhibit all four absorptions, whereas the stronger three features would be observable for surfaces with  $>2$  vol % ice (SI Appendix, Fig. S1). The three stronger (longer wavelength) absorptions were used as criteria to examine whether any individual  $M$  (3) spectra showed evidence for water ice, but the centers and widths of these features can vary with particle size (20). The band center and shoulder positions (widths) of ice absorptions for 50–2,000- $\mu\text{m}$  particle sizes were characterized by Clark (20) (SI Appendix, Table S1) and were used as additional criteria to examine  $M$  (3) spectra in shaded regions.

Potential ice-bearing  $M$  (3) pixels were identified in two steps. First, pixels in shaded regions whose spectra exhibited three absorption features matching those in SI Appendix, Table S1 were identified. Cubic spline smoothing (33) was applied to  $M$  (3) spectra to help identify absorption features in this step. Spectral continua of the upper and lower bounds of smoothed  $M$  (3) spectra were calculated, where the former highlight absorption shoulders and the latter define absorption centers. Absorption strength was calculated as the distance between the absorption center point

and the continuum determined by the two shoulder points on either side of the absorption. Although any absorption with an absorption depth greater than zero was considered, only those spectra with absorption center positions and shoulders within the range listed in SI Appendix, Table S3 were counted as possible ice detections.

The second step assessed the spectral angle (SA) between  $M$  (3) pixels identified in step 1 and laboratory spectra of pure water frost. VIS-NIR reflectance spectra of water ice exhibit strong blue continuum slopes (SI Appendix, Fig. S1), a trend that is opposite of typical lunar spectra that exhibit spectral reddening effects due to the presence of nanophase iron formed during space weathering (19). The SA metric can be used to assess the similarity between two spectra, including spectral slopes and absorptions. The spectral angles between individual  $M$  (3) spectra and spectra of pure water frost (Fig. 1) were calculated to assess the similarity of their spectral shapes, defined as

$$SA = \cos^{-1} \left( \frac{|\bar{M} \cdot \bar{I}|}{|\bar{M}| |\bar{I}|} \right), \quad [2]$$

where  $\bar{M}$  is the vector of  $M$  (3) spectra;  $\bar{I}$  is the vector of the spectrum of pure water frost. A 0° spectral angle means that the two vectors are parallel (spectrally similar), whereas a 90° spectral angle means that the two vectors are perpendicular (spectrally dissimilar). We found that spectral angles  $<30^\circ$  may be indicative of the presence of water ice, thus only pixels (spectra) from step 1 with values below this threshold were considered ice-bearing. The 30° threshold was determined by examining the spectral angles of hand-picked ice-bearing and ice-free  $M$  (3) spectra. Original  $M$  (3) spectra of possible ice-bearing pixels that met these criteria were then averaged (without smoothing) for the lunar southern and northern polar regions (75° N/S–90° N/S), respectively.

**ACKNOWLEDGMENTS.** We thank Dr. Roger Clark, Dr. Tim Glotch, and an anonymous reviewer for their fruitful comments. We also thank Dr. Roger Clark for pointing out the shift of the 1.5- $\mu\text{m}$  absorption, which has significantly improved the quality of this paper. We are grateful to Dr. Oded Aharonson for the discussion of the statistical test in this work.

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