

DETECTION OF A 850 NM ABSORPTION FEATURE AT HIGH LATITUDES ON THE MOON: POSSIBLE PRESENCE OF HEMATITE. S. Li¹, P. G. Lucey¹, V. Z. Sun², A. A. Fraeman²,
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Introduction: The possibility of alteration minerals on the Moon has been raised since sample 14301/9 was found to contain minerals consistent with alteration by water [1]. While further studies ultimately suggested those alteration phases were products of terrestrial contamination, the conclusion is not universal [2]. The recognition that the lunar poles may harbor water ice led to further studies regarding the possibility of alteration due to minerals in contact with ice [3], or vapor from sublimating ice [4]. Arnold [5] suggested that hydrogen may accumulate as chemisorbed water, and Cocks *et al.*, [3] suggested this process may be a precursor to formation of hydrated minerals.

The recent recognition that water or hydroxyl is pervasive on the surface of the Moon with its greatest concentration at high latitudes [6-10] led us to search for evidence of alteration due to the intimate contact of the surface water and silicate surfaces.

An indigenous lunar reaction capable of generating FeOOH proposed by [11] for sample 66095 was $\text{FeO} + \text{H}_2 = \text{Fe}^0 + \text{H}_2\text{O}$ (the solar wind implantation), $\text{Fe}^0 + 2\text{H}_2\text{O} = \text{FeOOH} + 3/2\text{H}_2$, and FeOOH was suggested to be stable under the lunar surface conditions [11]. However, lab experiments suggested that FeOOH is not stable and will break down to hematite or maghemite under the lunar surface condition [2]. Hematite is an excellent target for remote detection because of its unique spectral properties relative to common lunar material. In particular, its band near 0.85 microns is not shared by any common lunar mineral. The other relevant minerals, the three forms of FeOOH (goethite, akaganeite, and lepidocrocite) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) all show absorptions near 0.95 μm that overlap with

absorptions of pyroxene, which complicates their detections.

Data & Methods: We use the Moon Mineralogy Mapper (M³) data to search globally for hematite on the lunar surface. The L1B radiance data were downloaded from the PDS server and then converted to reflectance with the same method used in [12]. Because the relevant wavelengths are all less than 1.2 μm , thermal corrections are not needed for this work.

Lab spectra of hematite exhibit a unique absorption centered near 0.85 μm due to the ${}^4\text{T}_1 \leftarrow {}^6\text{A}_1$ charge transfer between Fe^{3+} and O^{2-} . The left shoulder of this absorption centers near 0.75 μm , while the right shoulder is near 1.2 μm (Fig. 1a). We converted all M³ reflectance spectra to single scattering albedo (SSA) using Hapke's model to minimize the effects from multiple scattering and albedo variation [13]. We then chose two tie points at 0.75 μm and 1.2 μm to perform a continuum removal for all M³ SSA. If a M³ SSA spectrum after continuum removal shows an absorption at the region of 0.75-1.2 μm and also exhibits an absorption minimum at 0.85 μm , it may indicate the presence of hematite and the absorption strength at 0.85 μm was calculated. We also compared the M³ spectra at hematite rich regions with the lab spectra of pure hematite to validate our detections. In addition to the minimum near 0.85 μm , we found the spectra also had a reflection maximum near 0.75 μm and shoulder near 0.66 μm , consistent with hematite (Fig. 1a).

Results: Almost all putative hematite detections are at latitudes above 60° - 70° at both hemispheres (Fig. 2) with hematite absorptions being deeper at latitudes greater than ~70°. Fig. 3 shows the maps of the absorption strength at 0.85 μm at the north and south polar regions from 75°

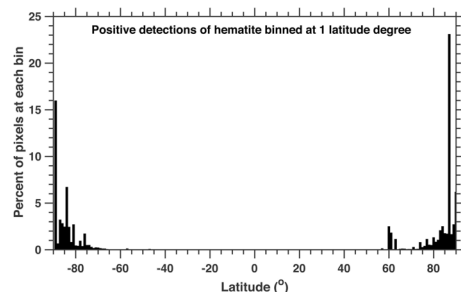


Fig. 2. Histogram of positive detections of hematite-like absorptions binned at 1 degree at the global lunar surface.

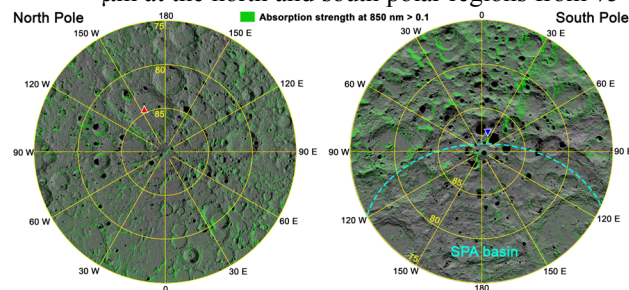


Fig. 3. Maps of absorption strength at 0.85 μm > 0.1, indicating the presence of hematite at the north and south polar regions, overlain on the LOLA shaded relief maps.

to 90° overlain on the LOLA shaded relief maps. At the north pole, hematite occurs principally at equator facing crater walls (Fig. 3) and is evenly distributed. At the south pole, hematite detections also dominantly occur on equatorial facing crater walls. However, within the South Pole-Aiken (SPA) basin hematite features are weaker than other regions in the south pole (Fig. 3).

Hapke's radiative transfer model [13] is applied to perform spectral mixing to estimate the abundance of hematite. In Fig. 1b, we show one example of a M^3 spectrum inside the Roshdestvensky crater (Fig. 3, red arrow). Assuming intimate mixing with lunar regolith, we fit the M^3 data with and without the hematite endmember. We assume hematite has the same particle size as other endmembers. Fits of the 0.85 μm band of lunar data are excellent with hematite included as an endmember; while fits are poor near 0.85 μm without the hematite endmember (Fig. 1b). If hematite exists as coatings of regolith, its abundance could be much lower. It may only require a few wt.% to reproduce the same absorption features. More comprehensive spectral unmixing analysis will be performed in future studies.

Discussion: The distribution of putative hematite on the lunar surface spatially correlates with water maps derived from the M^3 data [9]. M^3 data at latitudes above 60° - 70° show strong hematite absorption features in some locations at both hemispheres, which is consistent with the sharp increase of water content above the same latitude zone [9]. The SPA basin exhibits a lack of strong hematite absorptions (Fig. 3). Interestingly, the global water map of the Moon also shows strong suppression in the SPA basin, which could be due to the repelling of solar wind by the local magnetic anomalies [14]. The association of water and hematite suggests that the reaction proposed by [11] is widely occurring at high lunar latitudes. However, the FeOOH formed is not stable and breaks down to hematite or maghemite under the lunar surface condition.

There are no detections of hematite-like absorptions at latitudes less than ~60° of both hemispheres. However significant amount of water was seen in the large pyroclastic deposits in the equatorial region [9] suggesting that somehow pyroclastics are resistant to alteration. The water seen at pyroclastic deposits is quenched in glass beads and is not immediately proximate with Fe⁰ in the regolith rims. In contrast, the water seen at high latitude is most likely induced by solar wind implantation and would co-exist with Fe⁰ in the regolith rims, or, the Fe⁰ is able to meet with water

during impact, which makes the reaction occur. Finally, we do not see a clear correlation between the distribution of hematite and surface ice. For instance, no hematite is detected at Haworth crater walls, while surface ice was detected inside the crater [10]. However, the possible presence of altered minerals at PSRs cannot be ruled out.

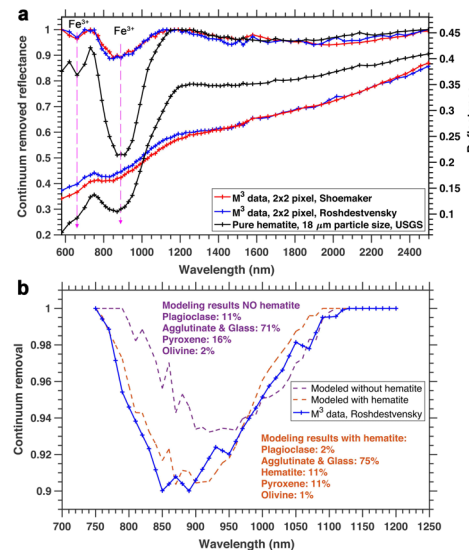


Fig. 1. a. Examples of M^3 spectra at hematite rich pixels compared with lab spectra of pure hematite, with (right axis) and without (left axis) continuum removal; b. spectral unmixing results for the M^3 spectrum inside the Roshdestvensky crater using Hapke's model.

Conclusion: Strong absorptions near 0.85 μm are detected in the lunar polar regions (60°-70° or high latitudes) and indicate the presence of hematite. Its distribution is spatially coherent with surface water maps derived from M^3 data. The formation of hematite on the lunar surface may suggest a new type of surface process involving solar wind implantation, water-rock reaction followed by dehydration, possibly aided by small impacts. It has important implications for other airless bodies that the formation of hematite may not need large amount of water.

References: [1]. S. Agrell *et al.*, *Meteoritics*, (1971). [2]. L. A. Taylor, J. C. Burton, *Meteoritics*, (1976). [3]. F. Cocks *et al.*, *Icarus*, (2002). [4]. J. D. Stopar *et al.*, *PSS*, (2018). [5]. J. R. Arnold, *JGR*, (1979). [6]. R. N. Clark, *Science*, (2009). [7]. C. M. Pieters *et al.*, *Science*, (2009). [8]. J. M. Sunshine *et al.*, *Science*, (2009). [9]. S. Li, R. E. Milliken, *Sci. Adv.*, (2017). [10]. S. Li *et al.*, *PNAS*, (2018). [11]. R. J. Williams, E. K. Gibson, *EPSL*, (1972). [12]. S. Li, R. E. Milliken, *JGR*, (2016). [13]. B. Hapke, *JGR*, (1981). [14]. H. Tsunakawa *et al.*, *JGR*, (2015).