Detection of Adsorbed Water and Hydroxyl on the Moon

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Data from the Visual and Infrared Mapping Spectrometer (VIMS) on Cassini during its fly-by of the Moon in 1999 show a broad absorption at 3-μm due to adsorbed water and near 2.8-μm attributed to hydroxyl in the sunlit surface on the Moon. The amounts of water indicated in the spectra depend on the type of mixing, and the grain sizes in the rocks and soils but could be 10 to 1,000 parts per million and locally higher. Water in the polar regions may be water that has migrated to the colder environments there. Trace hydroxyl is observed in the anorthositic highlands at lower latitudes.

The quest to find water on the Moon has been underway since the prediction of ice in the permanently shadowed craters in the lunar polar regions (1, 2). Water is a vital resource needed by a human colony, and played a fundamental role in planetary evolution (3). Spectroscopy is a tool that can be used to detect water and hydroxyl in the optical surface (the top few mm) using OH and H2O absorptions near 1.5, 2 and 3 μm.

It is thought that the Moon formed by a collision between the Earth and a Mars-sized body (4) about 4.4 Ga. The impact and the accretion of the debris heated the early Moon, creating an extensive Lunar Magma Ocean (LMO, 5, 6). These events are thought to have resulted in the loss of almost all volatiles in the Moon, and indeed evidence from Apollo and Luna samples indicate that lunar materials are deficient in volatiles compared to the Earth (3). However, 20 to 45 ppm water occurs in some Apollo lunar glasses (7).

In addition, neutron spectrometer data from Lunar Prospector (8, 9, 10) showed that hydrogen is present in the lunar polar regions. Here I use data from the Visual and Infrared Mapping Spectrometer (VIMS, 11) on Cassini, which flew by the Moon on August 19, 1999, to map the distribution of water (Fig. 1). VIMS obtained 11 full and 2 partial image cubes with a spatial resolution of about 175 km / pixel with spectral coverage over the 0.35 to 5-μm with some gaps due to sensor saturation (SOM).

Where the moon is warmed by solar radiation, thermal emission contributes to the observed signal, ([1 + T]/F, where I = measured radiance, plus thermal emission T, and πF = solar radiance. The thermal emission component and emissivity effects can mask weak water absorptions, but not strong ones, nor sharper absorptions due to hydroxyl. Thermal emission was computed and removed from lunar spectra (Fig. 2A) using a thermal model (12, 13, SOM) which included estimating the emissivity from reflectance using Kirchhoff’s law. Thermal-removed lunar spectra show water and hydroxyl absorptions in many but not all locations on the lunar disk (Fig. 1E, 1F, 2A, 2B). The linear, positive sloping spectral shape (Fig. 2A) is characteristic of the spectral signature of nanophase iron (14).

The lunar absorptions near 3 μm are characteristic of an O-H stretch fundamental in the H2O molecule commonly seen in spectra of materials with adsorbed water or due to hydroxyl-bearing materials (Fig. 2C, 2D, 15). The VIMS broad 3-μm absorption was strongest in the south lunar polar region and just north of Mare Crisium (Fig. 1E, 2B: spectra S6, S7). Narrower absorptions, characteristic of hydroxyl fundamentals near 2.7 to 2.9 μm, are mapped in both the polar regions and in lunar highlands (Fig. 1F, 2B). The hydroxyl absorption mapped strongest in the polar regions and weaker but present at lower latitudes and along the lunar terminator (Fig. 1F). The lunar south polar region was tilted toward Cassini during the fly-by thus showing better coverage of that pole.

The host minerals for the water and hydroxyl are difficult to determine because the adsorbed water absorptions are not particularly unique and the 0.016 μm bandpass of the VIMS instrument was low. The position of the 3-μm absorption is consistent with ice as well as adsorbed water (Fig. 2C, 2D, 3), but ice is not stable in sunlight on the lunar surface. The water must be adsorbed or trapped in glass or in minerals. Adsorbed water has a wide range of wavelength positions and shapes that depend on the hydrogen bonding (16). The absorption minimum near 2.9 μm indicates that the water is strongly hydrogen bonded, which is also consistent with the harsh lunar environment where only strongly bonded water might survive at the surface. Several minerals, including altered anorthite and pyroxenes have hydroxyl fundamentals near 2.8 μm (17) and show spectral structure consistent with the lunar spectra.

Radiative transfer models (17) of typical lunar soil show that a water abundance of about 1000 ppm could produce a 2% absorption in VIMS spectra at 3-μm (Fig. 3). The strength of the absorption in the lunar spectrum sp3 in Fig. 2A is about 3%. A molecular mixture, where the water molecules are uniformly mixed in the lunar rocks or soils, has the highest sensitivity. For a typical grain size of 25 μm, models for a molecular mixture indicate that a 3% absorption would require about 10 ppm water if the reflectance were 40% (Fig. 3). For lower reflectances, higher water abundances are indicated. If the water was attached to some minerals and not others, and those minerals were in an intimate mixture, 3% absorption would require 1,000 ppm water at 40% reflectance. Laboratory dehydration experiments on basalt (SOM, fig. S4) show that a water content of 2,500 ppm water at 18% reflectance yields a 9% absorption depth, so a 3% absorption would correspond to approximately 800 ppm.
assessing a linear trend. The VIMS spectra are consistent with a water content of the sunlit lunar surface of 10 to 1000 ppm.

The 3-μm absorption detected by VIMS is confirmed by the Moon Mineralogy Mapper (M3) on Chandrayaan-1 and Deep Impact (DI, 19). DI confirms that the water absorption extends to low latitudes but M3 only shows absorption in the polar region due to the limited spectral range making low water amounts difficult to map. Both VIMS and DI data indicate stronger absorption near the lunar terminator and (19) attribute this as evidence for movement of water with the diurnal cycle. However, viewing geometry might account for some or all of this apparent variability (SOM).

Lunar Prospector (LP, 8, 9, 10) found relatively high concentrations of hydrogen at both lunar poles and smaller abundances at lower latitudes (Fig. 1F). The water detected by VIMS as well as M3 and DI covers a larger area in the polar region than indicated by the LP hydrogen data. There is a correlation of the LP hydrogen data (Fig. 1G) and the VIMS absorptions (Fig. 1E, 1F). Both VIMS and LP data indicate that the maria have low water content. The LP data represent a signal up to 1 m depth, whereas the VIMS data are sensitive to water and OH in the top millimeter or so of the surface. Water at the surface is more susceptible to destruction or escape than the buried hydrogen, thus different patterns might be expected. The polar water seen in the VIMS data could be a thin surface effect from water migrating from low latitudes to the colder polar regions. Feldman et al. (8) argued against a surface deposit because it is not indicated by the fast neutron data. However, the neutron data are not sensitive to a low abundance, very thin (mm) surface layer [see figure 3 in (8)], the depth probed by the VIMS data. This may indicate that the water and OH observed in the VIMS data are not simply from a surface deposit in the polar regions but extend beneath the surface, and possibly has been mixed by impact gardening. At latitudes around the equator, VIMS detects some, but not widespread water, however, hydroxyl is detected at all latitudes. The LP neutron data show high absorption near the equator (Fig. 1G) and may be indicating buried hydrogen that is too deep for VIMS to have detected.

About 1013 kg of water has been delivered to the lunar surface by comets over the past 2 billion years, or about 0.5 kg/m2 (20). That amount distributed uniformly in the top millimeter of the surface would be about 50% abundance. Impact gardening would bury and mix that water in the top millimeter of the surface would be about 50% abundance. The 3-μm absorption detected by VIMS is confirmed by the Moon Mineralogy Mapper (M3) on Chandrayaan-1 and Deep Impact (DI, 19). DI confirms that the water absorption extends to low latitudes but M3 only shows absorption in the polar region due to the limited spectral range making low water amounts difficult to map. Both VIMS and DI data indicate stronger absorption near the lunar terminator and (19) attribute this as evidence for movement of water with the diurnal cycle. However, viewing geometry might account for some or all of this apparent variability (SOM).

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References and Notes
spectra in Figure 2A in the 2.4-μm apparent reflectance image. D) VIMS derived temperatures. E) Maps of 3-μm absorption strength (blue) and F) 2.8-μm OH strength (orange, green). F) Hydrogen map from Lunar Prospector (7-9) masked to give a similar view as the VIMS observation. The yellow bars indicated the equator position. The yellow cross indicates latitude 0, longitude 0.

**Fig. 2.** (A) Average VIMS spectra for the 3 regions indicated in Fig. 1C. The spectra before thermal emission are shown as dashed red lines. Spectrum sp1 is dominated by maria and show no water absorption. Spectrum sp2 is dominated by highlands and shows a weak absorption with a minimum near 2.8 μm, characteristic of hydroxyl. Spectrum sp3 includes the south polar region and indicates both a broad absorption from about 2.8 to 3.1 μm characteristic of trace adsorbed water as well as a stronger 2.8-μm absorption characteristic of hydroxyl. The water and hydroxyl absorptions are also seen in the sp2 and sp3 spectra with thermal emission. The blue dash-dot lines are continua that illustrate the 2.8 and 3-μm absorptions. For ease of comparison, the spectra were scaled by: 0.8 (sp1), 0.565 (sp2) and 1.0 (sp3). (B) Continuum-removed spectra showing varying 3-μm absorptions. The green areas in Fig. 1F have spectral shapes like that in spectrum s2, the orange areas have a ~2.85 minimum like that in s5-s7. (C) Spectrum s3 (top), from Fig 2B, is shown compared to laboratory spectra of minerals, a basalt, and a lunar soil. The olivine and anorthite are from (11), the basalt was measured for this study in Fig. 2B, and the Apollo 16 soil is from the RELAB spectral library, [http://www.planetary.brown.edu/relab](http://www.planetary.brown.edu/relab). (D) VIMS lunar spectra s2, s5, from Fig 2B, show broad absorption due to water with sharper absorptions attributed to hydroxyl. Spectra of minerals (11) show similar structure.

**Fig. 3.** Radiative transfer models of water and hydroxyl-bearing minerals in different conditions and amounts on a model Apollo 16 soil (containing no water or hydroxyl absorptions). Different scattering conditions and water abundances change the strength of the 3-μm water absorption.
The graph shows the reflectance of different water contents in lunar soil at various wavelengths. The reflectance is plotted on the y-axis, and the wavelength is shown on the x-axis. The graph includes the following labels:

- **No Water**
- **1.0% Ice**
- **10 ppm Water Molecular Mix**
- **10% Ice**
- **H₂O added to lunar soil (model)**

The graph illustrates how the addition of water to lunar soil affects reflectance at specific wavelengths.