Lunar OH/H$_2$O: Distribution, Variations, Origin and Mobility

Jean-Philippe Combe
Thomas B. McCord

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Lunar OH/H$_2$O

Distribution

Variations

Origins

Mobility
Lunar OH/H$_2$O

Prior to the observations: Models for the presence of OH and H$_2$O in polar permanently cold areas (Watson et al., 1961, JGR)

**Elemental hydrogen** detected by neutron detectors

OH/H$_2$O detected with ultraviolet and near-infrared spectroscopy

Possible distinction between OH and H$_2$O with near-infrared spectroscopy

**Mapping** of Elemental Hydrogen and OH/H$_2$O
Lunar Surface Elemental Hydrogen

Presence of H within the first meter below the surface, enrichment of the poles Lunar Prospector (Feldman et al., 1998; 2000)

First detection of elemental Hydrogen on the Moon by neutron count

Galactic cosmic rays (GCRs)
- Reactions with the nuclear constituents of near-surface material
- Neutrons of high energies (several hundred keV)
- Multiple elastic and inelastic collisions, scattering
- Neutrons of lower energies (thermal and epithermal range)

Measured neutron fluxes
- Rate of production depend on
  - The incident flux of GCRs
  - The relative abundances of certain elements such as Fe and Ti
- Rate of absorption is determined mostly by the relative abundances of Fe, Ti, Gd, and Sm [Lingenfelteert al., 1972].
- Rate of energy loss is determined mostly by the abundance of elemental hydrogen
  - The more hydrogen that is present, the faster is the rate of energy loss, which establishes a reduced flux of epithermal neutrons.
Distribution of Lunar OH/H₂O

Near-infrared spectroscopy of Lunar OH/H₂O

Laboratory measurements on lunar analogs
Hibbitts et al., 2011, Icarus 213

First detection of OH on the Moon by near-infrared spectroscopy

Fig. 2. Scaled reflectance. The 3-μm absorption is informative of physical state of water and hydroxyl. Adsorbed water and hydroxyl, and internal hydroxyl are distinct from bulk liquid water (model derived from optical constants) and ice (not shown, but with absorption band centered near 3.07-μm). The absorption minimum of adsorbed water on the basalt lunar analog JSC-1A is at a shorter wavelength than for bulk water and longer than for hydroxyl. Internal hydroxyl and adsorbed hydroxyl are spectrally similar. The JSC-1A spectra have been scaled by the same factor. Upon heating the JSC-1A under vacuum to 100 K, the depth of the band decreased ~50%, but the shape remained constant.

Sunshine et al. 2009, Science 326
Deep Impact High-Resolution Instrument-infrared spectrometer (HRIIR)

Pieters et al., 2009, Science 326
Moon Mineralogy Mapper (M3) onboard Chandrayaan-1

Clark, 2009, Science 326
Cassini Visual and Infrared Mapping Spectrometer (VIMS)
Possible Distinction Between OH/H$_2$O in the Near-Infrared

Absorption band analysis from $M^3$ near-infrared spectroscopy

McCord et al., 2011, JGR 116

Possible different spectral character:
- 2.8-µm band enhanced $\rightarrow$ OH
- 3.0-µm band enhanced $\rightarrow$ OH or H$_2$O

Diffuse, positive correlation of the two

$\rightarrow$ Distinction between OH and H$_2$O not yet formally demonstrated from $M^3$ spectra
Detection of Lunar H2O from UltraViolet Spectroscopy

Lyman-Alpha Mapping Project (LAMP)
Hendrix et al., 2012, JGR 117

Figure 5. Sample LAMP reflectance spectra of a sample mare region, a sample highlands region and two “fresh” regions: a bright ray and the young Giordano Bruno crater for comparison. Representative statistical error bars are shown.

Figure 6. Intimate mixture models for average lunar terrains with varying amounts of water ice. The slope in the 164–173 nm range is expected to increase (redden) with increasing water content; the slope in the 175–190 nm range should be unaffected by H2O content.
Global Mapping of Lunar Elemental Hydrogen and OH/H₂O

Epithermal Neutron flux from Lunar Prospector
Litvak et al., 2012, JGR 117

OH absorption band depth from M³ near-infrared spectroscopy
Clark et al., 2011, JGR 116

Absorption band analysis from M³ near-infrared spectroscopy
McCord et al., 2011, JGR 116

Higher Hydrogen content

Lower Hydrogen content

Simulation of the latitude variation of epithermal neutron flux
Feldman et al., 2001, JGR 106

Enhancement of volatile content at the poles consistent between neutron count and near-infrared spectroscopy
Polar Mapping of Lunar Elemental Hydrogen


Lunar Exploration Neutron Detector (LEND) on LRO

Permanently shaded region (example of Cabeus)

Enhancement of elemental hydrogen at the poles confirmed by measurements from two instruments

Maximum Hydrogen content in permanently shaded regions
Search for OH/H$_2$O in Permanently Shadowed Regions

Detection of water from an impact plume
Colaprete et al., 2010, Science 330

Fig. 3. (A to C) Model fits to the NIR reflectance spectra for three periods after impact. The measured spectral reflectance is shown with 1 SD error bars (measurement variance for the average of ~90 spectra). The fit (“Model Fit”) was produced using the various volatiles indicated by the curves (each curve is normalized to water ice to show relative abundances with respect to each other) at the lower part of each figure [H$_2$O(g) and H$_2$O(α) are water vapor and water ice, respectively]. Water vapor fluorescent emission is provided as a possible contribution but is not found to be necessary to fit the data within the uncertainty of the measurements. The total residual error between the observation and the model is shown (dark blue dashed line) and the 5% level indicated by a solid black line. In the wavelength range between 1.3 and 2.0 μm, residual error is typically <1.5%. The $\chi^2$/ν for each of the three fits is 1.16, 1.8, and 1.2, respectively.
Limitations for Polar Mapping of Lunar OH/H₂O

In deeply shaded areas: lack of solar illumination for accurate mapping with current dataset from spectrometers.
**Lunar OH/H₂O**

**Variations**

Investigations of temporal variations

Limitations in the interpretation of these variations
- Thermal emission
- Photometry
Possible variation of the 2.8-µm absorption band with time of day

Sunshine et al., 2009, Science 326
McCord et al. 2011, JGR 116

Figure 17. Examples of EPOXI observations of the 3 µm absorption for a lunar highlands region at different times of the lunar day. (a) The absorption has been isolated by removing a straight-line continuum fitted at each end of the absorption. (b) The band strength appears to vary and is strongest at lowest lighting.

→Possible temporal variations of the 3-µm band depth
Variations of signal sensitive to OH/H$_2$O

**Effects of Thermal emission on the Detection of Lunar OH/H$_2$O**

Domination by thermal emission

Absorption band analysis from M$^3$ near-infrared spectroscopy

McCord et al., 2011, JGR 116

The 3-µm absorption compensates the thermal emission

Method described in:

Clark, 1979, Icarus 40
and in Clark et al., 2011 JGR 116

$R_0' = R_0 + d_0^2 B_0(e,T)/F_{sun}$

The shape of these ratios is consistent with differences in thermal emission contributions

→ Underestimation of the thermal contribution

→ Limitation of the detectability of temporal variations form M$^3$ data
Variations of signal sensitive to OH/H$_2$O

NIR Investigations of Temporal Variations of Lunar OH/H$_2$O

Possible variation of the 2.8-µm absorption band with time of day

*Sunshine et al., 2009, Science 326*

*McCord et al. 2011, JGR 116*

Deep Impact: Variations of the 2.8-µm band depth

*M3: Kink at 2.7 µm in the ratio at crater Ryder*

→*Possible indication of temporal variations of the 3-µm band depth*

Possible variation of the 2.8-µm absorption band with varying illumination across Ryder crater

*McCord et al. 2011, JGR 116*
Variations of signal sensitive to OH/H$_2$O

**UV Investigations of Temporal Variations of Lunar OH/H$_2$O**

Hendrix et al. 2012, JGR 117

LAMP spectra on Lunar Reconnaissance Orbiter

Figure 6. Intimate mixture models for average lunar terrains with varying amounts of water ice. The slope in the 164–173 nm range is expected to increase (redden) with increasing water content; the slope in the 175–190 nm range should be unaffected by H$_2$O content.

→Possible variations of the content in H$_2$O with illumination

Figure 9. Reflectance spectra (normalized) of (a) a region on the lunar farside near 160°E at 4 different beta angles and (b) a longitude band near 92°E at 4 different latitudes. From March 23 2010 orbits when the beta angle was ~6°. The slopes in both wavelength ranges increase with latitude; this is particularly obvious at the longer wavelengths for the normalization used here. The slope increases with beta angle only in the 164–173 nm range, suggesting a diurnally variable composition related to H$_2$O.
Effects of surface Photometry on the Detection of Lunar OH/H$_2$O

Variations of signal sensitive to OH/H$_2$O

M$^3$ near-infrared spectroscopy
McCord et al., 2011, JGR 116

Absorption band depth is sensitive to the geometry of illumination and observation.

Multiple-scattering enhances the depth of absorption bands.

→ Photometry is a limitation factor in the detection of temporal variations.

→ Needs to be combined with a more accurate thermal emission correction.
Limitations for monitoring
Temporal variations of Elemental Hydrogen

Neutron flux must be integrated over long periods of times
→ Lack of flux and spatial resolution for time-dependance monitoring

Neutron detectors integrate flux from the first meter below the subsurface
→ Any variations may be smoothed out
Lunar OH/H₂O

Origins

Implantation of protons from the solar wind

Meteorites and comets

Endogenic
None of the models for the origin or delivery account for the observed distribution of elemental Hydrogen and OH/H$_2$O. After delivery on the surface, the observed volatiles have to be mobile.

Models for the origin of volatiles:
- Accretion (endogenic origin of volatiles)
- Delivery (comets, meteorites)
- Creation (implantation of protons from the solar wind)

Models for the mobility of volatiles:
- Chemical stability of H$_2$O in lunar materials and lateral transport from low latitudes to permanently cold areas
- Vertical transport from the surface to the subsurface for long-term preservation

Summary of the observations:
- Presence of elemental Hydrogen in the first meter of the regolith
- Presence of OH and possibly H$_2$O in the first millimeters of the regolith
- Enhanced contents of Hydrogen and OH toward the poles and in permanently shaded regions
- Possible OH content variability as function of local time of day and solar illumination
- Possible variations as function of the mineral composition

Crider & Vondrak, 2000, JGR 102
Implantation of protons from the solar wind
\[ \rightarrow \text{Formation of -OH} \]

\[(Zeller \textit{et al.}, 1966, \textit{JGR 71})\]

Further investigation, models and experiments:


\textit{Strazulla \textit{et al.}, 2005}

\textit{McCord \& Combe, 2011, \textit{LPSC} 1493}
Link between surface hydroxyl formation, optical maturation at magnetic anomalies and swirls

Pattern consistent with crustal magnetic anomalies creating variations of the flux of solar wind protons at the surface
Recent impact of a comet or asteroid onto the lunar surface
Shevchenko, 1999; Klumov and Berezhnoi, 2002;

Lunar swirls:
Schultz and Srnka, 1980; Pinet et al., 2000;
Starukhina and Shkuratov, 2004

Possible retention of water through comet or meteorite impact mechanisms
Ong et al., 2010, Icarus 207

Example of Vesta:
Evidence for major contribution by infalling volatile-rich meteorites (although in a different environment of the solar system)
OH/H₂O Brought by Accretion During the Formation of the Moon

First detection of water in lunar samples
→ Concentration profile from grain core to rim suggests endogenic origin and possible outgassing
(Saal et al., 2008, Nature)
Lunar OH/H₂O origin and delivery

Implantation of protons from the solar wind

Meteorites and comets

Endogenic

→ All mechanisms for the origin and delivery may contribute
Lunar OH/H$_2$O Mobility

Lateral transport from low latitudes to permanently cold areas by adsorption and desorption mechanisms of H$_2$O onto/from lunar materials combined with ballistic trajectories.

Vertical transport from the surface to the subsurface for long-term preservation.

Figure 1. The process involved with the migration and retention of volatiles to the lunar polar cold traps.
STABILITY OF LUNAR OH/H₂O IN LUNAR MATERIALS

Hibbitts et al., 2011, Icarus 213
- Adsorbed hydroxyl more stable than water
- Low latitudes hydroxyl may become mobile and recombinatively desorb as water
  → one explanation for the observed diurnal variation in the depth of 2.8-µm feature at low latitudes
  → consistent with the lack of lunar water in returned Apollo samples.
- Desorbed water → accumulates in cooler areas if not dissociated by other processes.

Fig. 4. Thermal desorption curves of water from (a) JSC-1A and (b) albite. Dosing occurred at 110 K. Adsorbed H₂O chemisorbs at low exposure and remains present to ~400 K. Water clusters begin to form at exposures of 1 L or more. A water ice peak occurs ~170 K, chemisorbed waters desorb at higher temperatures. Albite is more adsorbing than JSC-1A with chemisorbed water dominating over ice desorption at larger exposures.

Schorghofer, 2012, LPSC 1110

Figure 2: Steady-state distribution of water molecules on a global map (equal-area Hammer projection). There is an enhanced concentration of water molecules near the morning terminator, but not at the evening terminator. Colored contours are surface temperature with noon at the center. The morning terminator is to the left of the center.
LATERAL MIGRATION OF H₂O TO LUNAR COOLS

Water molecules on the lunar surface move on ballistic trajectories until they reach one of the extremely cold permanently shaded areas near the lunar poles where they accumulate.

Figure 2: Steady-state distribution of water molecules on a global map (equal-area Hammer projection). There is an enhanced concentration of water molecules near the morning terminator, but not at the evening terminator. Colored contours are surface temperature with noon at the center. The morning terminator is to the left of the center.

Figure 5. Histogram of the starting latitude of molecules which eventually became stable in the nominal Moon simulations, showing that equatorial molecules may become stable.
**Mobility of Lunar OH/H₂O**

**VERTICAL MIGRATION OF H₂O AT LUNAR PERMANENTLY COLD AREAS**

_Schorghofer and Taylor, 2007, JGR 112_

H₂O delivered on permanently cold areas

→ Two ways of accumulating H₂O ice in the subsurface
  1. Diffusive migration to the subsurface
  2. Pumping by diurnal temperature oscillations

Transport with partial or multiple molecular layers

Survival time of ice buried beneath porous regolith

*Figure 10.* Numerical model calculations of H₂O migration into the lunar subsurface with an initial ice layer on the surface that disappears after 1 million years. The mean temperature is 110 K, and the amplitude is 5 K. (a) Column integrated ground ice mass as a function of time. (b) Instantaneous depth profiles of ice density. (c) Maximum number of molecular H₂O layers, max_e/θ, as a function of time. Vertical dotted lines separate the four phases of the time evolution. Dots mark the times of the 5 snapshots in Figure 10b.
Mobility of Lunar OH/H\textsubscript{2}O

**Summary**

**Distribution**
Higher content of volatiles at higher latitudes
More OH/H\textsubscript{2}O associated to highlands (according to UV and NIR spectroscopy)
Detection of H\textsubscript{2}O at permanently shaded regions

**Observed signal variations ≠ mobility of volatiles**
Elemental hydrogen from epithermal neutron → Not enough data
OH/H\textsubscript{2}O from reflectance in the UV and NIR → Possible, although not fully demonstrated yet (limitations from residuals of thermal emission and photometry)

**Origins & Delivery mechanisms: All may exist**
Endogenic: from lunar samples → Probably not enough to explain the surficial OH/H\textsubscript{2}O
Comets & meteorites → May explain the observed amount of OH/H\textsubscript{2}O
Proton implantation from the solar wind → Consistent with space weathering and lunar swirls

**Mobility, following the delivery of volatiles at the surface**
Necessary to explain the observed enhancement of H, OH/H\textsubscript{2}O towards the poles
Retention/release mechanisms are chemically possible
Lateral mobility → From initial even distribution or point source to polar distribution
Vertical mobility → From surface deposits: Burial and long-term preservation
Scientific Motivations for Future Investigation of Lunar OH/H₂O

“Enable identification of lunar ice deposits at small (~100 m) spatial scales suitable for future extraction, sample analysis, and in-situ resource utilization.”

**Scientific investigations:**

- **Compositional state** (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

- **Source(s)** for lunar polar volatiles.

- **Transport, retention, alteration, and loss processes** that operate on volatile materials at permanently shaded lunar regions.

- **Polar regolith physical properties** (cold and possibly volatile rich).

- What the cold polar regolith reveals about the ancient solar environment.

- Determine the importance of polar volatiles for the history of the solar system

- **Tracking back the volatile flux** over the latter part of solar system history
Thank you for your attention…