New (and evolving) Views of the Moon’s Volatiles from the Lunar Reconnaissance Orbiter

Paul Hayne¹ and the Lunar Reconnaissance Orbiter Science Team

¹Jet Propulsion Laboratory, Caltech

Lunar Exploration Analysis Group – Annual Meeting – Oct 2015
Lunar Volatiles

**Science**
- Delivery of Water to Earth/Moon system
- Interaction with space environment
- Volcanism and outgassing
- Mobility and redistribution of volatiles
- Low temperature physics

**Exploration**
- Hydrogen and oxygen for fuel production
- Oxygen for astronauts to breathe
- Water to drink and grow plants
- Heat sink for thermal control systems

Isotopic abundances
- Spatial distribution
- Concentration
- Composition
- Vertical distribution and layering
- Spatial heterogeneity & accessibility

Spatial heterogeneity & accessibility
Distribution and concentration of ice is variable:

- **Vertically**
  - Vapor diffusion
  - Burial
  - Outgassing/sputtering/photolysis

- **Laterally**
  - Molecular hops
  - Water-rich impactors
  - Thermal environments

---

<table>
<thead>
<tr>
<th>Technique</th>
<th>Result</th>
<th>Sensitivity</th>
<th>Depth</th>
<th>Resolution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth-based radar</td>
<td>Non-detection</td>
<td>&gt;10-cm ice blocks</td>
<td>~1 m</td>
<td>125 m</td>
<td>Stacy et al. [1997]</td>
</tr>
<tr>
<td>Orbital monostatic radar</td>
<td>Disputed detection</td>
<td>&gt;10-cm ice blocks</td>
<td>~1 m</td>
<td>75 m</td>
<td>Spudis et al. [2013]</td>
</tr>
<tr>
<td>Orbital bistatic radar</td>
<td>Disputed detection (Clementine);</td>
<td>&gt;10-cm ice blocks</td>
<td>~1 m</td>
<td>75 m</td>
<td>Patterson et al. [2014]</td>
</tr>
<tr>
<td></td>
<td>improved data pending (LRO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron spectroscopy</td>
<td>Detection of [H] = 1700 ± 900 ppm (~1% H₂O) average &gt;70° latitude</td>
<td>H atoms at greater than ~100 ppm</td>
<td>~1 m</td>
<td>~50 km</td>
<td>Feldman et al. [2000, 2001]</td>
</tr>
<tr>
<td>Neutron spectroscopy</td>
<td>Detection of [H]; specific PSRs with</td>
<td>H atoms greater than ~100 ppm</td>
<td>~1 m</td>
<td>~10-50 km</td>
<td>Mitrofanov et al. [2012]</td>
</tr>
<tr>
<td></td>
<td>~200 – 4500 ppm (0.1% - 4% H₂O)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrared spectroscopy of impact</td>
<td>Detection of 5.6 ± 2.9% H₂O at single point (84.7°S, 310.6°E)</td>
<td>H₂O ice and vapor at greater than ~1wt%</td>
<td>~3 m</td>
<td>30-m crater</td>
<td>Colaprete et al. [2010]</td>
</tr>
<tr>
<td>plume</td>
<td>Possible detection in the PSRs; detection of H₂O (and diurnal variations) at low latitudes</td>
<td>H₂O with abundance greater than ~0.5wt%</td>
<td>~1 μm</td>
<td>240 m</td>
<td>Gladstone et al. [2012], Hendrix et al. [2012]</td>
</tr>
<tr>
<td>Ultraviolet spectroscopy</td>
<td>Detection of 10 – 100 ppm OH and H₂O on mineral surfaces under direct solar illumination</td>
<td>H₂O and OH with abundance greater than ~10 ppm</td>
<td>~10 μm</td>
<td>140 m</td>
<td>McCord et al. [2011]</td>
</tr>
<tr>
<td>Infrared solar reflectance</td>
<td>Detection of ~0 – 1wt% H₂O in igneous melt inclusions</td>
<td>Various</td>
<td>Surface</td>
<td>-</td>
<td>Boyce et al. [2010], Liu et al. [2012]</td>
</tr>
</tbody>
</table>
Mercury: a “slam dunk” for polar volatiles?
Mercury: well-defined ice boundary follows PSR (Chabot et al., 2014)

Moon: no obvious albedo anomaly in PSR (Koeber et al., 2014)
LAMP Ice Index and Diviner Temperatures

H$_2$O ice:
- $\sim$1 – 10 wt%
- Patchy, heterogeneous distribution
- Supply rates $\sim$ destruction/burial rates

Some evidence for CO$_2$ ice

Hayne et al. (2015)
Diviner-L LOLA Comparison

Diviner temperatures show well-defined cold traps, where LOLA often sees high-albedo deposits, consistent with surface frost (D. Paige, Diviner PI)
Diviner, LAMP and LOLA Comparison
LEND
Mini-RF

- Mini-RF monostatic observations do not show consistent evidence of widespread H₂O ice in PSRs.

- New bi-static observations show phase behavior consistent with cm-scale ice layers (Patterson et al., in prep).
CRaTER

- Latitude trend in proton albedo suggests a 1-10 cm layer of hydrated regolith that is more prevalent near the poles [Schwadron et al., submitted]
Mobility of Volatiles on the Moon

- Some evidence of diurnal variations in hydration: M$^3$, LAMP, LEND

- Mobility = source for cold traps

- Must be checked for consistency across datasets, and exospheric measurements

Sunshine et al. (2009)

Hendrix et al. (2012)

Livengood et al. (2015)
Impact gardening mixes ice and regolith. Sources compete with losses.
85° latitude

Impact ejecta bury ice layers
Volatiles migrate to very coldest surfaces
Extremely cold surfaces may trap more exotic volatiles (e.g., CO$_2$ < 70 K)
Preliminary LRO Volatiles Results and Future Measurements

• What we think we understand:
  – UV, visible, and near-IR reflectance data consistent with small quantities (~1%) of H$_2$O ice intimately mixed and/or patchy at small scales in the PSRs
  – Near-IR and neutron data consistent with very small quantities (up to ~100 ppm) outside the PSRs and at lower latitudes

• What we don’t understand fully:
  – High concentrations of H in regions of thermal instability
  – Diurnal variations with magnitude large enough to fill cold traps with ice
Preliminary LRO Volatiles Results and Future Measurements

- **Exciting new measurements to watch out for in the next LRO Extended Mission:**

  - Mini-RF bi-static observations could reveal locations of “blocky” subsurface ice
  
  - CRaTER albedo proton measurements could confirm presence of hydrated upper cm layer in polar regions → highly complementary to LEND and LPNS data
  
  - New mode of LAMP observations with up to ~10x signal-to-noise for measuring dayside and nightside hydration → tests diurnal variation hypothesis
  
  - Evidence for polar wander in the epithermal neutron data? (Siegler et al., submitted)
Backup slides
What kind of ice?

- Patchy ice
- Intimate mixtures / Pore-filling ice
- Frost
- Ground ice

Siegler et al. (2012)
“The Three Amigos”
“The Three Amigos”

- Each crater actually has quite a different average and range of thermal environments
- Haworth is by far the coldest on average
- Faustini has the greatest diversity, with both < 80 K and even some > 100 K regions
- Trend in LAMP in increasing apparent ice content: Haworth >> Faustini > Shoemaker
How Much Ice?

- Intimate mixture model: data consistent with ~1–2% water ice by volume
- Area mixing model: up to ~10% water ice by area