The Young Age of the LAMP-Observed Frost in Lunar Polar Craters

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Water Thermal Stability Model
Paige et al 2010
White areas= water stable at surface
Orange areas= water stable in first 10 cm
Stable = Ice loss rate of < 1 mm per billion yrs

FUV signature of > 1% icy regolith
LAMP 500nm – 1000 nm sensing depth
Hayne et al., 2015
Dark = cold polar crater
Blue= ratio of high and low wavelength bands

‘Frost’ sensed by the LRO/LAMP FUV system
Any low density icy regolith on the crater floor is also being disrupted!

- For an **exposed surface**, have added effects:
  - Have **solar wind plasma sputtering, micrometeoroid vaporization, and impact ejecta** that will also erode and release surface water from a 1% icy-regolith concentration
  - Disruption of the icy surface by ‘corpuscular’ or discrete injections of energy from the space environment
  - Conclude: Surface water not ‘stable’ to the space environment
Redistribution of top layer (0.5-1 μm) of the cold trap deposit by meteoric impact vaporization and impact ejecta

Water spills over crater onto topside by meteor impacts and plasma sputtering

Also, get a redistribution of water within the crater itself

1% water ice/regolith (soil) mixture on crater floor
How much water is released from the crater floors?

Environmental Release of Water from PSRs with 1% icy regolith mix (LAMP-like situation)

Non-Thermal Process (not driven by the ambient surface temperature - mostly)

Solar wind sputtering: \( S = YF \sim 8 \times 10^7 \) waters released/m\(^2\)-s

- Yield: \( Y = 4 \times 10^{-3} \) molecules released per incident proton at 1% water-regolith mix
- Flux: \( F \sim 2 \times 10^{10} / \text{m}^2\)-s (\( \sim 1\% \) of the solar wind gets diverted to crater floor)
- Large variability in ambipolar diverted proton influx to crater floor

Micrometeoroid Impact Vaporization: \( 4 \times 10^9 \) waters released/m\(^2\)-s

- Impacts release vapor: \( 1.2 \times 10^{-14} \) kg/m\(^2\)-s [Pokorny et al., 2019]
- 1% wt ice in the surface being vaporized yields \( \sim 1.2 \times 10^{-16} \) kg of water/m\(^2\)-s

Impact Ejecta: \( 7 \times 10^9 \) waters released/m\(^2\)-s

- Upward particle flux \( F \sim 13 / \text{m}^2\)-s for \( a > 0.1 \) microns [Szalay et al., 2019]
- \( <a> \sim 0.5 \) microns and \( <m> \sim 1.3 \times 10^{-15} \) kg
- Upward particulate mass flux: \( F<m> \sim 2 \times 10^{-14} \) kg/m\(^2\)-s
- 1% wt ice in this upward flux yields \( \sim 2 \times 10^{-16} \) kg of water/m\(^2\)-s
Ambipolar Expansion Model into Shoemaker Crater

Analytical model of Solar Wind Plasma Inflow into Craters [Farrell et al., 2010; Jackson et al., 2011; Zimmerman et al., 2011, 2012; Rhodes and Farrell, 2019]

Solar wind flow

These 1 keV protons are a source of sputtering to remove surface frost
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Sporadic meteoroid sources Helion, Antihelion, Apex, Anti-apex sense by LDEX
Added north toroidal and south toroidal sources
\(<a> \sim 0.5 \text{ microns}\)
Comparison of Thermal vs Non-Thermal Ice Loss Processes

Water Loss Rate: Sublimation, Desorption, and Space Environment

- Non-thermal processes dominant
- Impact Ejecta (1% Ice)
- IV and Sputtering (1% Ice)
- Sublimation
- Desorb, 0.46 eV
- Desorb, 0.5 eV
- Desorb, 0.6 eV
- Desorb, 0.7 eV

Log of the Emitted Flux ($H_2O/m^2.s$)

Temperature (K)
### Time to Erode a LAMP-sensed 1% icy regolith Layer (500 nm in depth)

- Assume LAMP UV wavelength extends 3 wavelengths or 500 nm into surface
- 1% icy regolith = $4 \times 10^{20}$ water molecules per square meter in 500 nm layer

<table>
<thead>
<tr>
<th>Process</th>
<th>Water Loss Rate ($H_2O/m^2-s$)</th>
<th>Water Erosion Time (kyrs)</th>
<th>Water Exospheric Density (cm$^{-3}$)</th>
<th>Water fraction returning within 20 km of source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sputtering</td>
<td>$8 \times 10^7$</td>
<td>158</td>
<td>0.04</td>
<td>0.04-0.3%</td>
</tr>
<tr>
<td>Impact Vaporization</td>
<td>$4 \times 10^9$</td>
<td>3.1</td>
<td>1.5</td>
<td>1%</td>
</tr>
<tr>
<td>Impact Ejecta</td>
<td>$7 \times 10^9$</td>
<td>1.8</td>
<td>10 (in dust)</td>
<td>13%</td>
</tr>
</tbody>
</table>

**Conclude:**
- The icy-regolith LAMP is sensing has to be dynamics on the kiloyears time scales
- The material that gets redistributed within a 40 km polar crater is primarily icy particulates
Haworth
\[<T_{\text{max}}>=75\]

Off/On Ratio

(b) Off/On ratios greater than 1.2

% of Values > 1.2

Temperature (K)

LAMP data from set used by Hayne et al 2015

> 1% icy regolith
One non-unique interpretation:

Space environment erodes this deposit.
One non-uniform interpretation:

Space environment erodes this deposit forming a dynamic thin frost in warm regions that migrates to a local cold trap or back to the original deposit.
Debris Field Model

30% icy regolith outcrop (Li et al., 2018)

See details in Farrell et al., GRL 2019
Conclusions

• The cold trap top layer is continually disrupted by the injection of corpuscular or discrete space environmental energy events

• LAMP possibly observing a surface frost (in top 500 nm) that is a convolution of thermal process (sublimation/condensation or sorption) modulated/enveloped by space environmental ‘disruption’ processes
  – May explain why the lunar frost in PSRs does not strictly follow temperature (as pointed out by Fisher et al., 2017)

• LAMP observed icy regolith layer (~500 nm) is dynamic on time scales of a few kiloyears
Zimmerman et al. 2012

Expansion of solar wind plasma into polar crater

Ambipolar Expansion of Solar Wind into PSRs – 2D Particle-in-Cell simulation [Zimmerman et al., 2012]

SW proton flux actually reaching the floor of the crater is about 1% of the original solar wind proton flux
- 100-m x 100-m area on cold trap floor
- $10^6$ seconds or ten days
- Meyer-Vernet et al [2009] predicts about 1111 impact events in range from $10^{-7}$ kg to $10^{-10}$ kg
- Simulated water molecules released as a Maxwellian distribution at 4000K

Farrell et al., 2015
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Log of the Emitted Flux (H$_2$O/m$^2$-s)

Temperature (K)
Environmental Losses to Polar Water Frost

Frost is Exposed to the Space Environment: Its Dynamic! These environmental release processes may exceed those from sublimation.