Lunar Volatiles

I. State of knowledge
II. Processes controlling distribution
III. Exploration issues

Dana M. Hurley

Dana.Hurley@jhuapl.edu
10 April 2014
Virtually all information about volatiles on the Moon comes from impacts. The Apollo missions suffered from a lack of data, but recently, many missions have reanalyzed the Apollo samples, and new data is coming in from lunar orbiters. The consensus is that there are indeed volatiles on the Moon. Without a doubt, the evidence for volatiles on the Moon is overwhelming.
Three brands of volatiles:

- Sequestered volatiles in cold traps
  - Either episodic delivery of large quantities or constant delivery of small quantities or both

- Internal volatiles trapped in minerals and glasses
  - Leftover from lunar formation

- Global surface volatiles
  - Transient veneer either produced and lost in place diurnally or involved in migration
Three brands of volatiles:

- Sequestered volatiles in cold traps
- Internal volatiles trapped in minerals and glasses
- Global surface volatiles

Paige et al. (2010) Science
### LRO LAMP Surface Frost

- **Three brands of volatiles:**
  - Sequestered volatiles in cold traps
  - Internal volatiles trapped in minerals and glasses
  - Global surface volatiles

---

LRO Lyman Alpha Mapping Project (LAMP)
Gladstone et al. (2012) JGR
Neutron and Radar Data

- Three brands of volatiles:
  - Sequestered volatiles in cold traps
  - Internal volatiles trapped in minerals and glasses
  - Global surface volatiles

- Neutrons (LPNS & LRO LEND)
  - Enhancements in hydrogen content in top meter of regolith in PSRs
  - Heterogeneous distribution

- Radar evidence still evolving (Mini-RF)
  - Moon’s PSRs aren’t full of big ice blocks, unlike Mercury

SPUDIS ET AL. (2013)
LCROSS in Cabeus

- Three brands of volatiles:
  - Sequestered volatiles in cold traps
  - Internal volatiles trapped in minerals and glasses
  - Global surface volatiles

Gladstone et al. (2010) Science

Colaprete et al. (2010) Science
Ongoing Investigations

Basic questions

- What is present-day distribution/abundance on lunar volatiles?
- What is the composition of the volatiles?

Significance

- Resource location, potential extraction methods
- Delivery and retention processes
- Markers for lunar formation, inner Solar System inventories, comets
- Informs utilization schemes
Sources and Migration of Volatiles to Cold Traps

SOURCES
- comets
- solar wind $p^+$
- micro-meteorites

$\text{H}_2\text{O} \rightarrow \text{H} + \text{OH}$
$\text{H}_2\text{O} + \gamma \rightarrow \text{e}^- + \text{H}_2\text{O}^+$

SINKS
- Jeans escape
- solar wind pickup

1) thermal desorption
2) sputtering release
3) impact vaporization
4) outgassing

adsorption thermalization re-emission
condensation in cold trap
Modifications to Lunar Cold Traps

- **Photolysis** from UV zodiacal light, starlight, Earthshine; reflected sunlight.
- **Impact vaporization** from all sizes of meteoroids.
- **Ion sputtering** from solar wind particles.
- **Diffusion** into the regolith.
- **Sublimation** from thermal effects
Impact Gardening in Polar Cold Traps

- Initial ice layer—abundance is stratified with depth
- Impacts poke holes in ice layer—anomalous regions have lower abundance than average
- Few ice blocks remain—anomalous regions have higher abundance than average
- Water is mixed with depth—few anomalous regions
- The amount of ice present today is not the amount delivered to the cold traps.

- Retention of ice is shown as a function of the initial thickness of the ice.

- \( f = b - 0.38 \log(t) \)
  where \( b \) is a function of the thickness, \( x \)

- 15 cm thick, 600-700 Myr old scenario implies that <30% of the original ice remains.
What fraction of drill sites in a 20 m x 20 m area contains buried ice?

For a ~500 Myr old ice deposit, there is a finite chance that a 20 m x 20 m exploration grid would be completely dry. However, it is most likely that 30-50% of the exploration grid contains ice.

Assuming 20 m x 20 m search area
Assume initial ice layer was 15 cm thick
Best correlation with relative altitude of lowest point

- Average dz
- Dz of lowest point
- Dz of highest point

1000 Myr

- R = 0.76
- R = 0.78
- R = 0.29

Icy area factor
‘Spillage may occur!’

Moon- spillage activated by harsh space environment?

- Part of OH Veneer signature: ‘Redistribution’ or transport of polar crater volatiles to mid-latitudes

Clark et al, 2010
3 micron IR

Courtesy of W. Farrell (NASA/GSFC)
Emission Rates and Surface Veneer

- Assume in crater fractional water content of 0.1%wt
- **Impact Vaporization:** For this water content, a $10^{-8}$ kg micrometeoroid near 10 km/sec releases $\sim10^7$ H$_2$Os /m$^2$-s [Cintala, 1992; Farrell et al., 2013]
- **Sputtering:** For this water content, yield is $\sim10^{-3}$ water molecules/ion released also generates about $\sim10^7$ H$_2$Os /m$^2$-s but water released more energetically than from impacts
- For a 20 km radius crater, the water molecules **redistributed** to the surrounding 400 km diameter topside region is on average $\sim2 \times 10^4$ H$_2$Os /m$^2$-s
- For a shadowed region residence time of 1/2 of lunation, a **volatile ‘veneer’ should** form in topside shadowed region at $\sim10^{10}$ H$_2$Os /m$^2$ (mostly from impact vaporization).
Effects of Operations on the Environment
Exhaust Plume Impingement During Landing

impingement of water (cm$^{-2}$)

1 monolayer--slab

1 monolayer--grain surface

distance (km)

impinging water molecules cm$^{-2}$
Volatile: What’s Next?

Basic Questions

- What is present-day distribution/abundance?
- What is the composition?

Status

Data Needed

- *In situ sampling, bi-static radar, IR, higher spatial resolution mapping*
- *In situ sampling, sample return, isotopic analysis*
Ice in lunar polar regions has a heterogeneous distribution.

- Processes of scientific interest produce the heterogeneity.
- The heterogeneity drives the design of any mission to sample volatiles in situ on the Moon.

Many processes act simultaneously as a source and a sink to volatiles

- Impacts both bury (protect) polar volatiles and excavate (remove) them
- Operations that use volatiles also deposit volatiles in the environment

Science and exploration should coordinate to meet their synergistic goals pertaining to lunar volatiles

- Exploration missions will provide data for scientific interpretation of history of volatiles and physical processes acting on the Moon.
- Intense international robotic lunar exploration in the past decade has transformed the understanding of lunar volatiles.
Future Directions

Ultimate Questions

- What are the sources of volatiles and relative importance?
- What processes affect the delivery and retention of the volatiles?
- When were the volatiles introduced to the Moon?
- What do they tell us about the formation of the moon, early volatiles in inner solar system?
- How do we mine and utilize the volatiles in future missions?