VORTICES

VOlatile Regolith Thermal Investigations Consortium for Exploration & Science

Lunar Volatiles

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

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Volatiles on the Moon

- State of knowledge circa 2004: Are there volatiles on the Moon?

Analytical Tools

- Mapping
- Thermal analyses
- Spectroscopic analyses
- Laboratory experiments
- Impact experiments
- Modeling
- Reanalysis of Apollo samples
- Particle analyses (energetic particles, neutrals, neutrons, ions)

Answered

Recent Data

- LADEE
- LRO
- LCROSS
- Chandrayaan-1
- Lunar Prospector
- EPOXI, Cassini
- ARTEMIS
- IBEX
- Kaguya
- Apollo samples

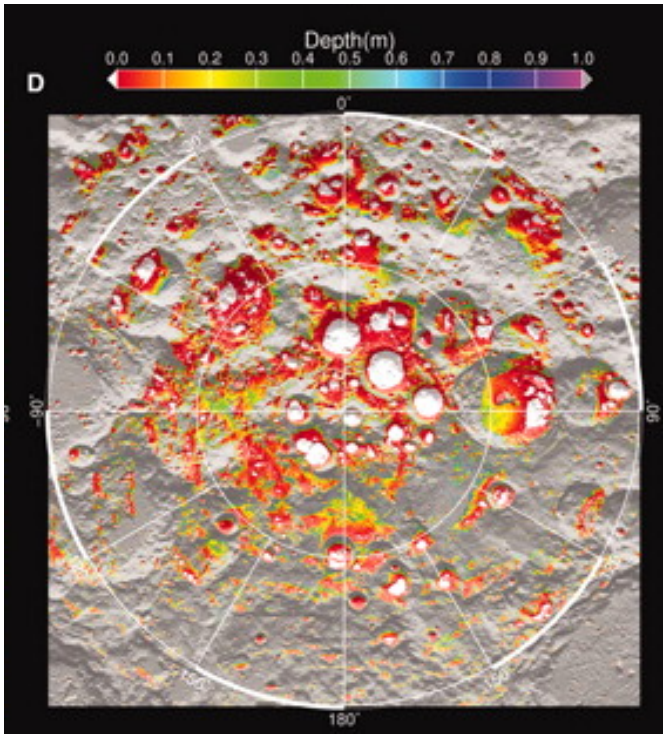
Volatiles on the Moon

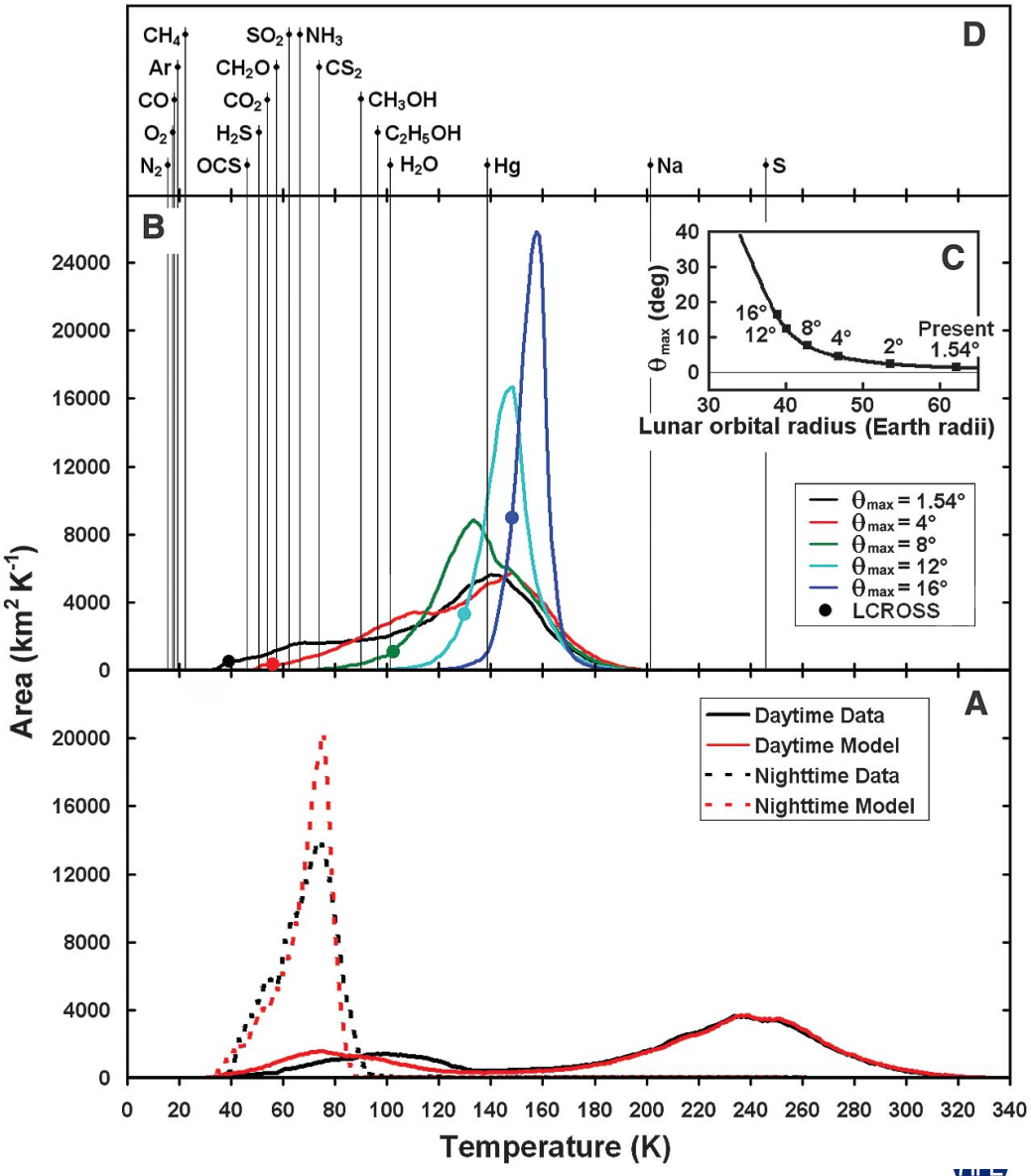
- **Three brands of volatiles:**
  - **Sequestered volatiles in cold traps**
    - **Either episodic delivery of large quantities or constant delivery of small quantities or both**
  - **Internal volatiles trapped in minerals and glasses**
    - **Leftover from lunar formation**
  - **Global surface volatiles**
    - **Transient veneer either produced and lost in place diurnally or involved in migration**

LRO Diviner and Thermal Analysis

- **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:**
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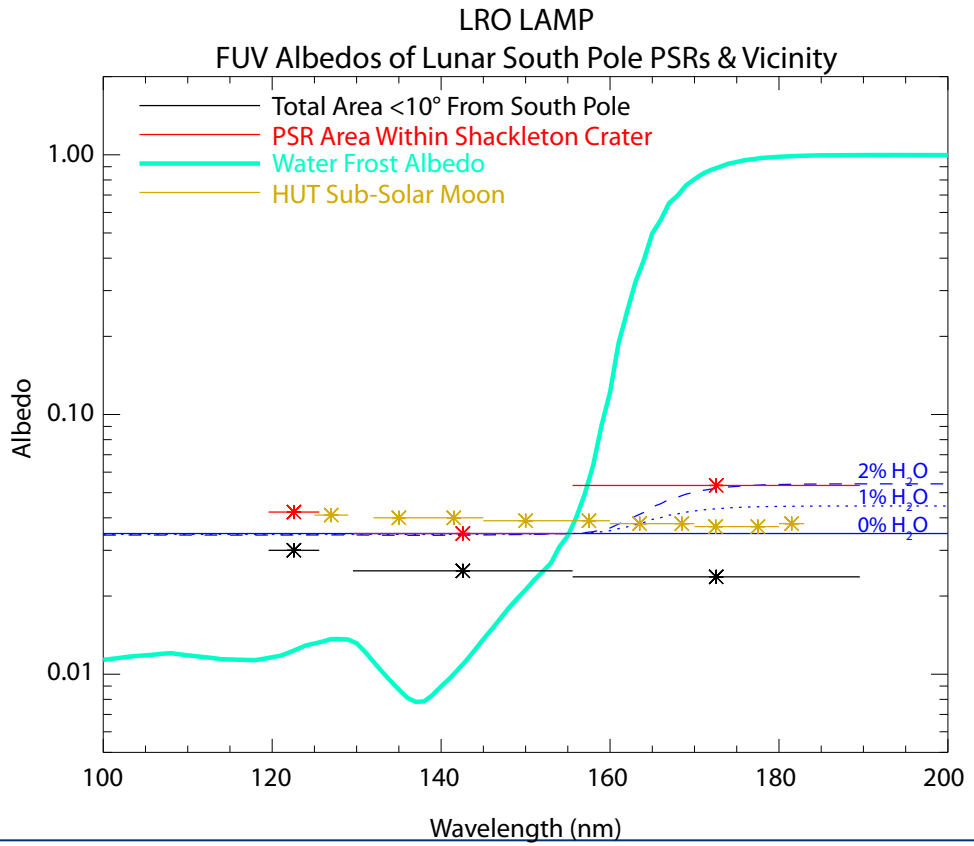
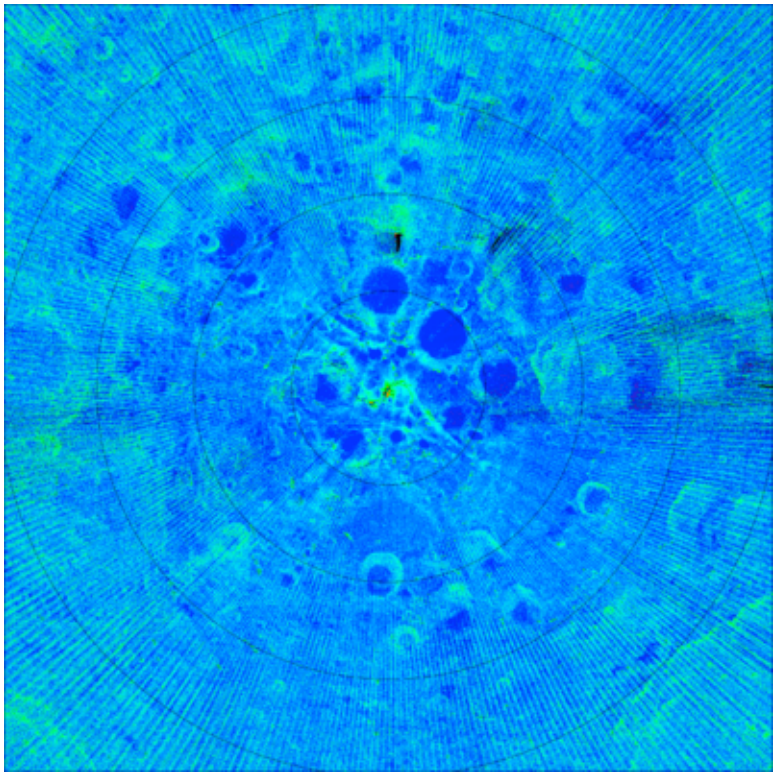


LRO Lyman Alpha Mapping Project (LAMP)
Gladstone et al. (2012) JGR



Neutron and Radar Data

- **Three brands of volatiles:**
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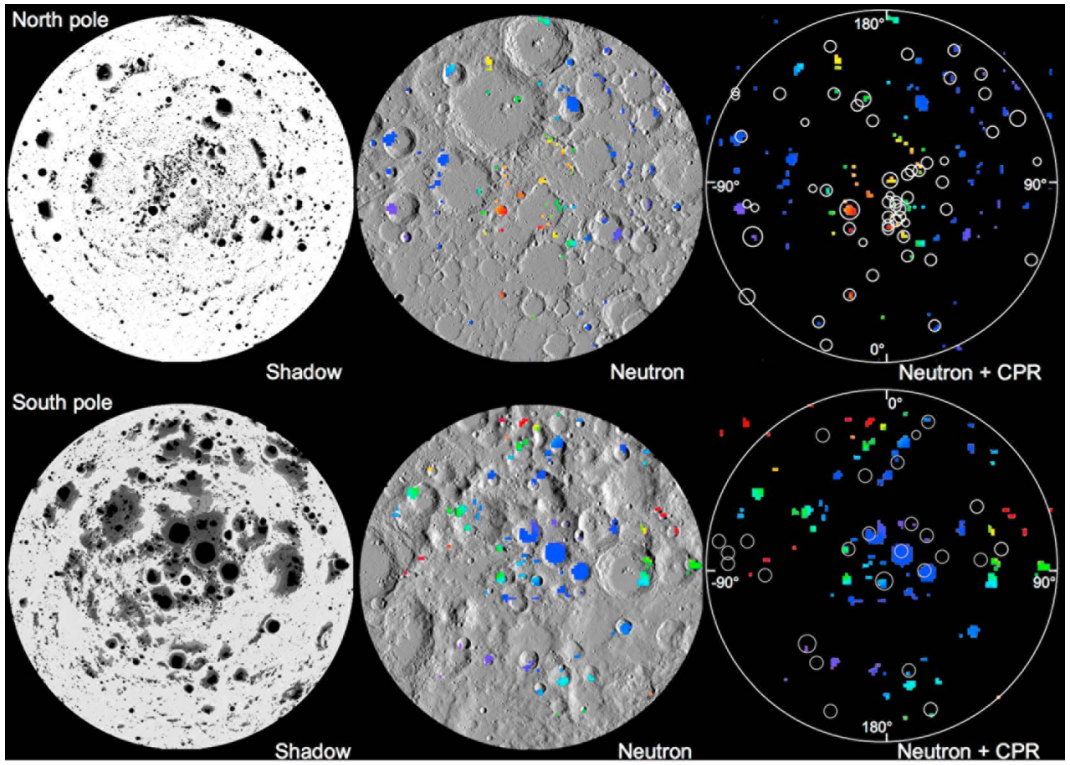

SPUDIS ET AL. (2013)

- **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**

LCROSS in Cabeus

- **Three brands of volatiles:**
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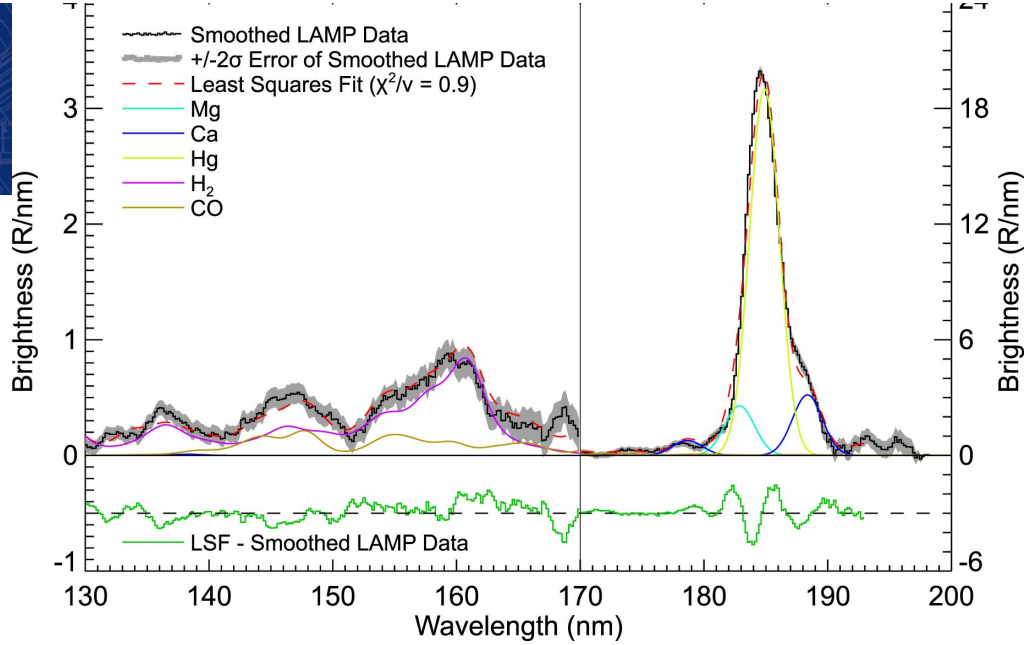
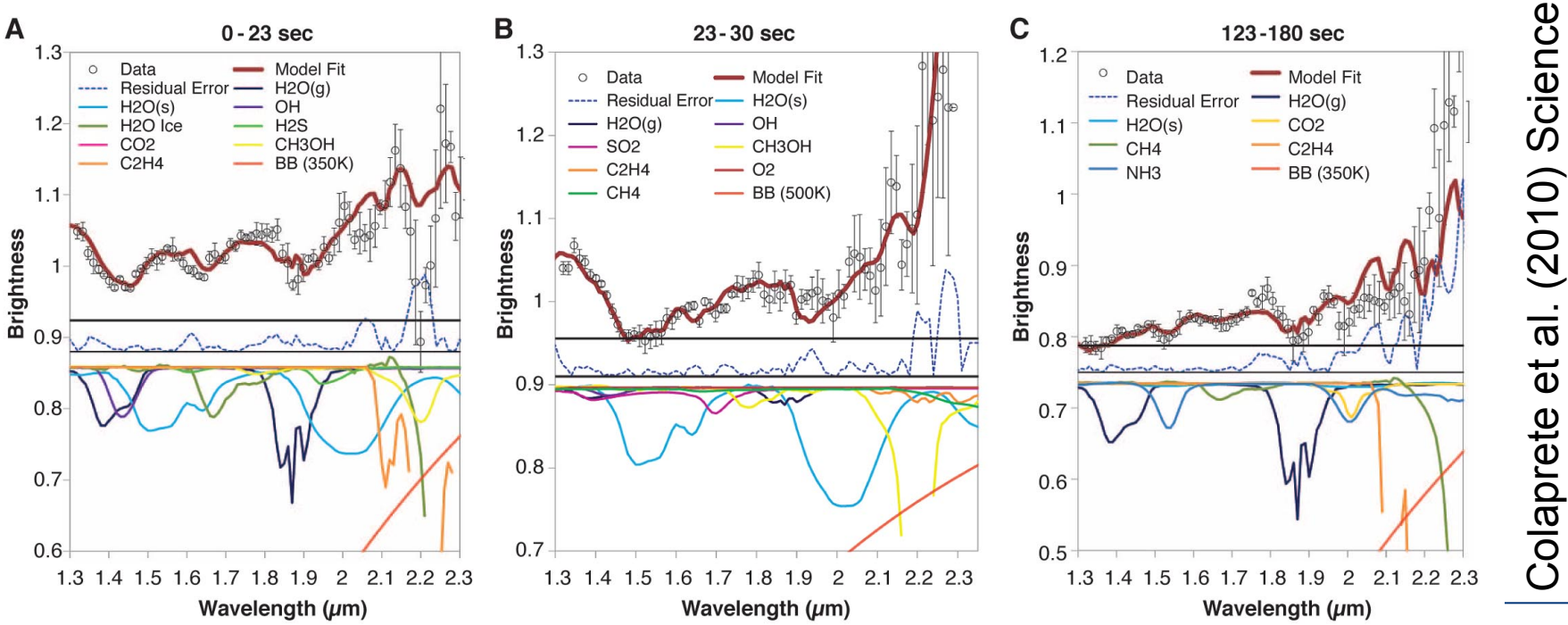


Gladstone et al. (2010) Science



Colaprete et al. (2010) Science

Ongoing Investigations

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Basic questions

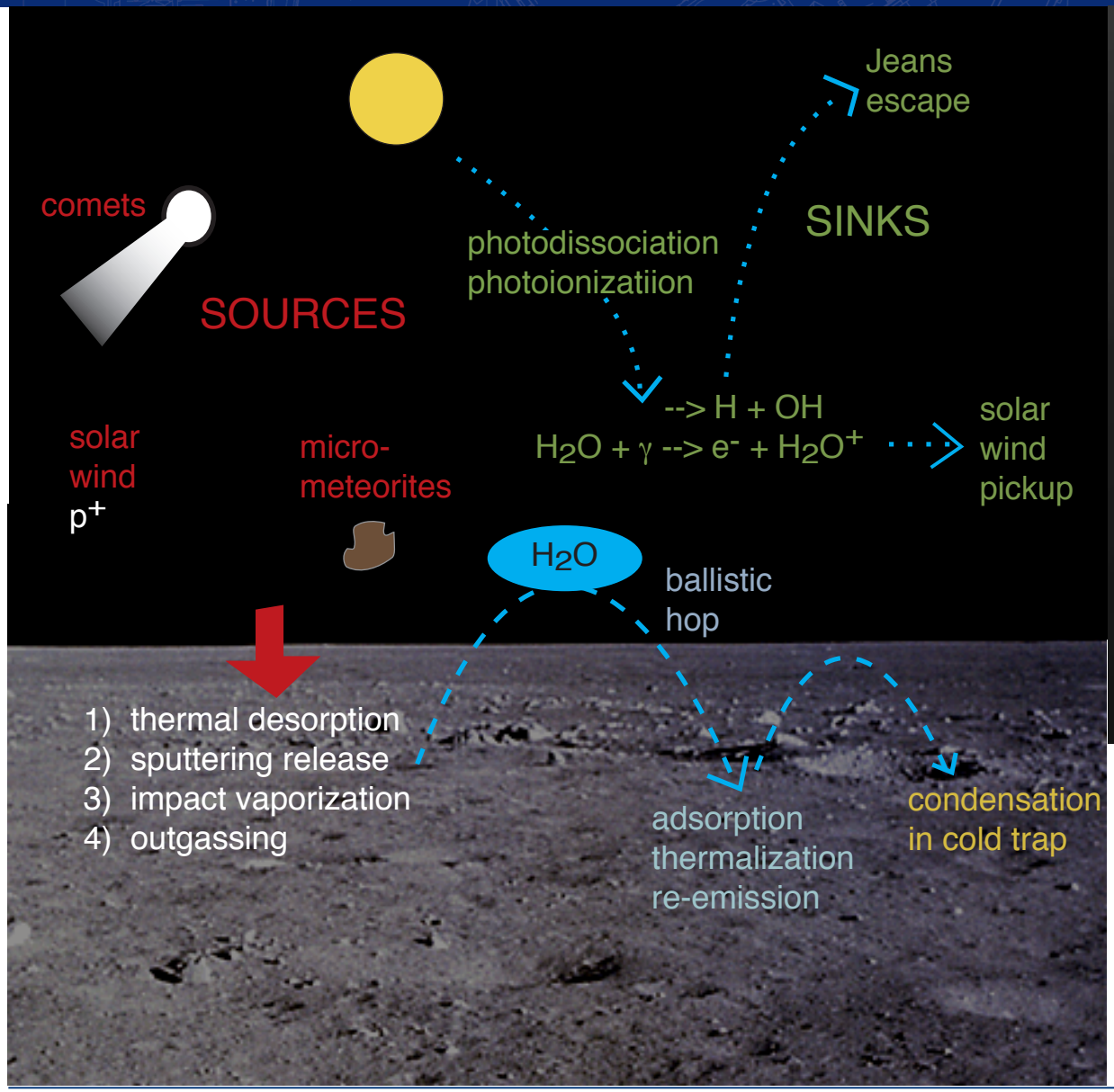
- What is present-day distribution/abundance on lunar volatiles?
- What is the composition of the volatiles?

Significance

- Resource location, potential extraction methods
- Delivery and retention processes
- Markers for lunar formation, inner Solar System inventories, comets
- Informs utilization schemes

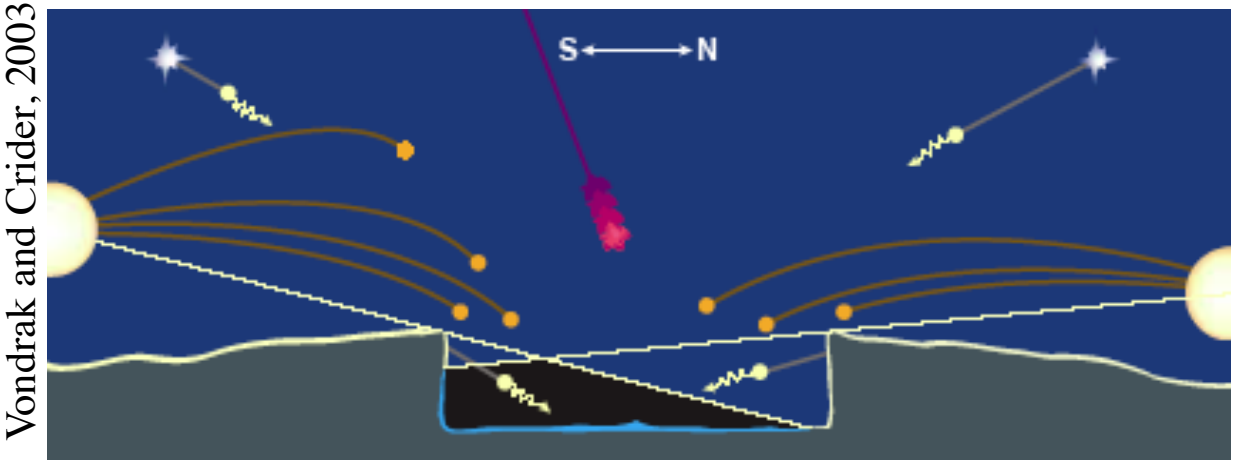
APL

Sources and Migration of Volatiles to Cold Traps



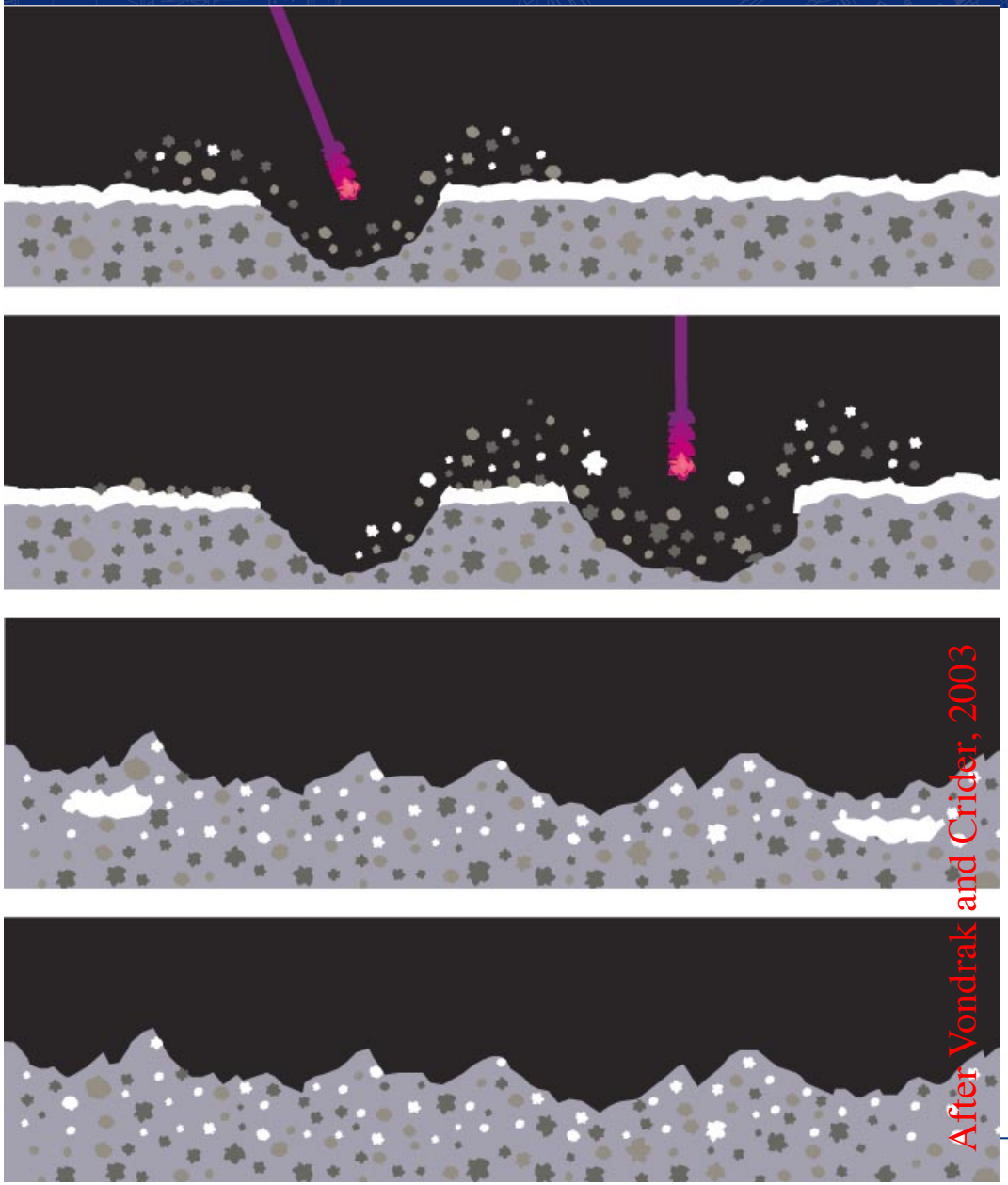
Modifications to Lunar Cold Traps

- **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



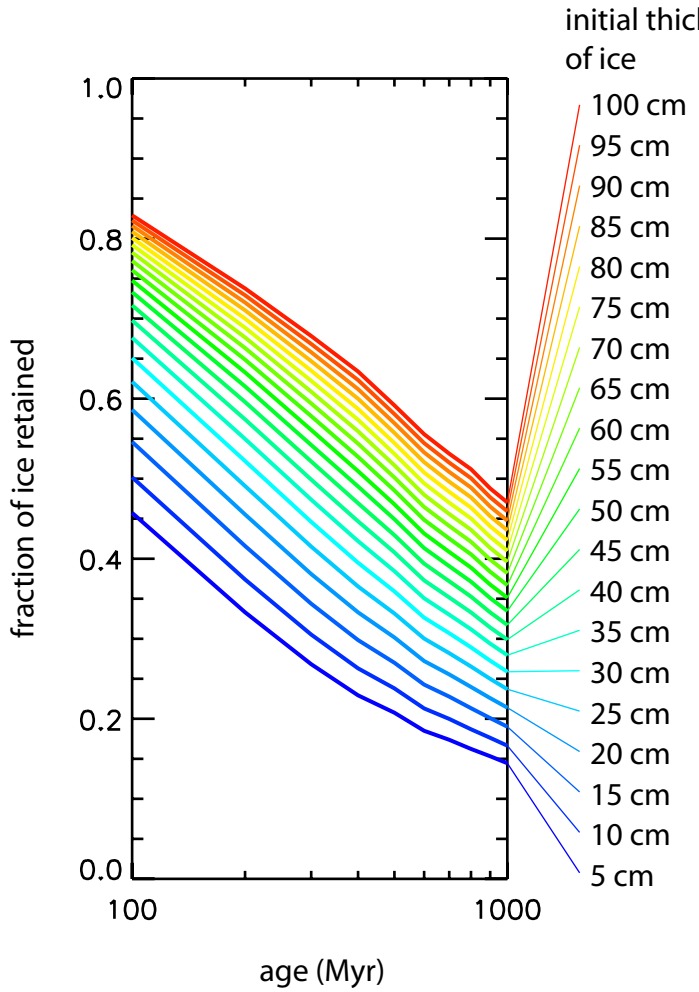
Vondrak and Crider, 2003

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

Ice Retention



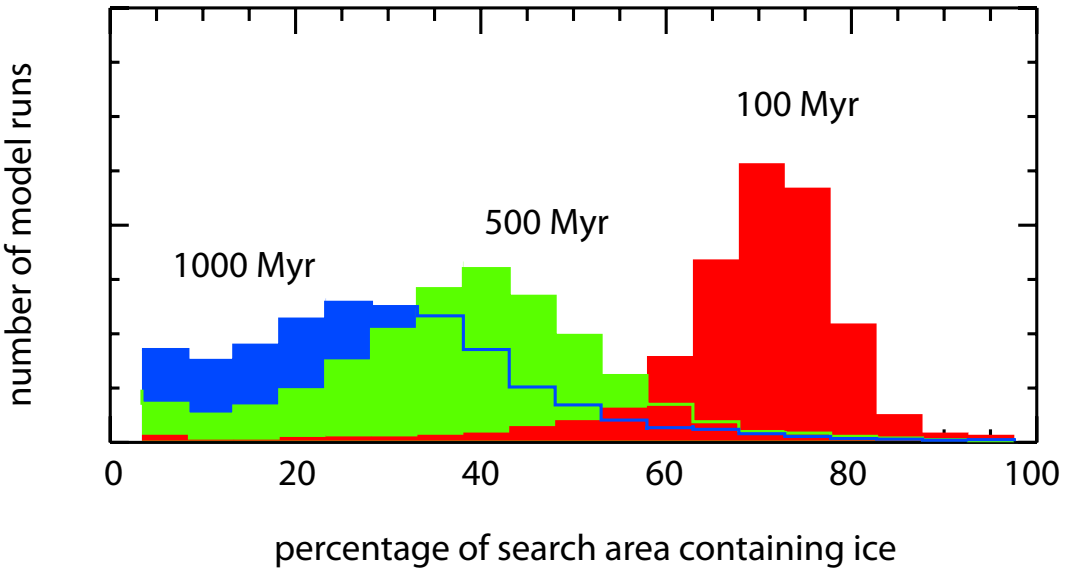
- **The amount of ice present today is not the amount delivered to the cold traps**
- **Retention of ice is shown as a function of the initial thickness of the ice**
- **f = b - 0.38 log (t)**

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.**

Mobility Requirements

What fraction of drill sites in a 20 m x 20 m area contains buried ice?



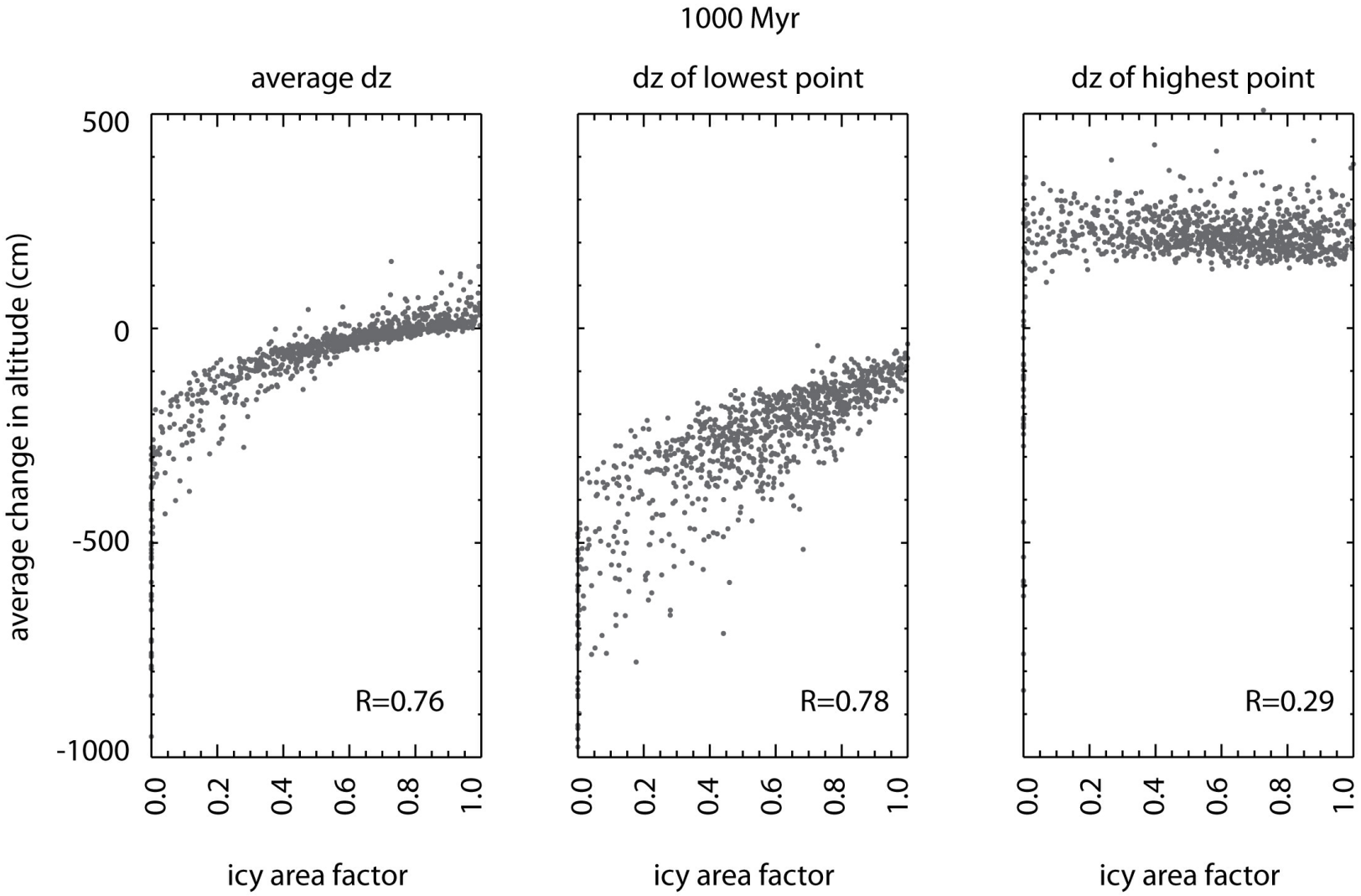
For a ~500 Myr old ice deposit, there is a finite chance that a 20 m x 20 m exploration grid would be completely dry. However, it is most likely that 30-50% of the exploration grid contains ice.

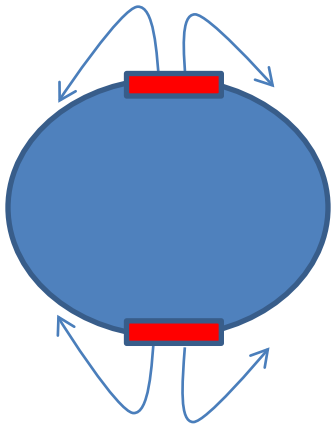
Assuming 20 m x 20 m search area

Assume initial ice layer was 15 cm thick

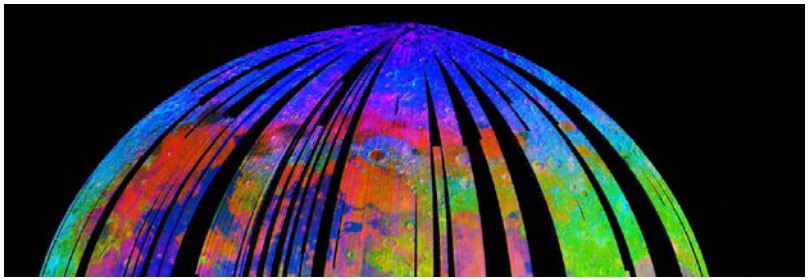
Model Results

- **Best correlation with relative altitude of lowest point**





‘Spillage may occur!’



Clark et al, 2010
3 micron IR

Moon- spillage activated by harsh space environment?

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

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 micrometeroid near 10 km/sec releases ~10^{7} H_2Os /m^2-s [Cintala, 1992; Farrell et al., 2013]
- **Sputtering:** For this water content, yield is ~10^{-3} water molecules/ion released also generates about ~10^{7} H_2Os /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 ~2 x 10^{4} H_2Os /m^2-s
- For a shadowed region residence time of 1/2 of lunation, a **volatile 'veneer' should** form in topside shadowed region at ~10^{10} H_2Os /m^2 (mostly from impact vaporization).

Courtesy of W. Farrell (NASA/GSFC)

Effects of Operations on the Environment

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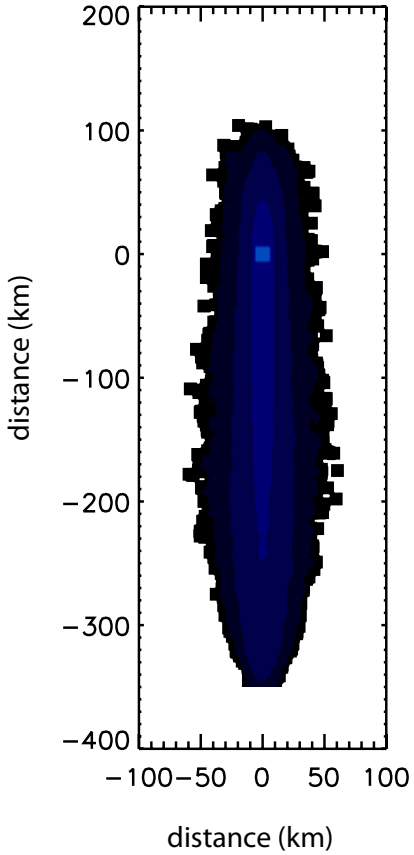
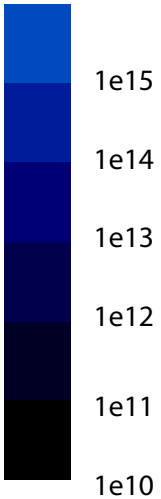
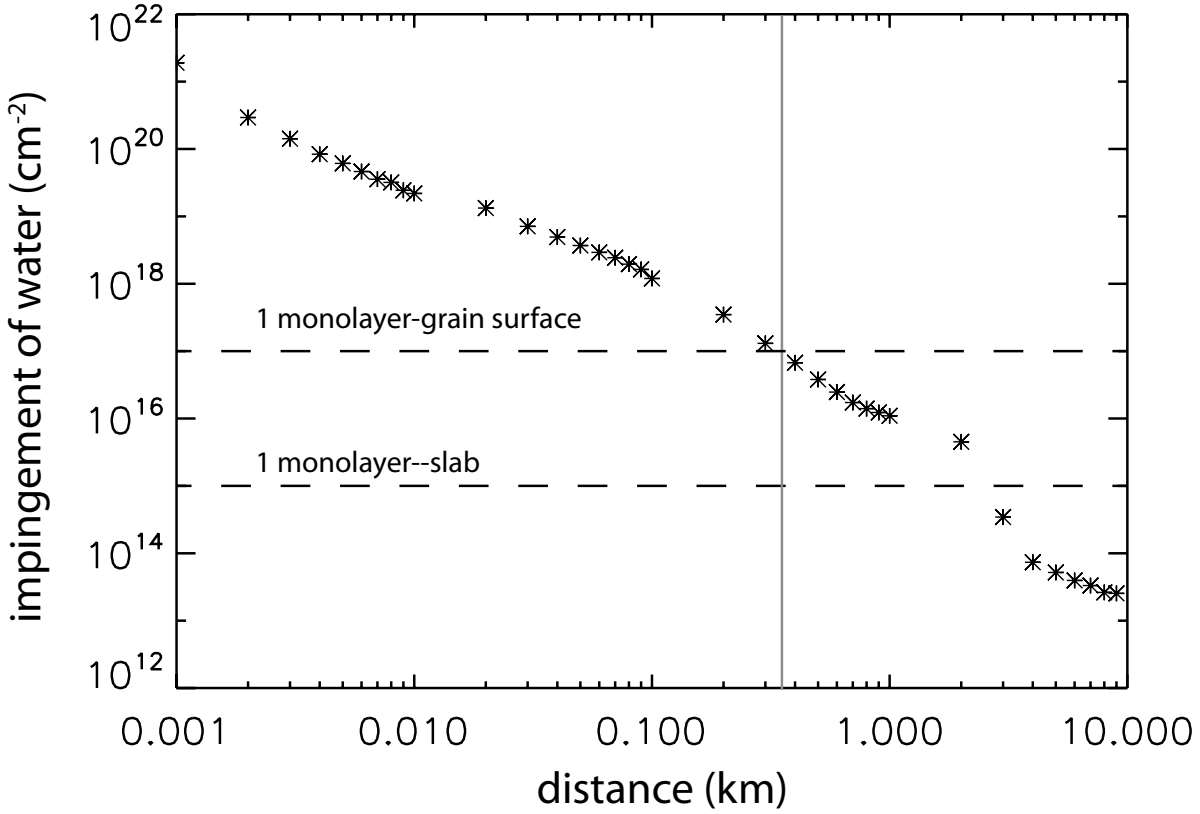
Exhaust Plume Impingement During Landing







Volatiles: What's Next?

Basic Questions	Status	Data Needed
▪ What is present-day distribution/abundance?		▪ *In situ sampling, bi-static radar, IR, higher spatial resolution mapping*
▪ What is the composition?		▪ *In situ sampling, sample return, isotopic analysis*

Conclusion: Science and Exploration

- **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

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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?

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