VORTICES

VOlatile Regolith Thermal Investigations Consortium for Exploration & Science

Lunar Polar Volatiles: Evaluation of Existing Data Sets

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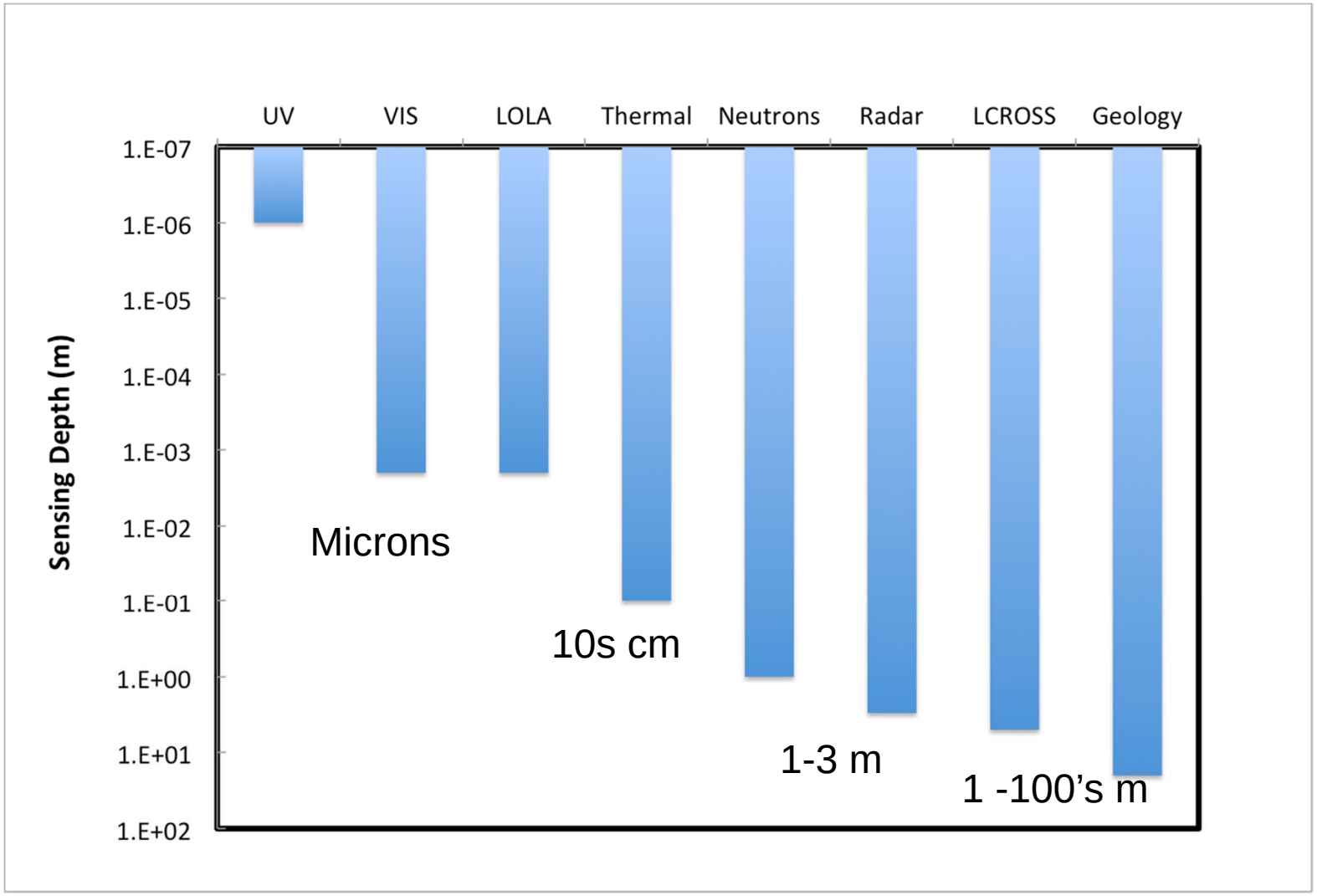
Introduction

- **Background**
  - **Lunar volatiles are potentially a valuable resource for exploration – life support and fuel.**
  - **Understanding of volatiles is evolving as new data emerge and scientists synthesize data, theory, lab experiments, and models.**
  - **Data sets are nuanced in ways that are not always obvious to the outside observer.**

- **White paper**
  - **Its purpose is to evaluate the existing data sets and summarize the caveats for those external to the field.**
  - **Community input – Friends of Lunar Volatiles.**
  - **It will be submitted to NASA HEOMD.**

Interrogation Depth



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)**

Current status:

Answered

Recent Data

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

Volatiles on the Moon

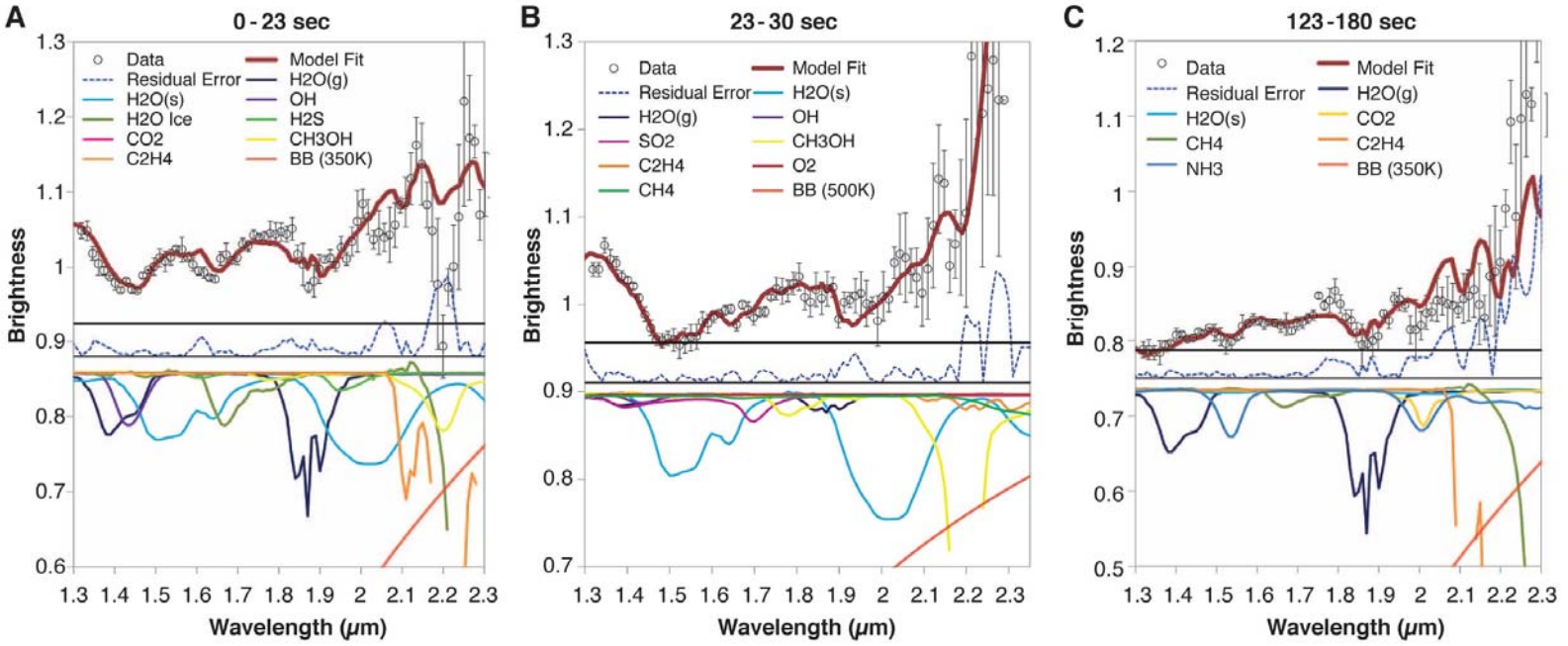
- **Three brands of volatiles:**
  - **Sequestered volatiles in cold traps**
    - **Episodic delivery of large quantities (e.g., cometary impact) or constant delivery of small quantities (surface formation) or both.**
  - **Internal volatiles trapped in minerals and glasses**
    - **Pyroclastics**
    - **Leftover from lunar formation.**
  - **Global surface volatiles**
    - **Transient veneer either produced and lost in place diurnally or involved in migration (H_2O, OH).**

Focus on Polar Volatiles (water ice)

- **Current Issues: Obtaining measurements of the following aspects:**
  - **Abundance**
    - **Exploration rationale: assess value and extraction techniques**
    - **Science rationale: tied to abundance of sources**
  - **Composition**
    - **Exploration: additional resources**
    - **Science: chemical fingerprint of source**
  - **Distribution**
    - **Exploration: scale of operations and extraction technique**
    - **Science: age of deposits; redistribution and retention processes**
  - **Physical State**
    - **Exploration: extraction technique; operational paradigm**
    - **Science: interactions between volatiles and regolith**

Existing Data: COMPOSITION

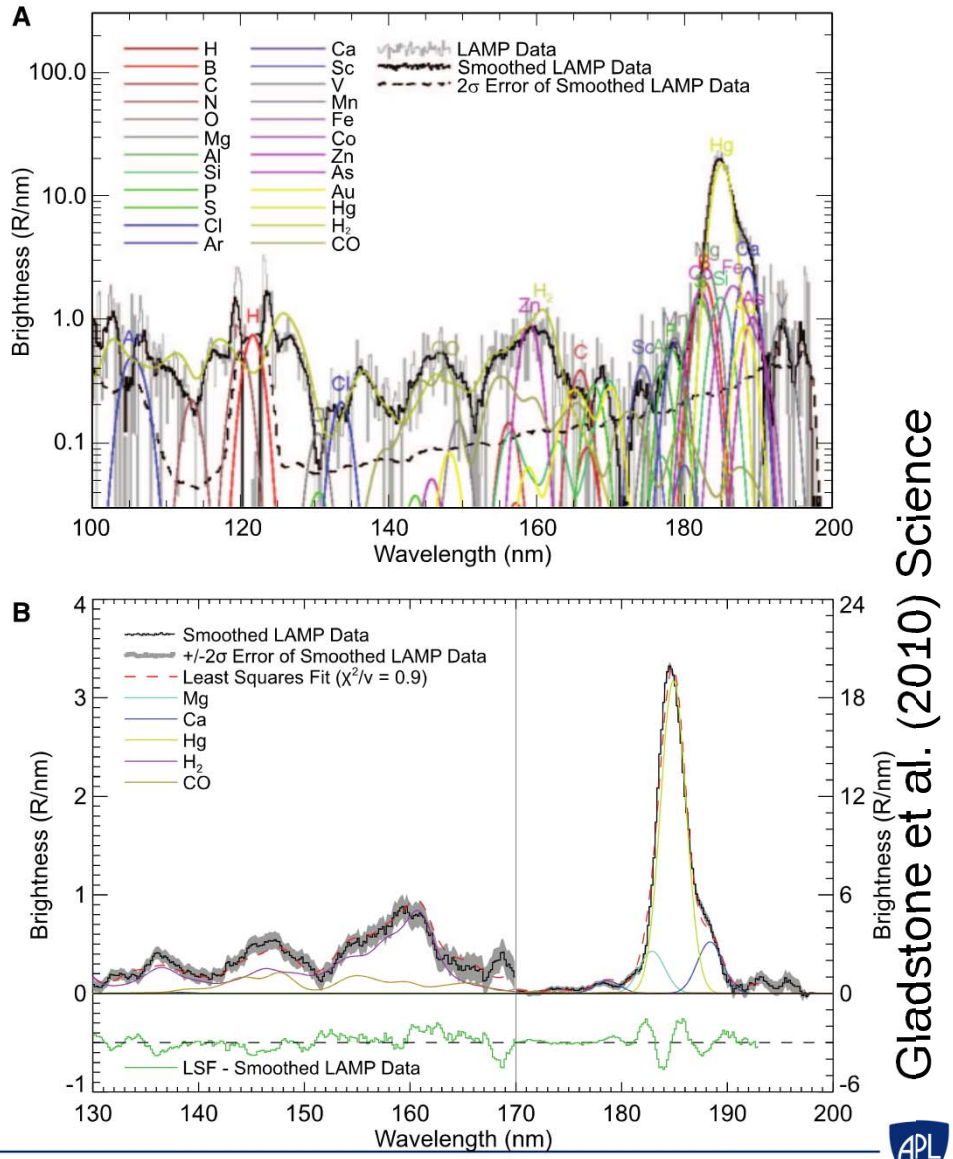
- **LCROSS impact into Cabeus**
- **Spectral identification of H_2O in both solid and gas phases**
  - **High resolution spectra provide strong evidence for the chemical composition.**
  - **Lofted material into sunlight providing a strong illumination source.**
  - **Question arises about any impact-induced chemistry and contributions from the impactor vs. the target material.**



Colaprete et al. (2010) Science

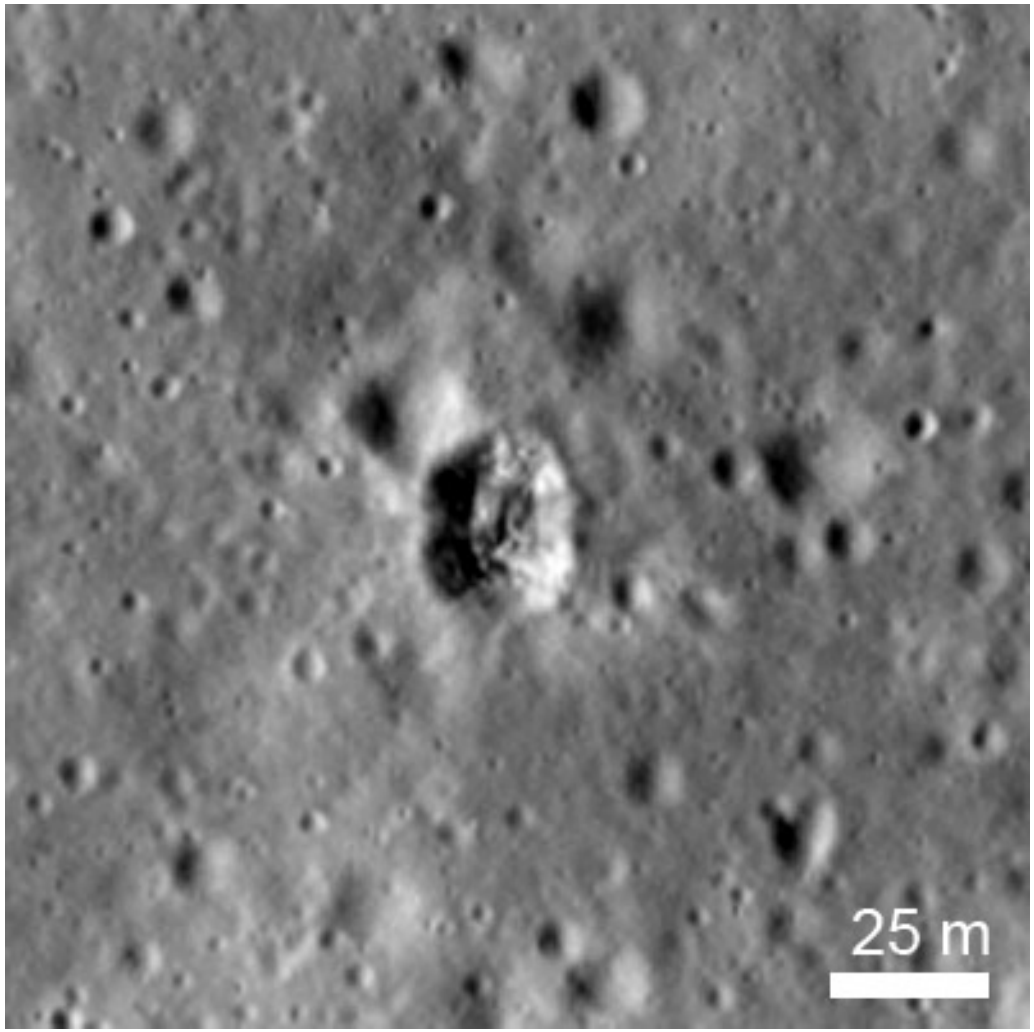
Existing Data: COMPOSITION

- LCROSS impact into Cabeus
- Spectral identification of other volatiles in the vapor
- From LCROSS
  - H_2S, SO_2
  - NH_3, CO_2
  - Hydrocarbons
  - OH
- From LRO
  - Hg, Mg, and/or Ca
  - CO
  - H_2
- From Earth
  - Na



Gladstone et al. (2010) Science

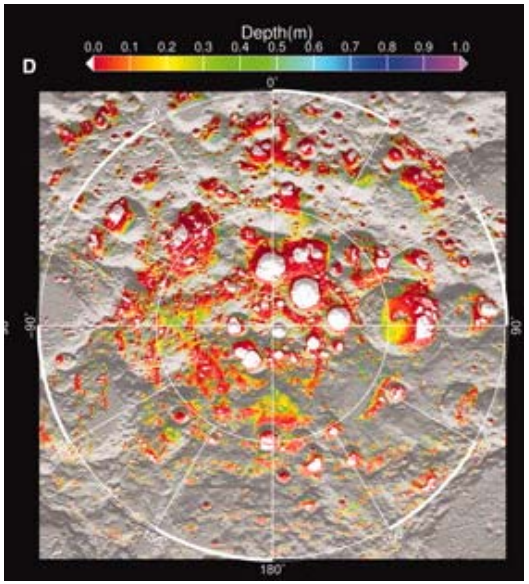
LCROSS Impact



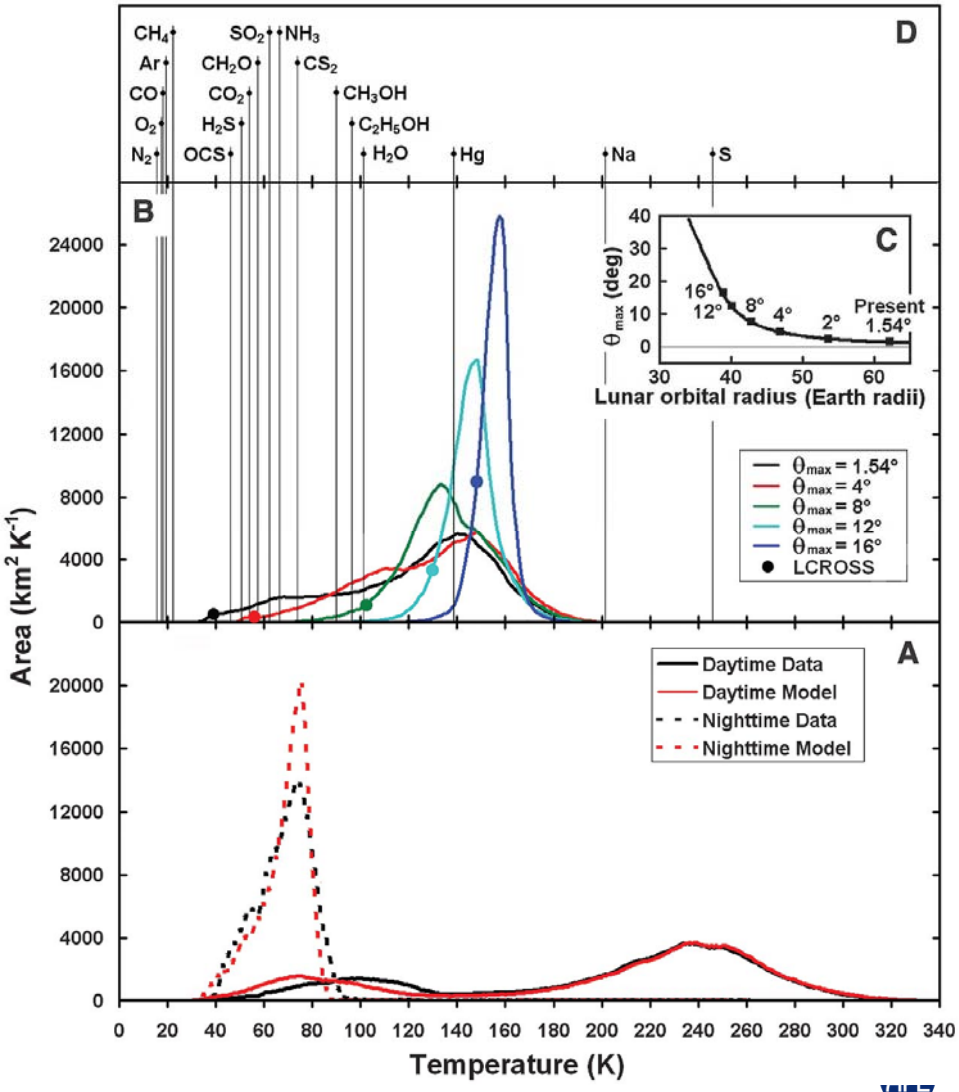
Apollo 16 S-IVB impact crater

Existing Data: COMPOSITION & DISTRIBUTION

- **LRO Diviner temperature measurements and thermal analysis**
  - **Provides map of where different compounds are stable against sublimation.**
  - **Modeling predicts the depth to a thermally stable layer.**



Paige et al. (2010) Science



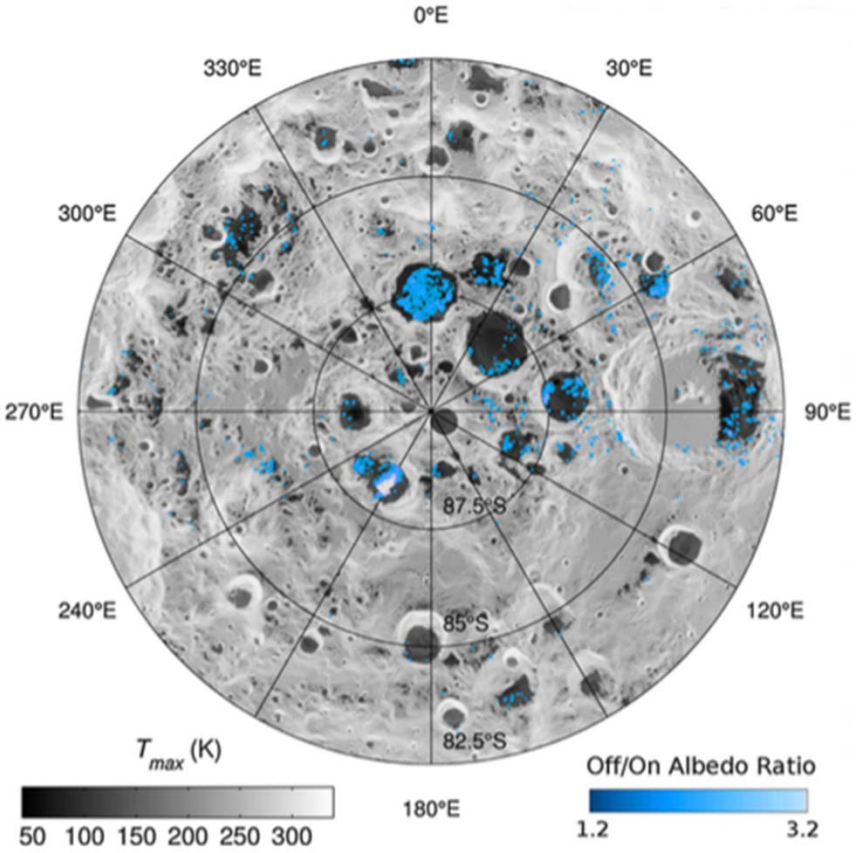
Existing Data: DISTRIBUTION

- **Heterogeneous lateral distribution**

- **Surface frost**
  - **Signature of water ice at 165 nm - analysis shows surface frost is not evenly distributed in cold regions.**

  - **LRO LAMP data - low illumination with very coarse spectral binning, thus are better as supporting data than standing alone.**

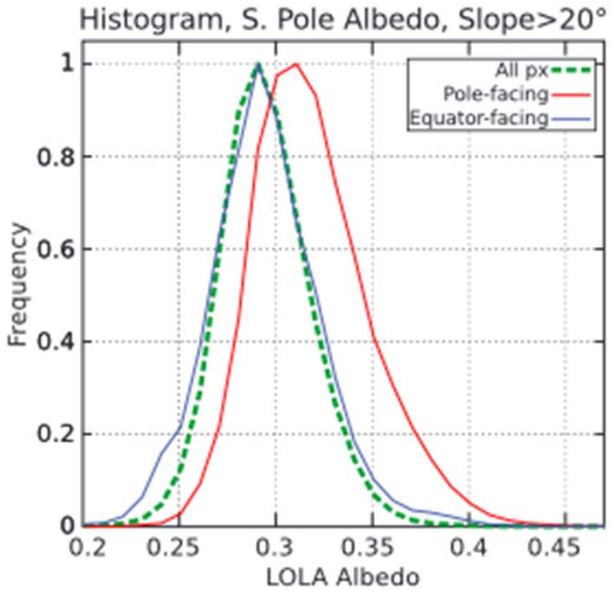
Hayne et al. (2015) Icarus

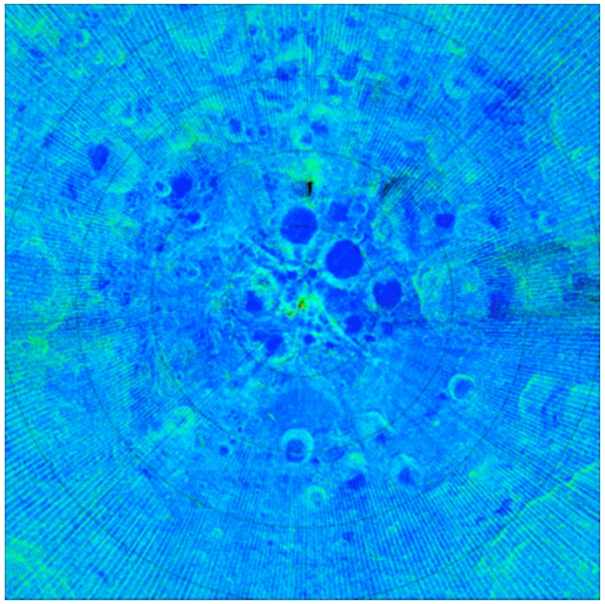


Existing Data: DISTRIBUTION

- **Apparent difference in equator-facing slopes and poleward-facing slopes.**
- **LRO LAMP Lyman Alpha albedo and LOLA 1064 nm albedo show difference in poleward-facing slopes.**
- **Multiple effects can produce these including the presence of frost, but no certain conclusions can be drawn on these data alone.**

Lucey et al. (2014) JGR

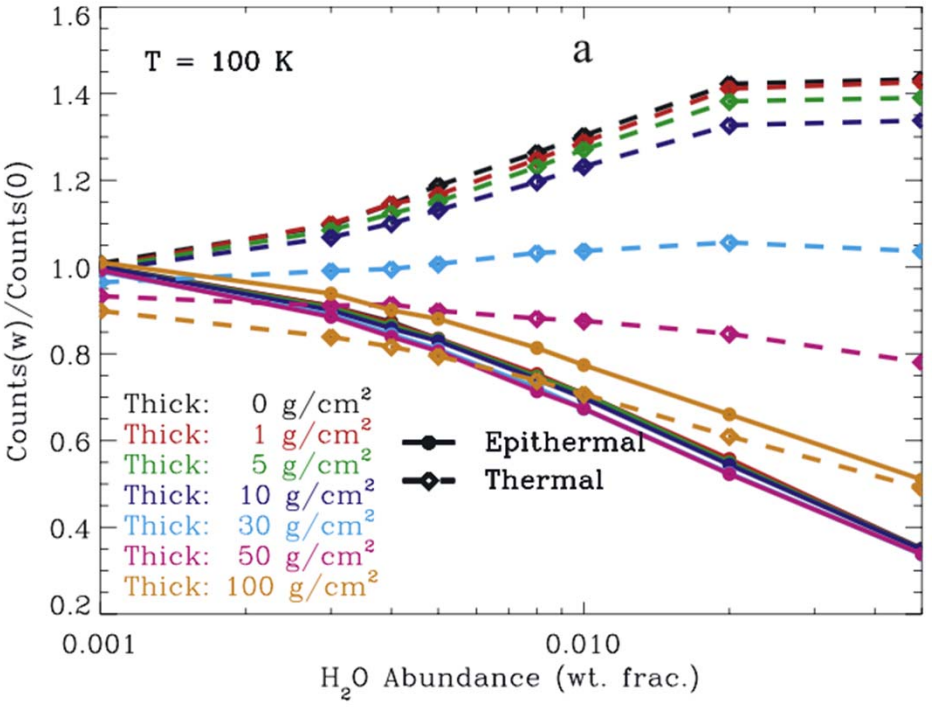




Gladstone et al. (2012) JGR

Existing Data: DISTRIBUTION

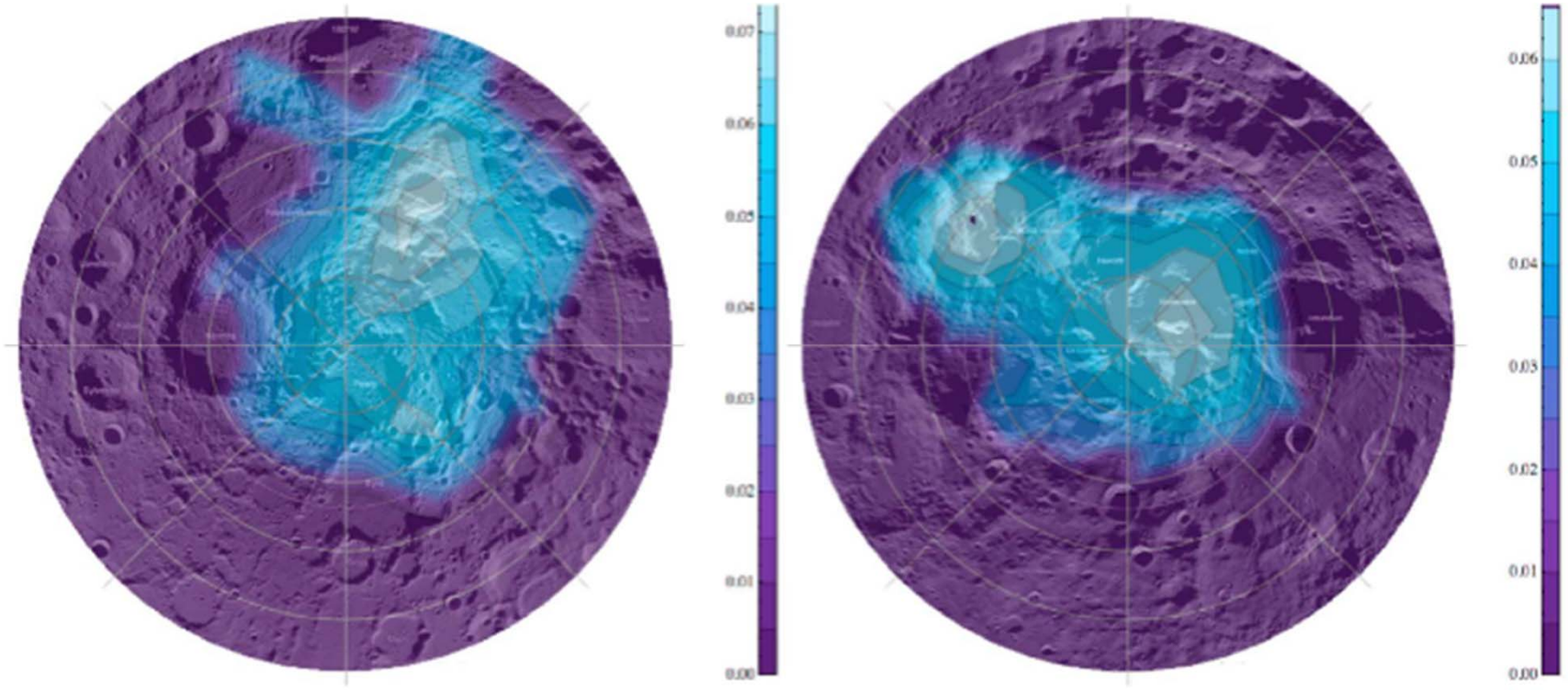
- **Neutron spectroscopy senses through the top 1-2 m of regolith.**
  - **Depth integrated measurements differ from surface frost measurements: Shoemaker and Haworth.**
  - **Comparing neutron data from different energy ranges gives idea of depth distribution.**
  - **Many sites are most consistent with a dry layer* about 10 cm thick over top of a layer with higher hydrogen abundances.**
  - ***Dry = average lunar background. Apollo data indicate 100-200 ppm background***



Lawrence et al. (2006) JGR

Existing Data: ABUNDANCE

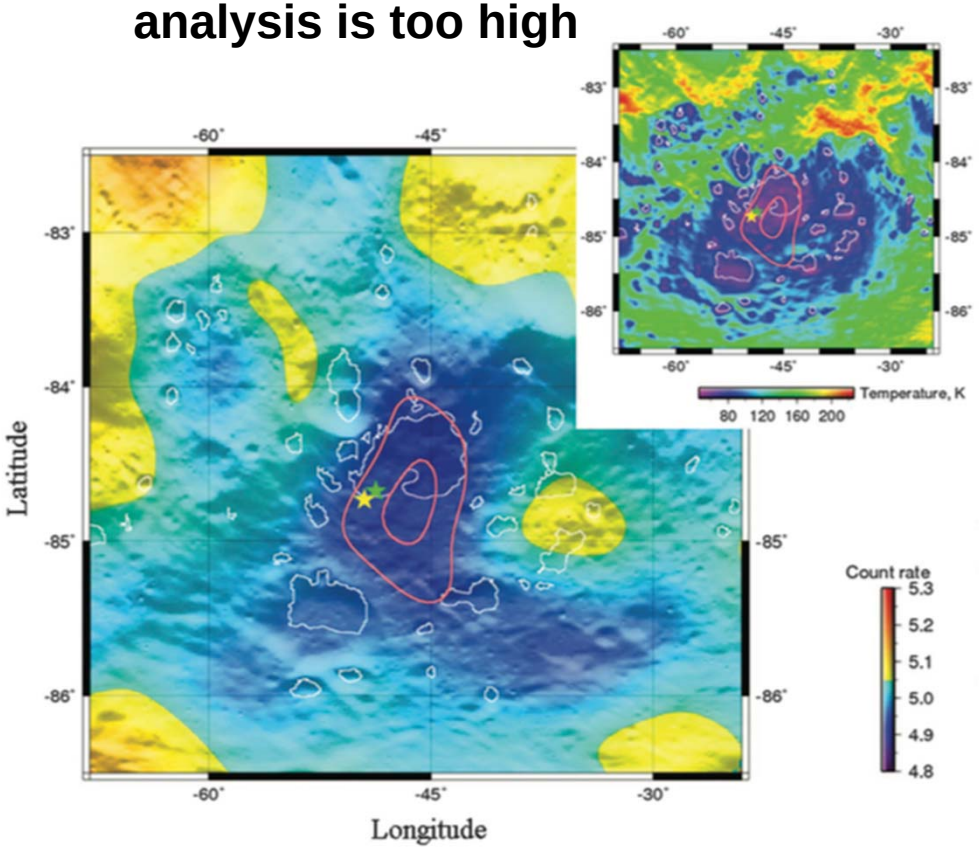
- **Neutron data – Hydrogen abundance (H, OH, H_2O, C_2H_6O)**
  - **Average 0.01% wt. water equivalent hydrogen poleward of 80° and in the top 1-2 m**
  - **If water, amounts to 9.8 x 10^{10} kg (1/1000 of Lake Tahoe)**



Miller et al (2012) JGR

Existing Data: DISTRIBUTION/ABUNDANCE

- **Sub-pixel heterogeneity**
- **LCROSS plume was consistent with 5 ± 3% water**
  - **Impact excavated to a depth of ~3 m and diameter ~20 m**
  - **Impact may be shallow Apollo S-IVB**
- **LEND neutron data are consistent with 0.45% water in Cabeus**
  - **Neutrons are sensitive to hydrogen content in top m**
  - **Neutron spatial resolution is >>> 20 m**
- **Possible explanations**
  - **Impact site was enriched laterally compared to surroundings**
  - **Water is enriched below 1 m depth**
  - **Inferred abundance from LCROSS analysis is too high**



Mitrofanov et al (2010) Science

Existing Data: PHYSICAL FORM

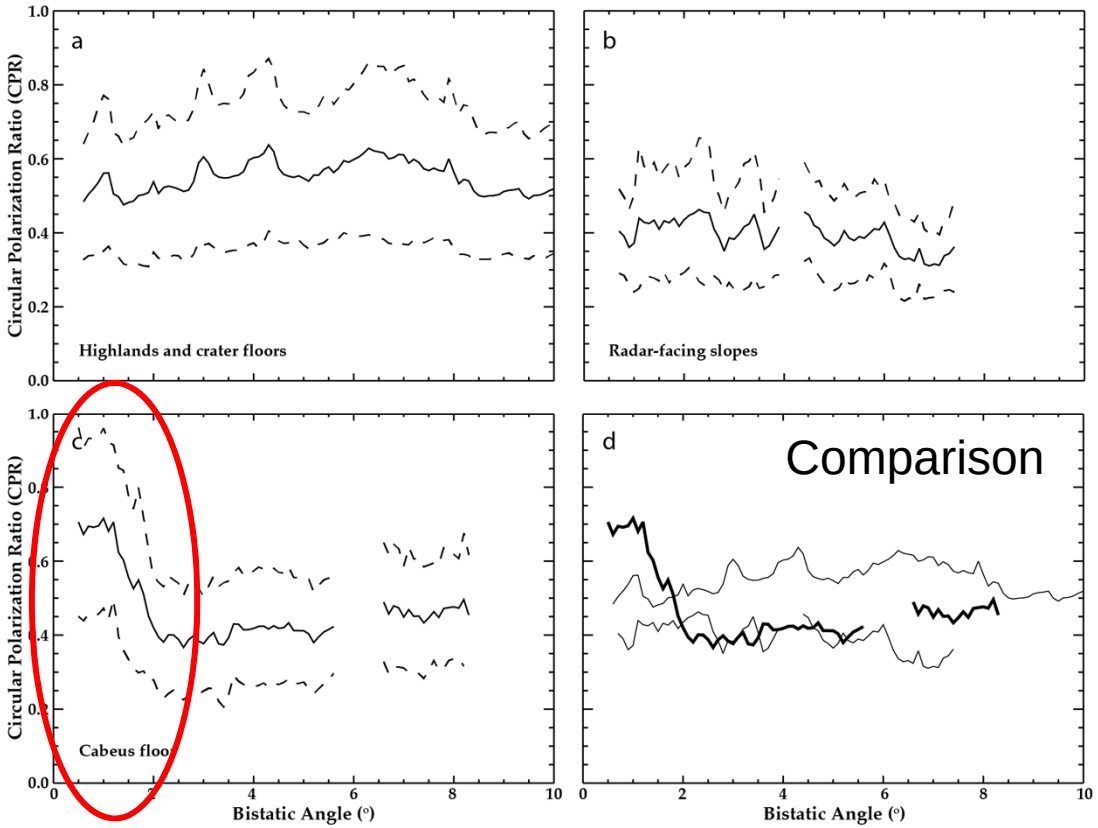
- **Radar data**

- **Coherent backscatter is sensitive to relatively pure blocks of ice of scale >10 cm.**
  - **On Mercury, radar data are consistent with thick, continuous, pervasive ice sheets in cold regions. Visible in MESSENGER images.**
  - **On the Moon, some craters show an anomalous signal where high circular polarization ratio (CPR) is observed inside the crater but not in the ejecta, unlike the majority of fresh craters.**
    - **Spudis et al. interpret these as craters that have ice at the bottom.**
    - **This a controversial interpretation.**

- **We can rule out pervasive "skating rinks" on the Moon.**
  - **We don't need the Zamboni.**

Existing Data: PHYSICAL FORM

- **Bistatic radar uses the change in circular polarization as a function of phase angle to distinguish rock from ice.**
  - **Mini-RF data from Cabeus are consistent with ice present on the floor of Cabeus.**



Patterson et al. in review

Summary: State of the Art

Question	Answer	Data Needed
Composition	H_2O – LCROSS Hydrogen-bearing material may / may not be water ice Hg, CO, H_2S, NH_3, and potentially hydrocarbons	*In situ sampling, sample return, isotopic analysis, active spectroscopy*
Distribution	Heterogeneities exist on many scales Latitudinal, Slope, Depth, Lateral Pole-ward of 80°: ~10^{11} kg of water PSRs: 1-2% by weight if H is water Surface measurements: <2% frost	*In situ sampling with subsurface access, bi-static radar, higher spatial resolution mapping*
Form	Blocks suggested. Smaller ice grains have been detected. Small amounts of surface frost possible. Pore-filling ice and hydrated minerals are also possible.	*In situ sampling, sample return, active spectroscopy*

Conclusions

- Water ice has been confirmed to exist in Cabeus crater through spectroscopic detection.
  - Other volatiles including Hg, CO, and H_2 have also been detected.
  - In situ sampling and isotopic data are not yet available.
- Ice in lunar polar regions has a heterogeneous distribution both horizontally and with depth.
  - Processes of scientific interest produce the heterogeneity.
  - The heterogeneity drives the design of any mission to sample volatiles in situ on the Moon.
  - Data with better spatial resolution will improve planning of operations for ISRU.
- Hydrogen-bearing material, if in the form of water, has an abundance of ~1-2% by weight integrated over the polar regions and 1-2 m depth.
- Large, thick, coherent ice deposits have been ruled out.
  - Small ice blocks ~10 cm, pore-filling ice, hydrated minerals, and frosts are still possibilities