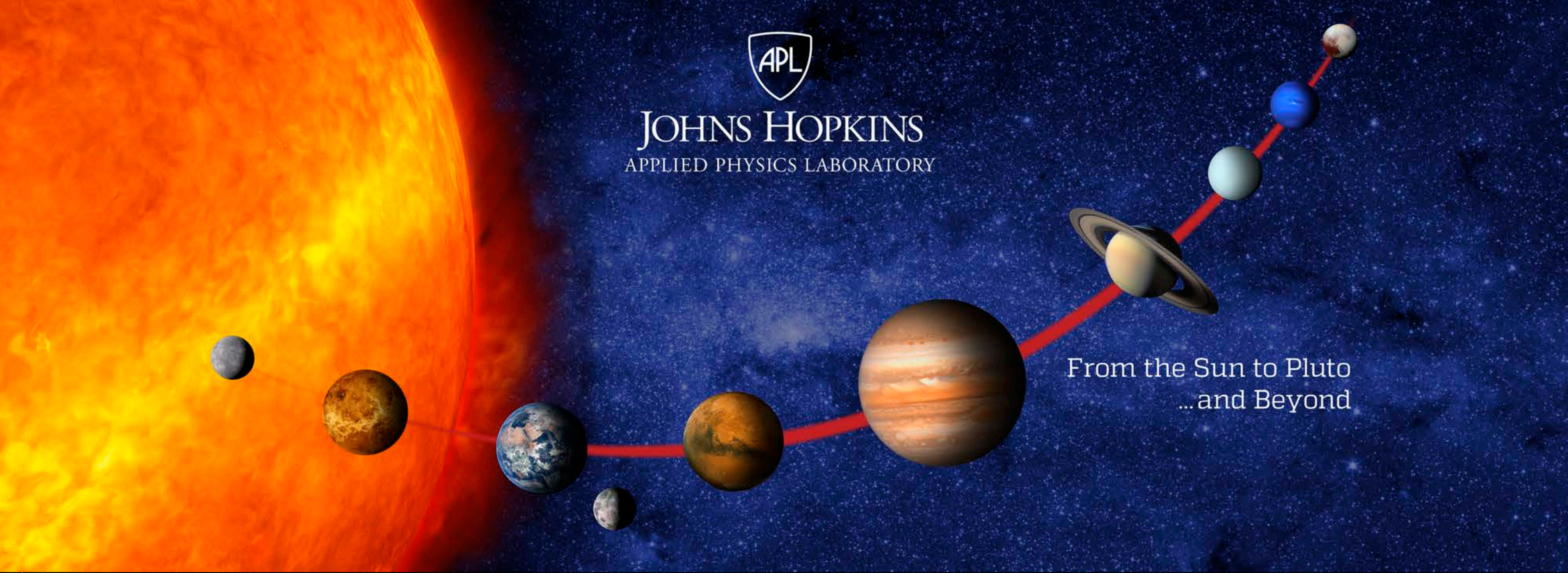
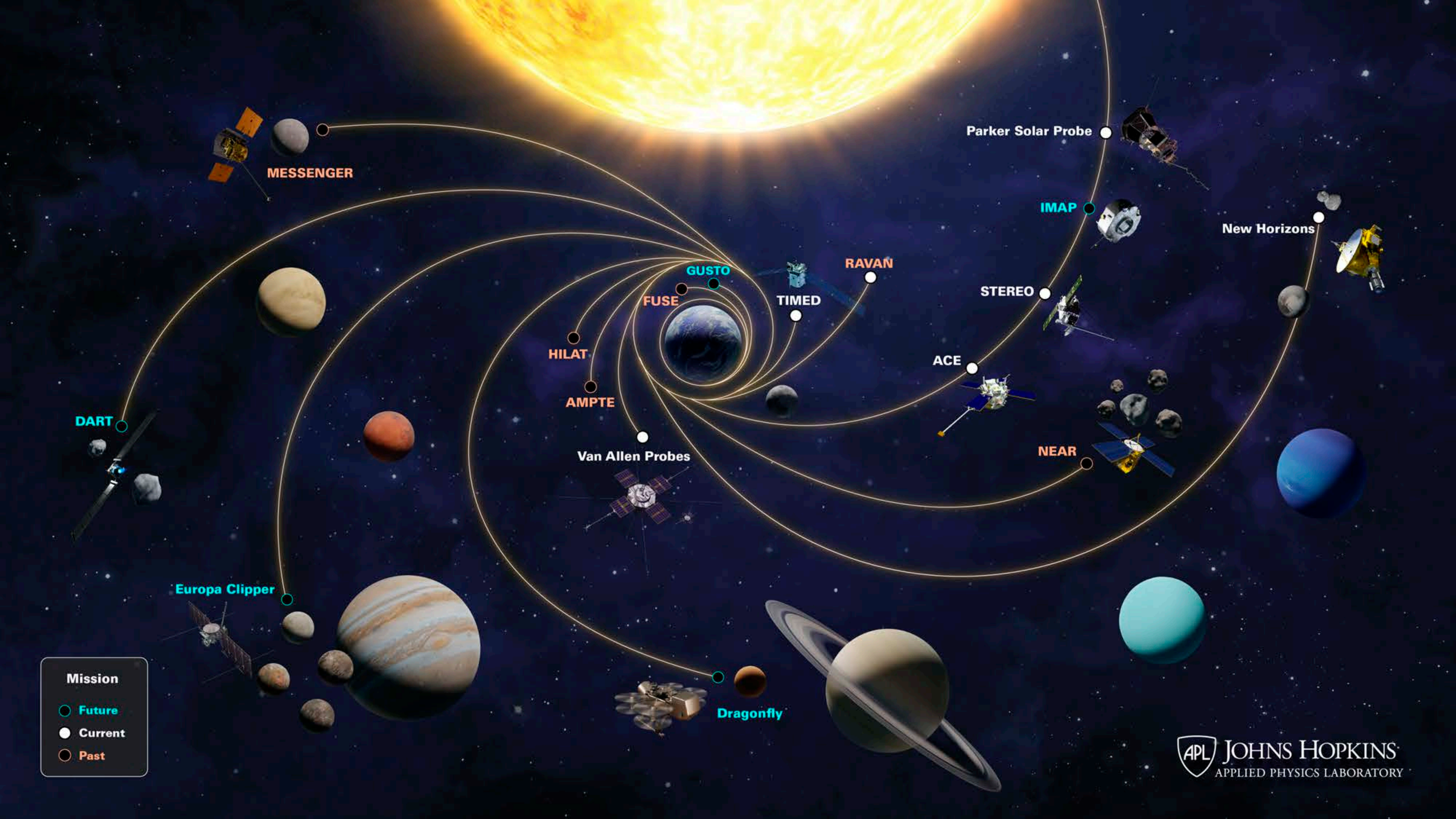


JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Lunar Polar Volatiles

A Primer

Dana Hurley and Parvathy Prem
Johns Hopkins Applied Physics Laboratory
Dana.Hurley@jhuapl.edu; Parvathy.Prem@jhuapl.edu


MESSENGER
Parker Solar Probe
IMAP
New Horizons
GUSTO
RAVAN
FUSE
TIMED
STEREO
HILAT
ACE
AMPTE
DART
Van Allen Probes
NEAR
Europa Clipper
Dragonfly
Mission
Future
Current
Past
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

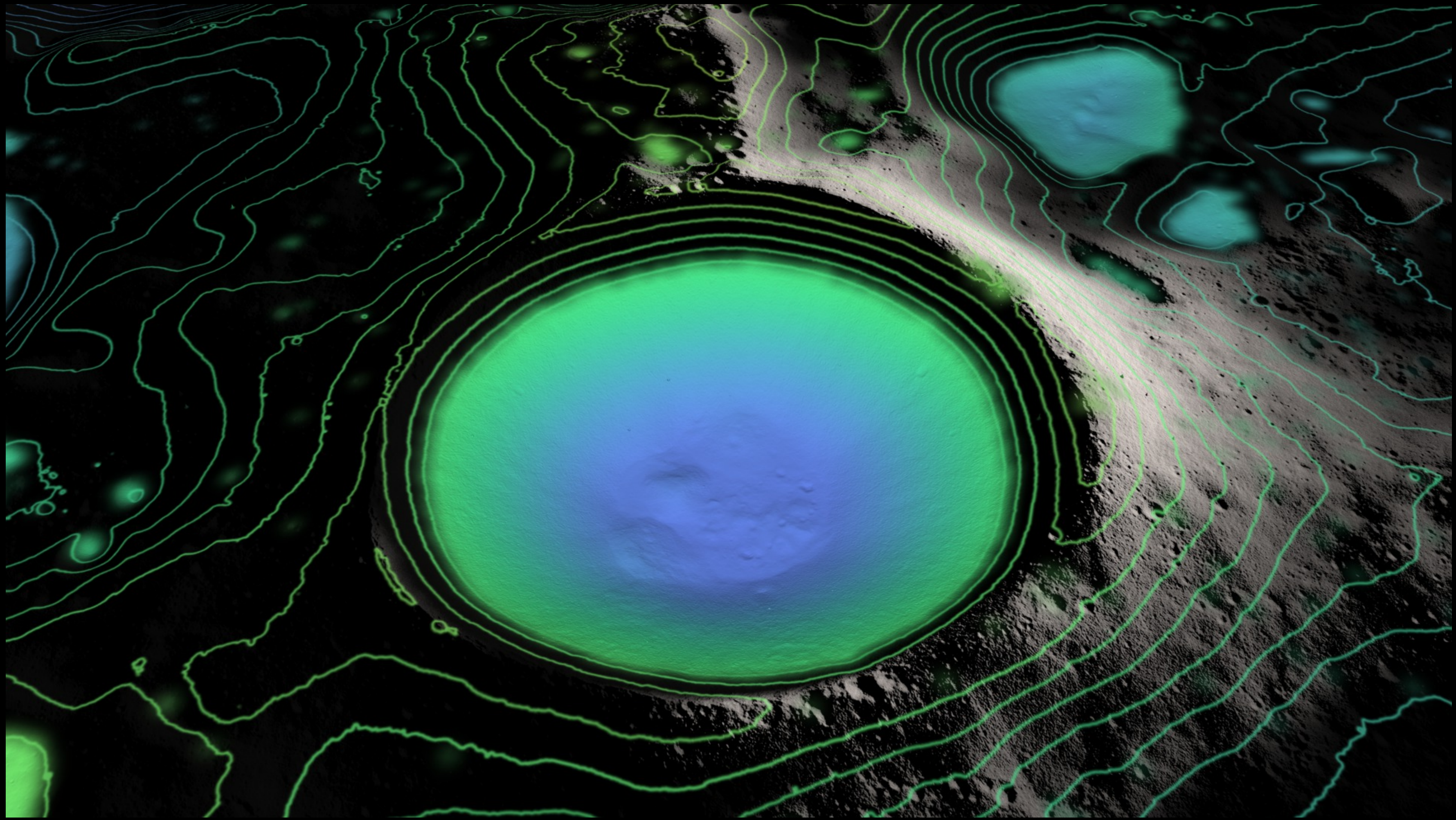
Introduction

- Background:
  - Lunar volatiles are potentially a valuable resource for exploration.
  - Lunar volatiles are a valuable scientific resource, holding information about sources and history of volatiles in the inner solar system.
  - 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.
- Purpose:
  - To provide an overview of the present state of knowledge.
  - To explain the level of certainty/uniqueness of the results.
  - To discuss the interplay between exploration and science.

Volatiles on the Moon

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

Lunar Permanently Shadowed Regions

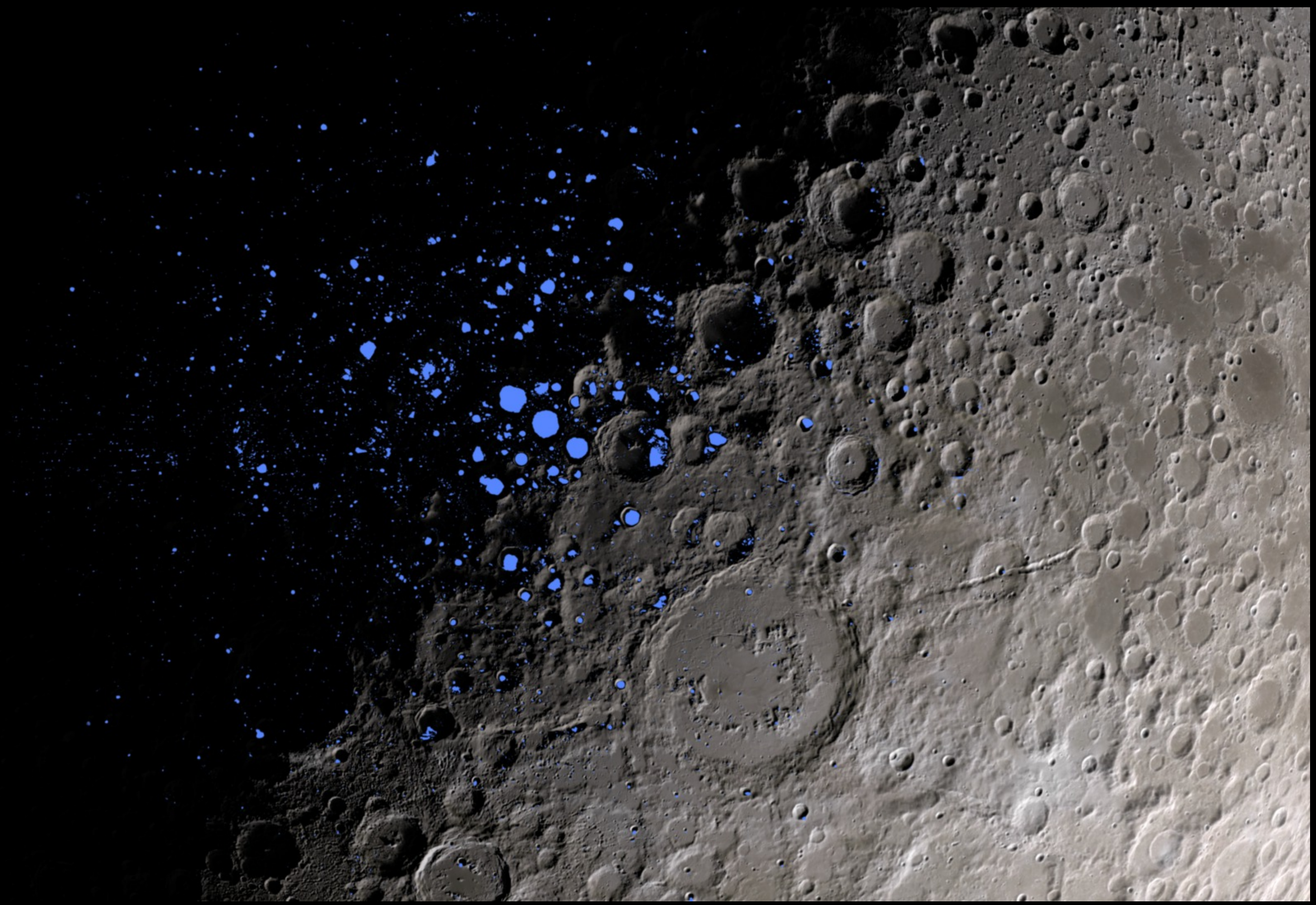


NASA SVS

- Low obliquity.
- At high latitudes, topography creates permanently shadowed regions.
- >10^4 km^2 area of PSR.
- These exist on size scales ranging from sub-mm to 10 km.

https://svs.gsfc.nasa.gov/4043

Lunar Permanently Shadowed Regions



NASA SVS

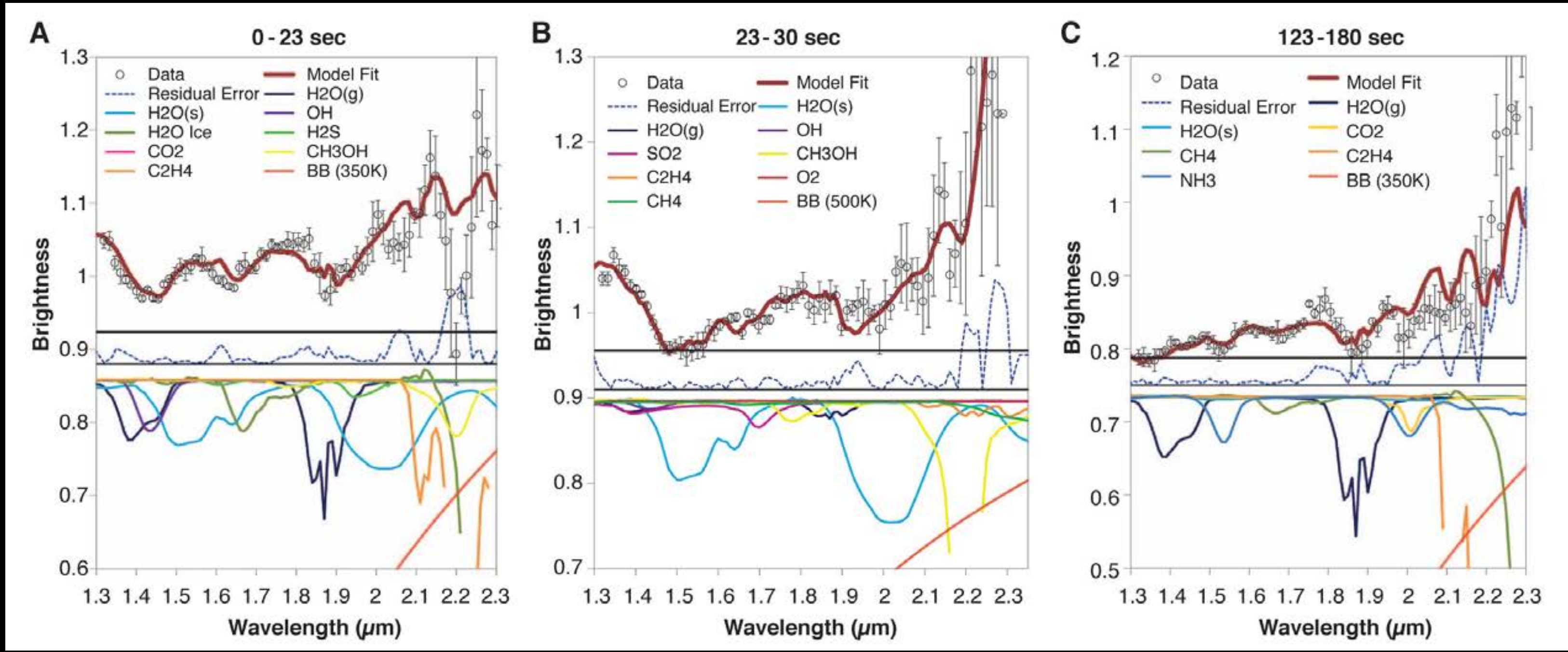
- Low obliquity.
- At high latitudes, topography creates permanently shadowed regions.
- $>10^4$ km^2 area of PSR.
- These exist on size scales ranging from sub-mm to 10 km.
- Cold traps can exist on scale sizes from cm to 10 km.
- They extend to latitudes below 75°.

Measurements of Polar Volatiles (Water Ice)

- Current focus – Obtaining measurements of the following quantities:
  - Abundance.
    - Exploration rationale: assess value and extraction technique.
    - 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

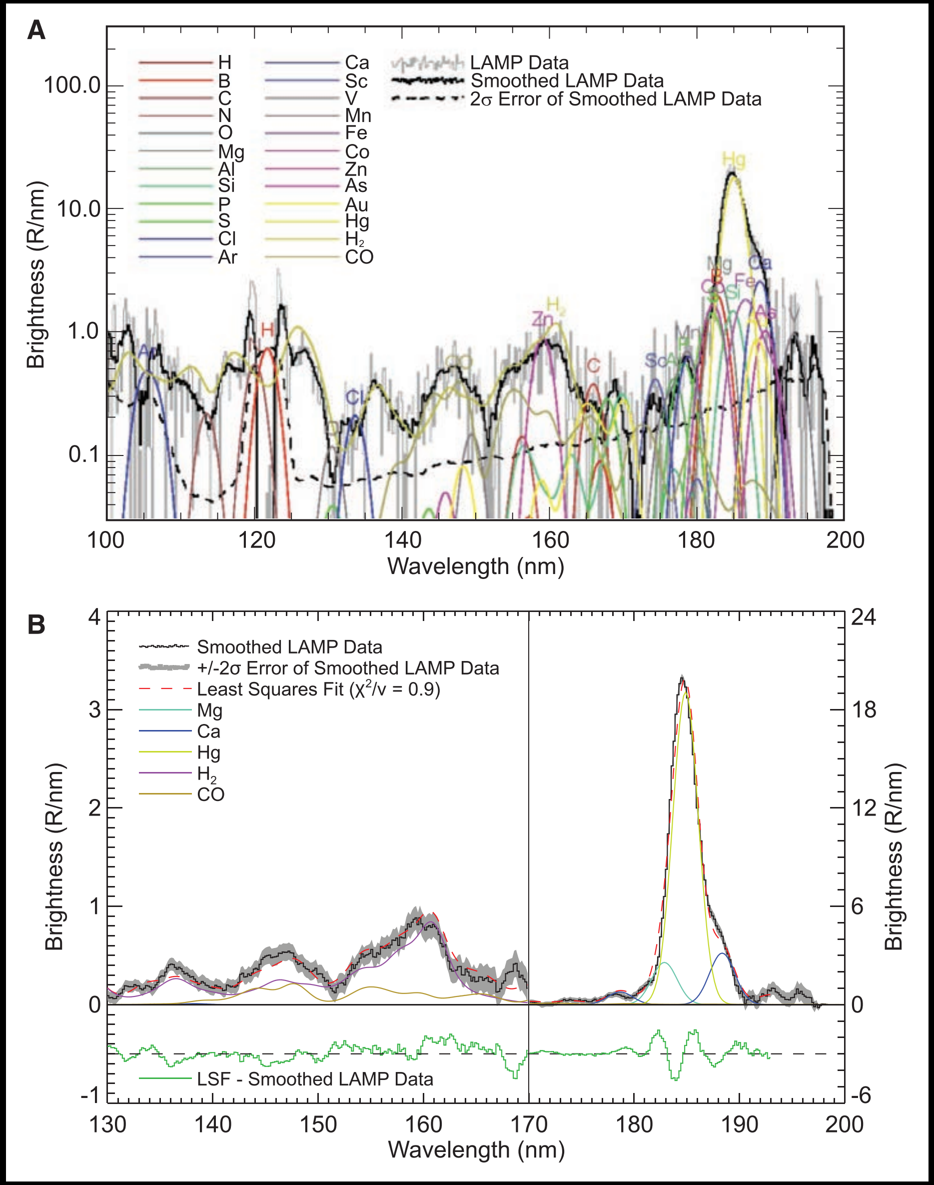
- LCROSS impact into Cabeus.
- Spectral identification of water in both solid and gas phases.
  - High resolution spectra provide strong evidence for the chemical composition.
  - LCROSS measurement has advantage of having lofted material into sunlight providing a strong illumination source.
  - Question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



Colaprete et al. (2010) Science

Existing Data: COMPOSITION

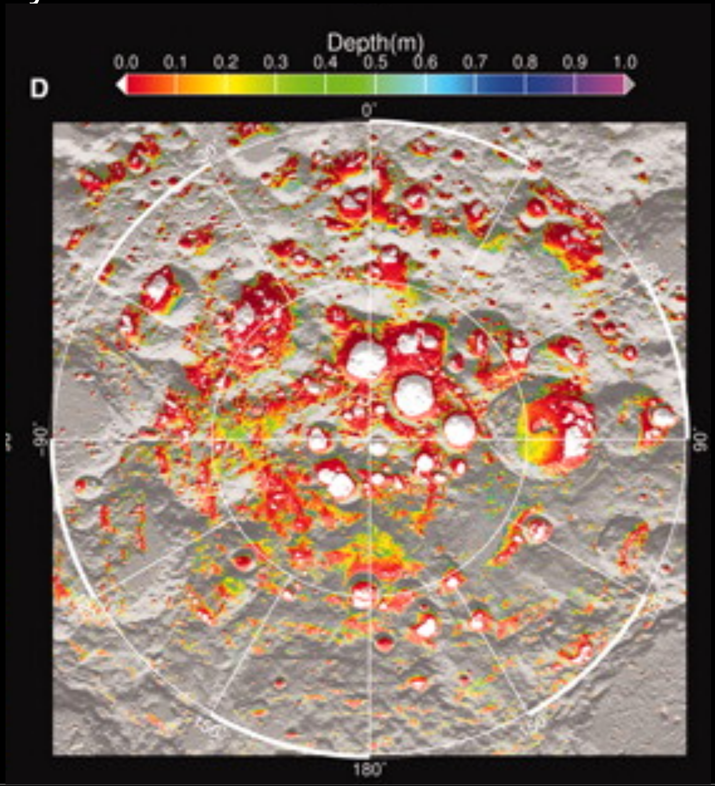
- LCROSS impact into Cabeus.
- Spectral identification of other volatiles in the vapor.
- From LCROSS:
  - H_2S, SO_2
  - NH_3, CO_2
  - Hydrocarbons
  - OH
- From LRO:
  - Hg, Mg, and/or Ca
  - CO
  - H_2
- From ground:
  - Na

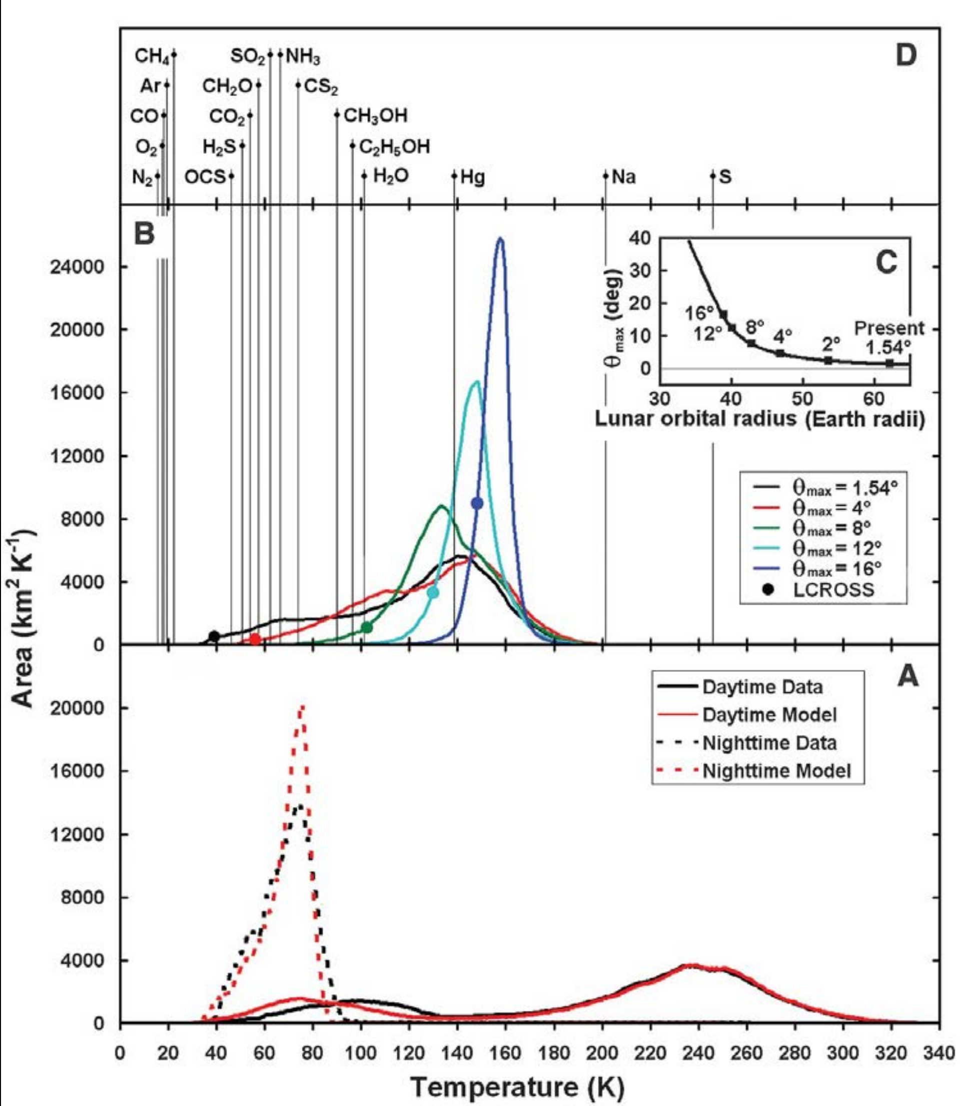


Gladstone et al. (2010) Science

Existing Data: COMPOSITION & DISTRIBUTION

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

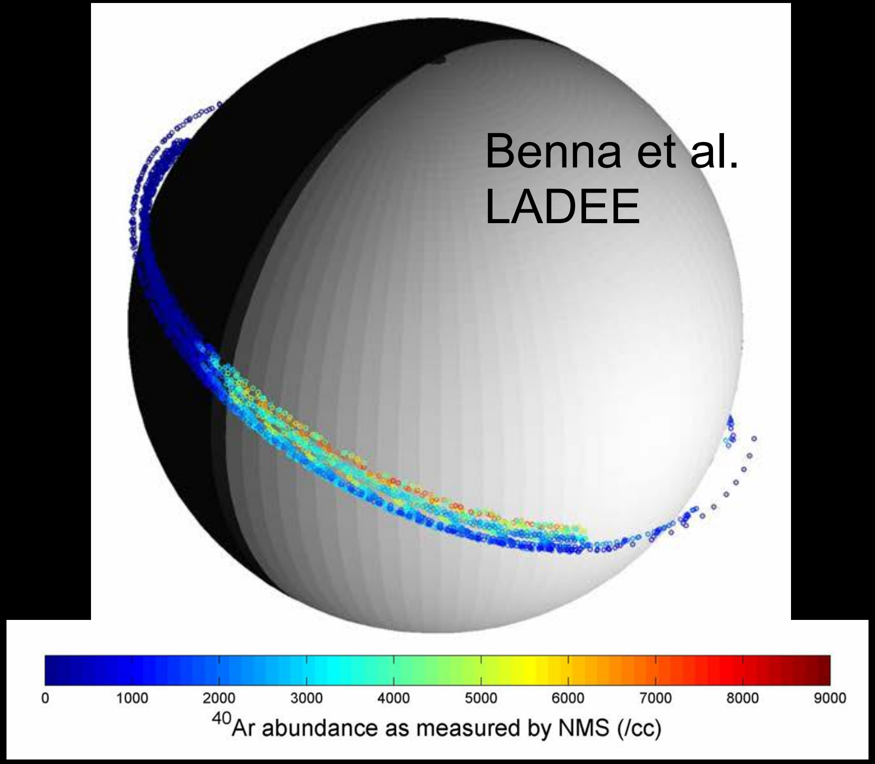


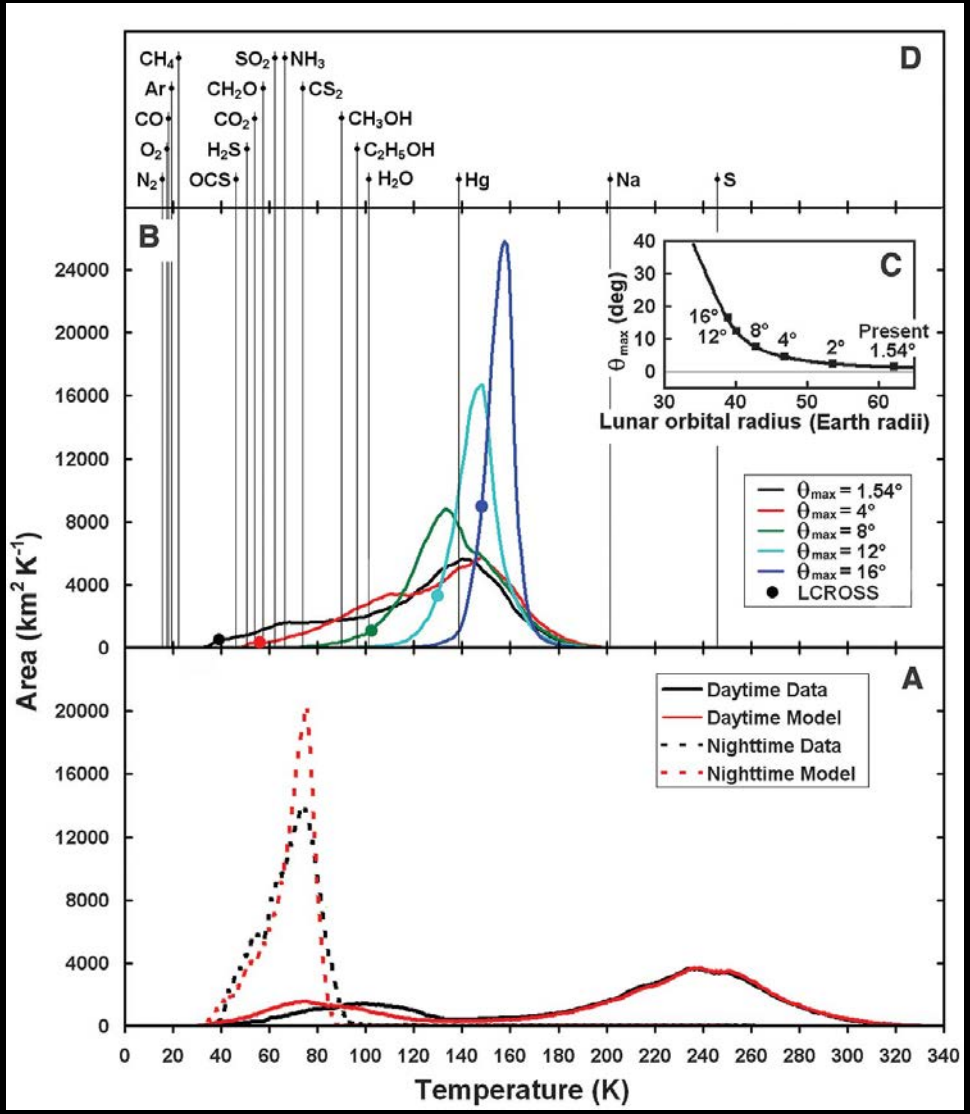


Paige et al. (2010) Science

Existing Data: COMPOSITION & DISTRIBUTION

- However we know that some exospheric species adhere to the surface at higher temperatures.
- Timescale and surface interactions are important.



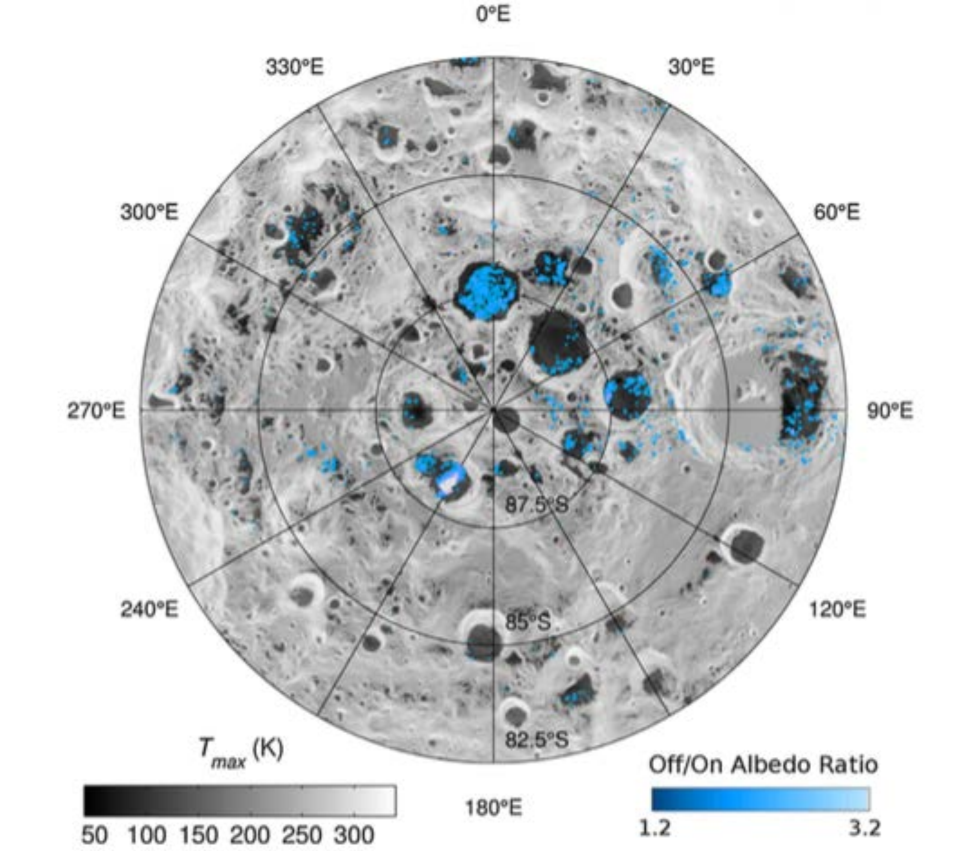


Paige et al. (2010) Science

Existing Data: DISTRIBUTION

- Heterogeneous lateral distribution.
  - Within a single PSR.
  - From one PSR to another.
- Surface frost.
  - Using the signature of water ice at 165 nm, this analysis shows that surface frost is not evenly distributed in cold regions.
  - LRO LAMP data are low illumination with very coarse spectral binning, thus are better as supporting data than standing alone.

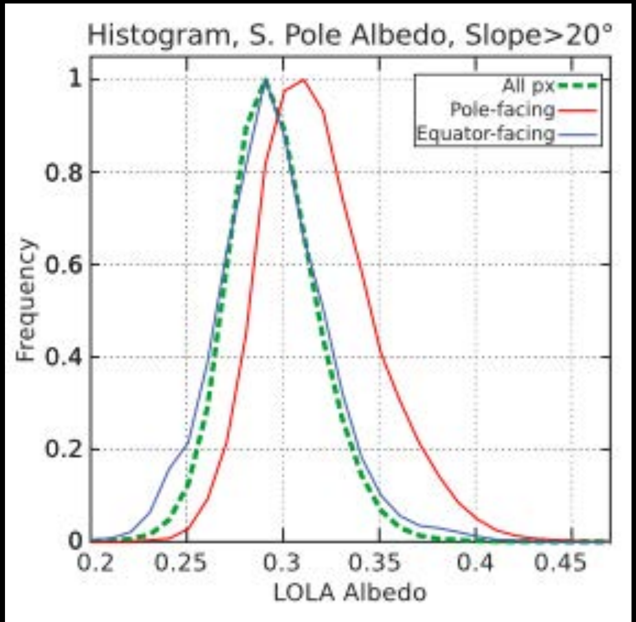
Hayne et al. (2015) Icarus

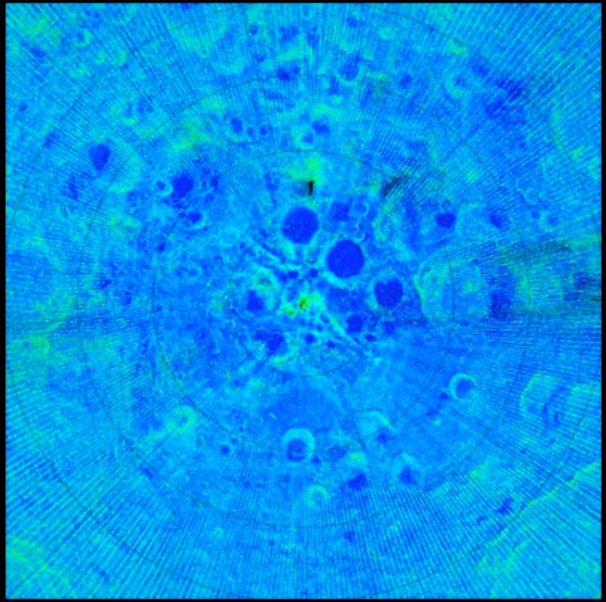


Existing Data: DISTRIBUTION

- 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

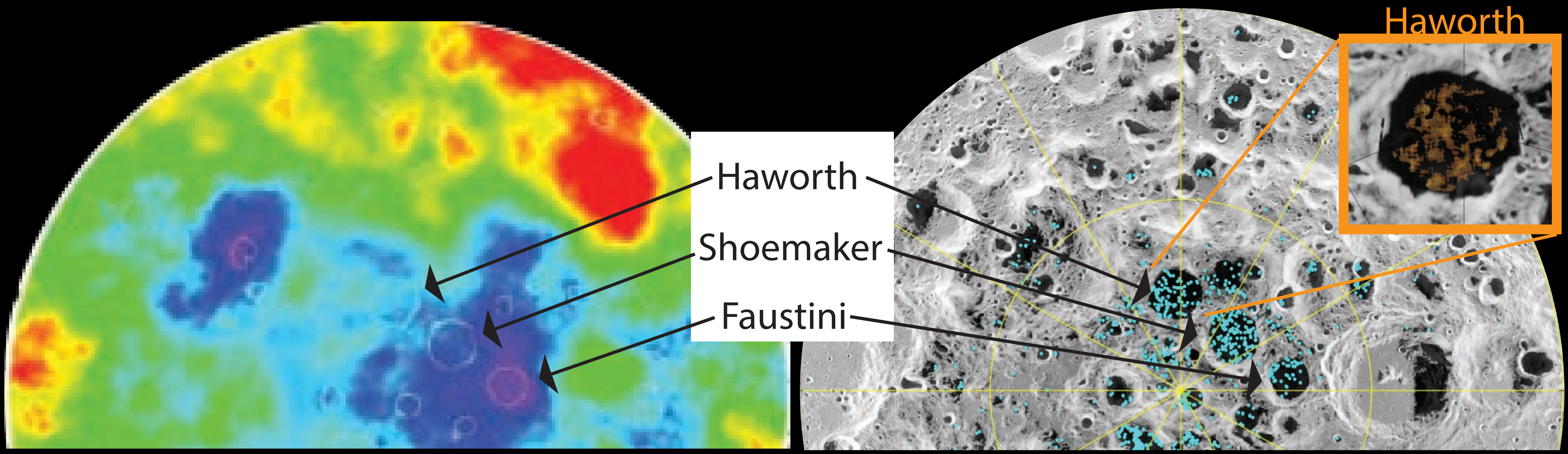




Gladstone et al. (2012) JGR

Existing Data: DISTRIBUTION

- Neutron spectroscopy senses through the top 1 m of regolith.
- IR spectroscopy senses the top 1 mm of the surface.
  - Hydrogen values from depth-integrated measurements differ from surface frost measurements, especially in Shoemaker, Haworth, and Cabeus.

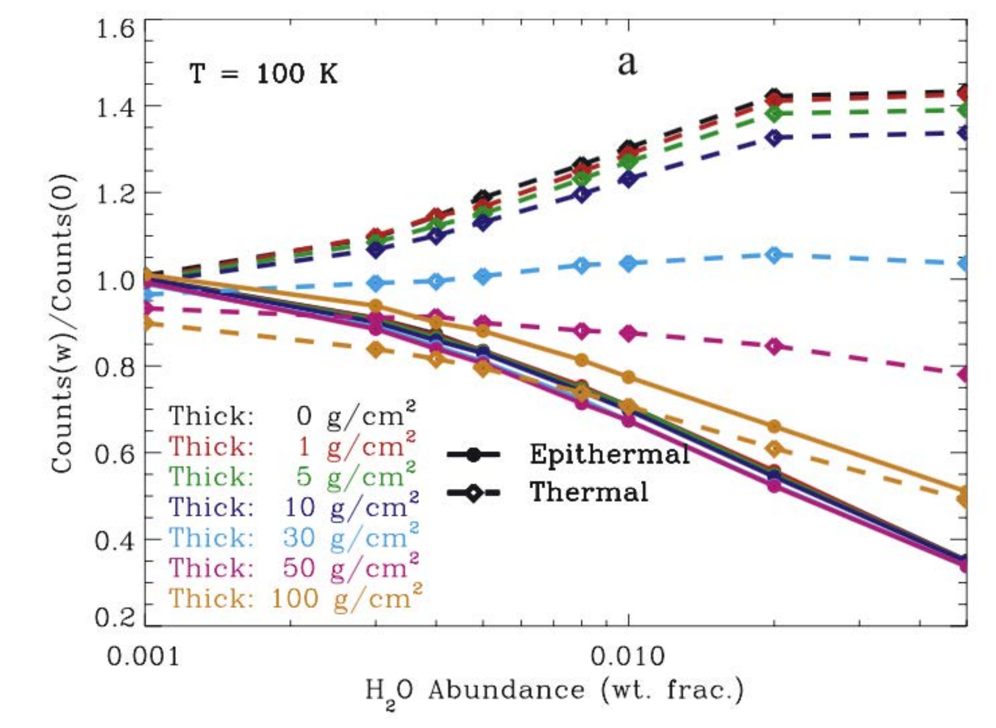


McClanahan et al., 2018

Li et al., 2018

Existing Data: DISTRIBUTION

- Neutron spectroscopy senses through the top 1 m of regolith.
  - 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.

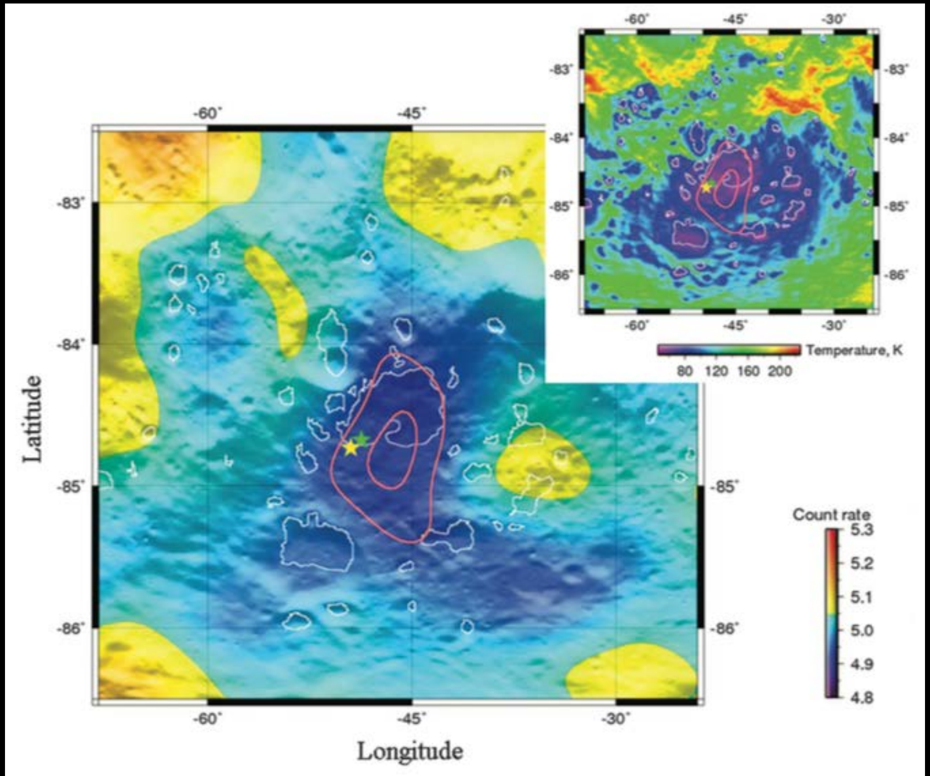


Lawrence et al. (2006) JGR

Existing Data: DISTRIBUTION/ABUNDANCE

- Sub-pixel heterogeneity.
- The LCROSS plume was consistent with 5% ± 3% water.
  - Impact excavated to a depth of ~3 m and diameter ~20 m.
- 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.

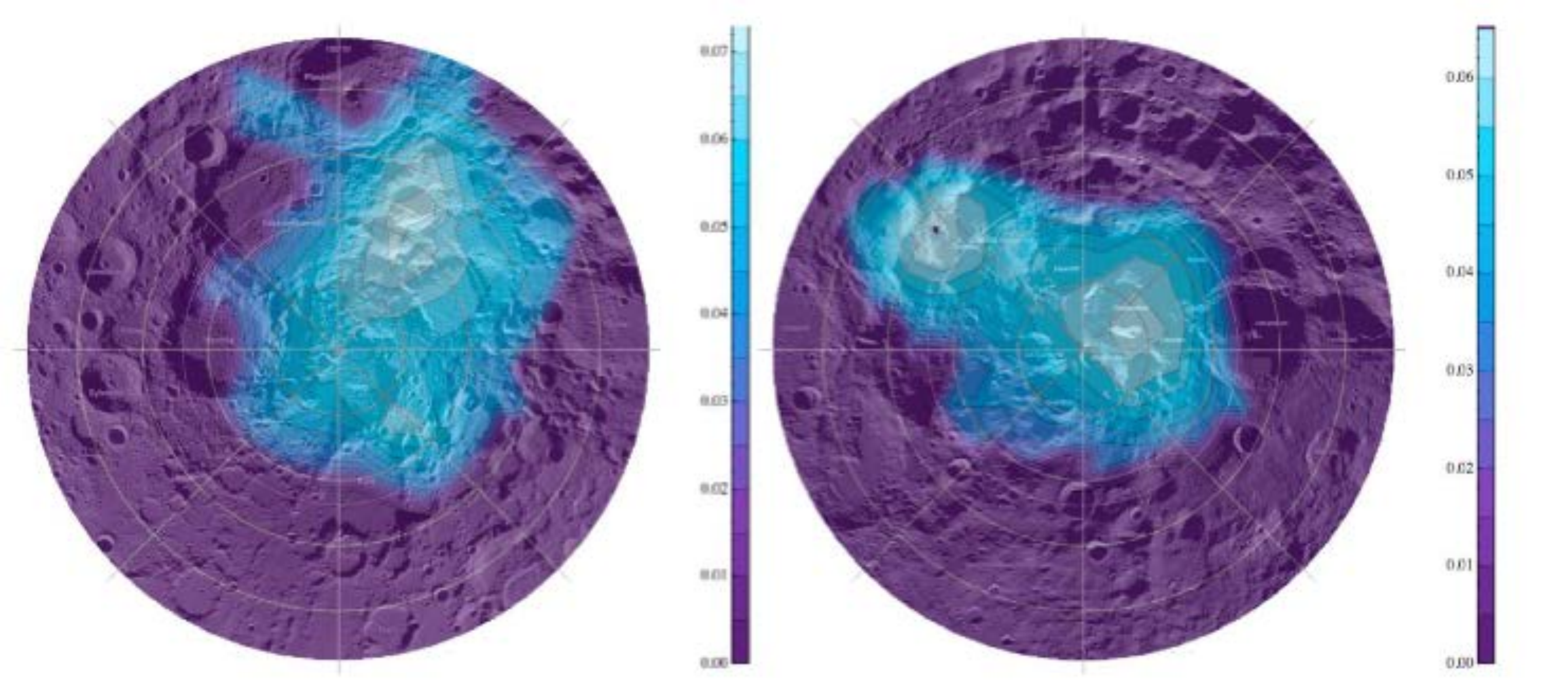
- **Possible explanations:**
  - **Impact site was enriched laterally compared to surroundings.**
  - **Water is enriched below 1 m depth.**
  - **Inferred abundance from LCROSS analysis is too high.**



Mitrofanov et al (2010) Science

Existing Data: ABUNDANCE

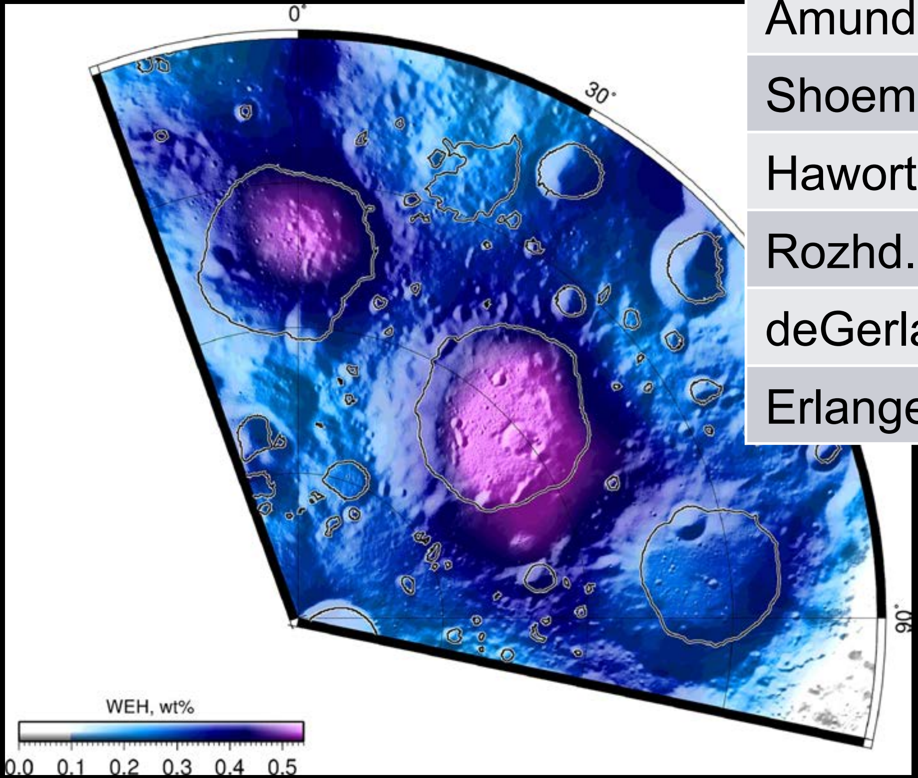
- Neutron data:
  - Average 0.01% wt. water equivalent hydrogen poleward of 80° and in the top 1 m.
  - If water, amounts to 9.8 x 10^{10} kg (1/1000 of Lake Tahoe or .3 mErie).



Miller et al (2012) JGR

Existing Data: ABUNDANCE

Crater Name	Mass of water in top 1 m (kg)	µEries (10^{-6} Lake Erie)	Lincoln Memorial Reflecting Pools
Cabeus	7.7×10^{10}	160	3900
Amundsen	5.1×10^{10}	110	2600
Shoemaker	1.9×10^{10}	40	970
Haworth	1.6×10^{10}	34	820
Rozhd. U	1.0×10^{10}	21	510
deGerlache	5×10^{9}	11	270
Erlanger	7×10^{8}	1.5	37



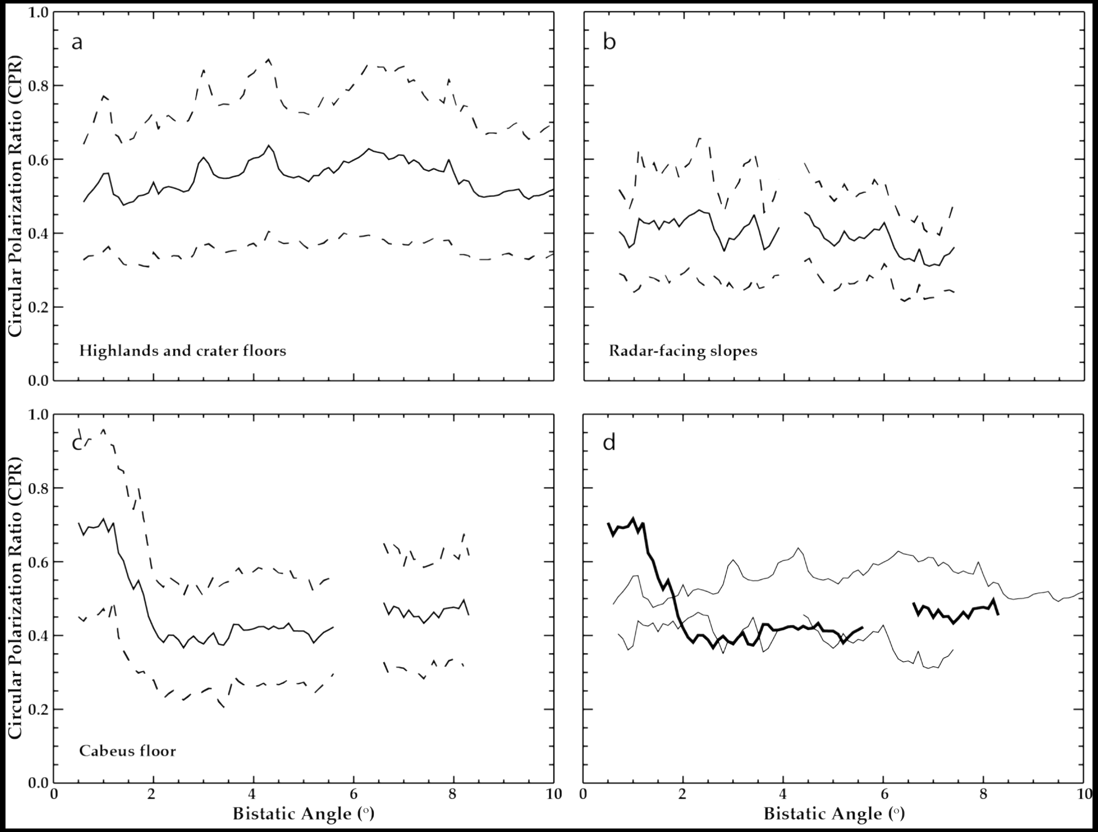
Sanin et al (2016) Icarus

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.
  - 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.

Existing Data: PHYSICAL FORM

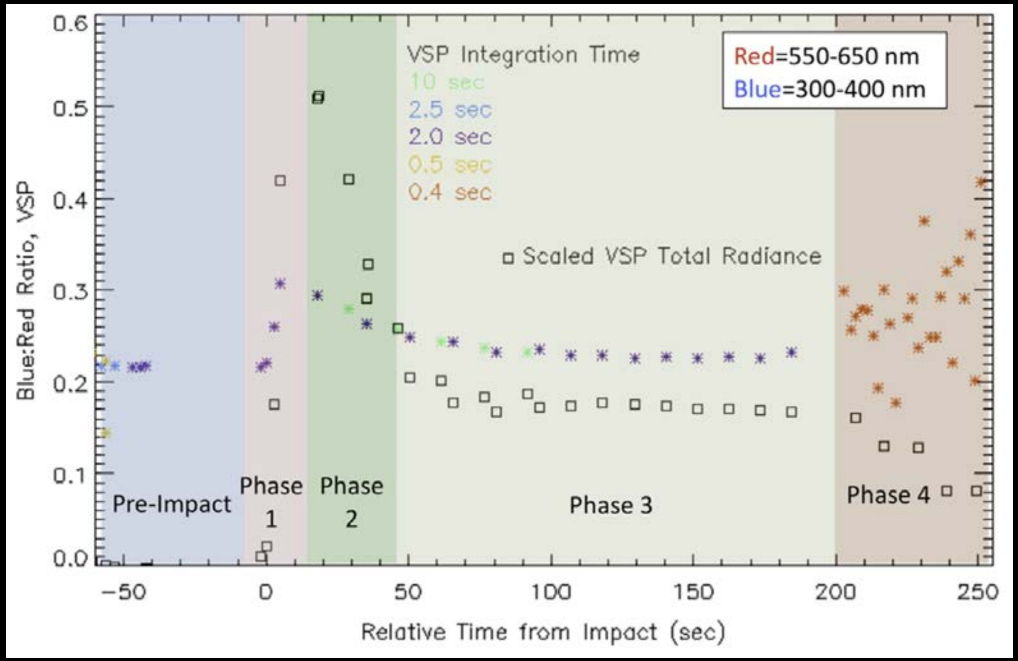
- Bistatic radar uses the change in circular polarization as a function of phase angle to distinguish rock from ice.
  - Mini-RF data from Cabeus are consistent with ice present on the floor of Cabeus.



Patterson et al. (2017) Icarus

Existing Data: PHYSICAL FORM

- LCROSS Visual Spectrometer.
- Increasing Blue/Red interpreted as decreasing grain size from sublimating ice.
- At least some ice is present in grains.

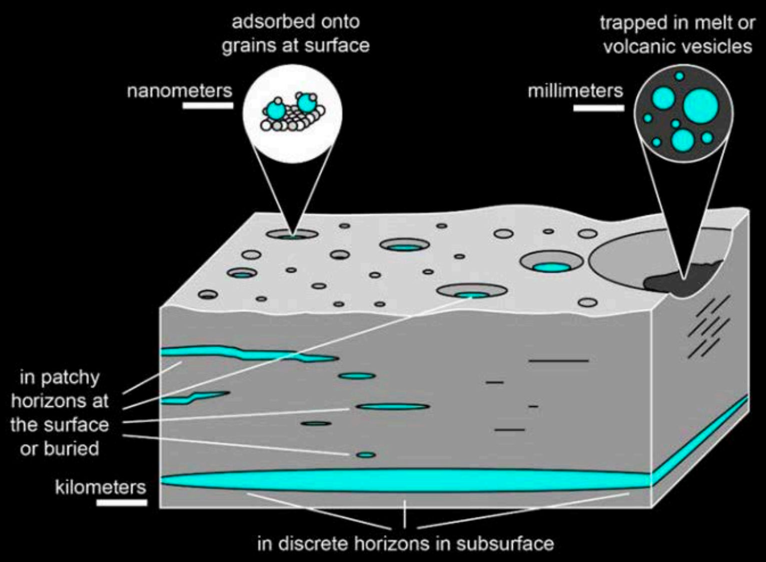


Heldmann et al., 2015

Processes for Polar Volatiles (Water Ice)

- Current focus: Understanding the lunar water system from source to sink.

Needham and Kring (2018)



SOURCES

Comets
Meteoroids
Outgassing/internal
Solar wind

SINKS

Sublimation/thermal desorption
Photodissociation
Impact
Sputtering
Chemistry

REDISTRIBUTION

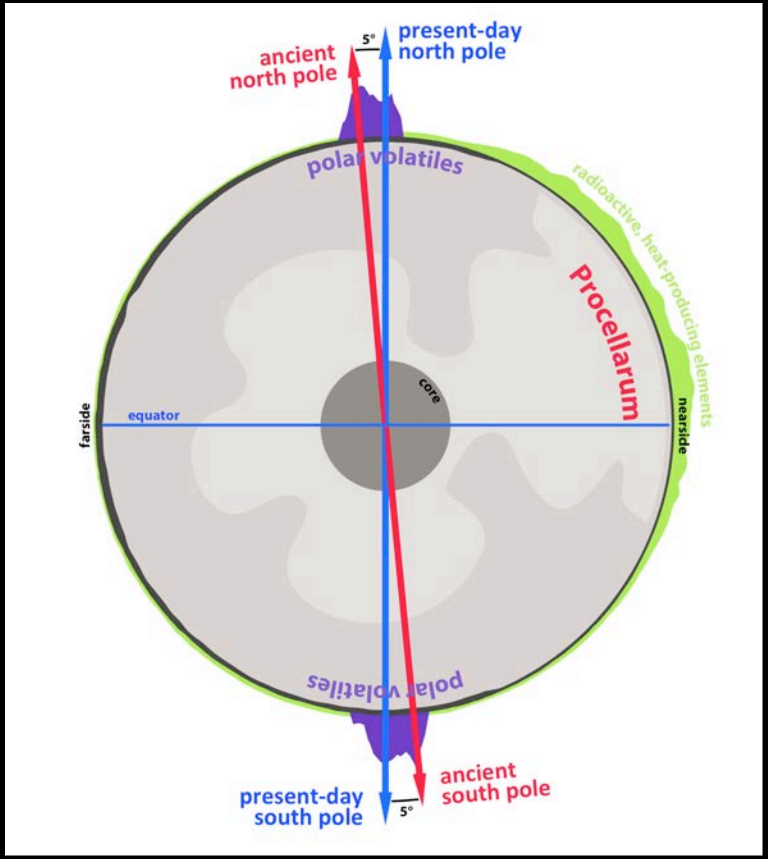
Migration/hopping
Migration/thermal vertical
Impact gardening

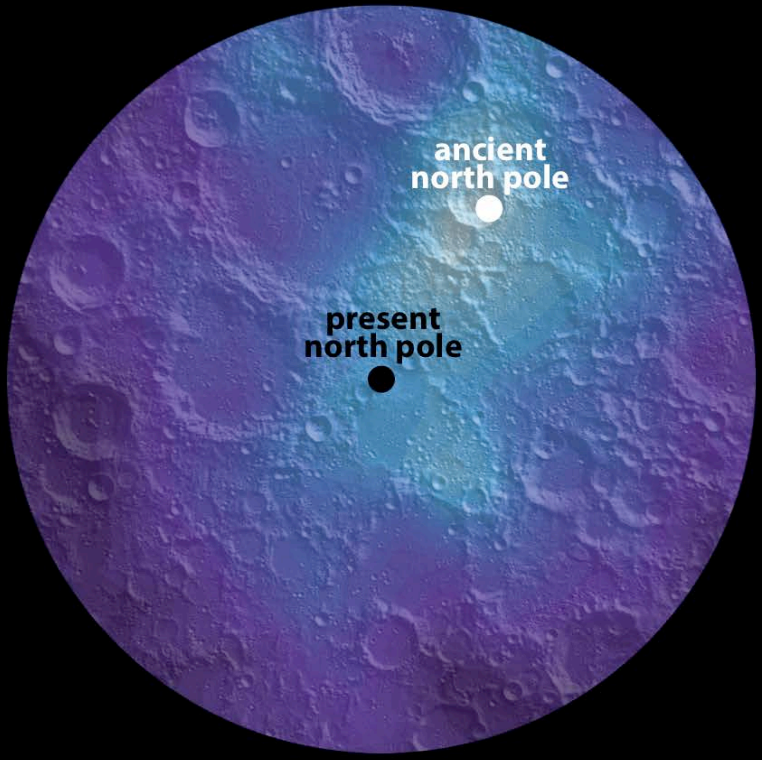
Ultimate Questions

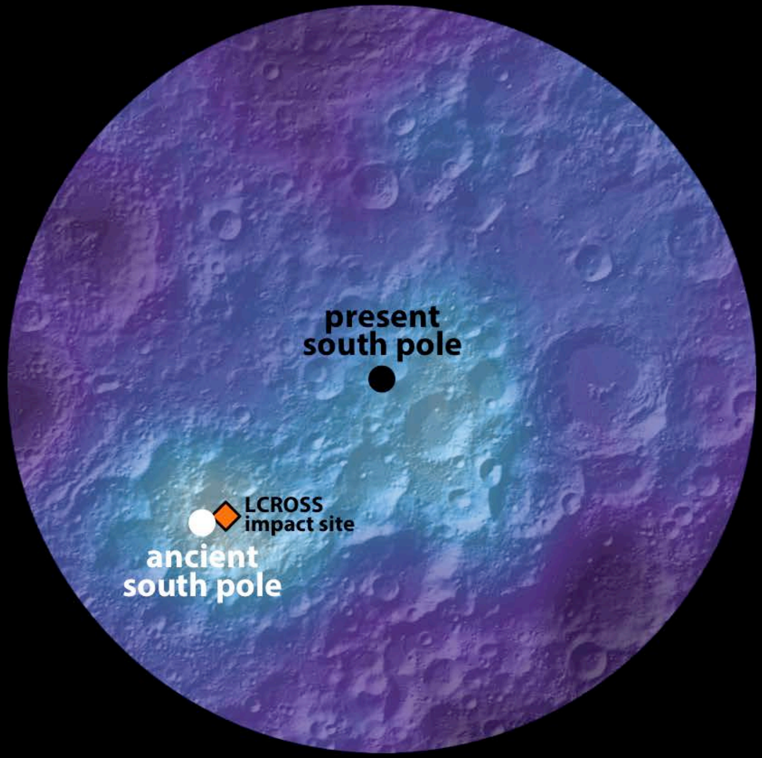
- What are the sources of volatiles and relative importance?
- What processes affect the delivery and retention of the volatiles?
- When were the volatiles introduced to the Moon?
- What do they tell us about the formation of the Moon, early volatiles in inner solar system?
- How do we mine and utilize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

Age: Lunar Polar Wander

- Enhancements off of the present day poles line up with potential locations of paleopoles.
- This would indicate that some of the hydrogen detected has been in place for billion of years.



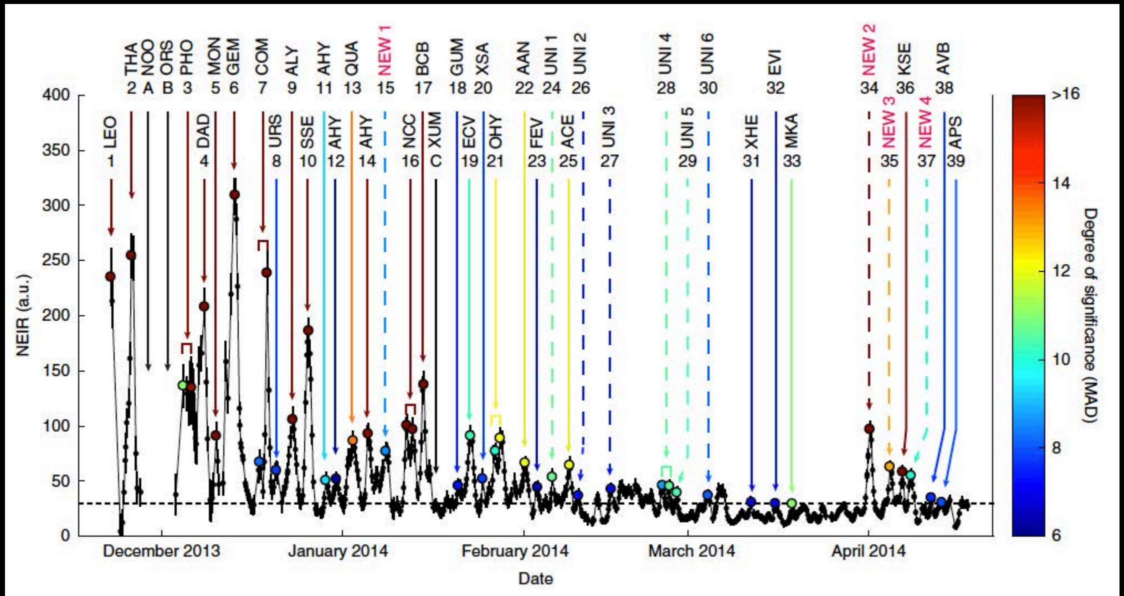




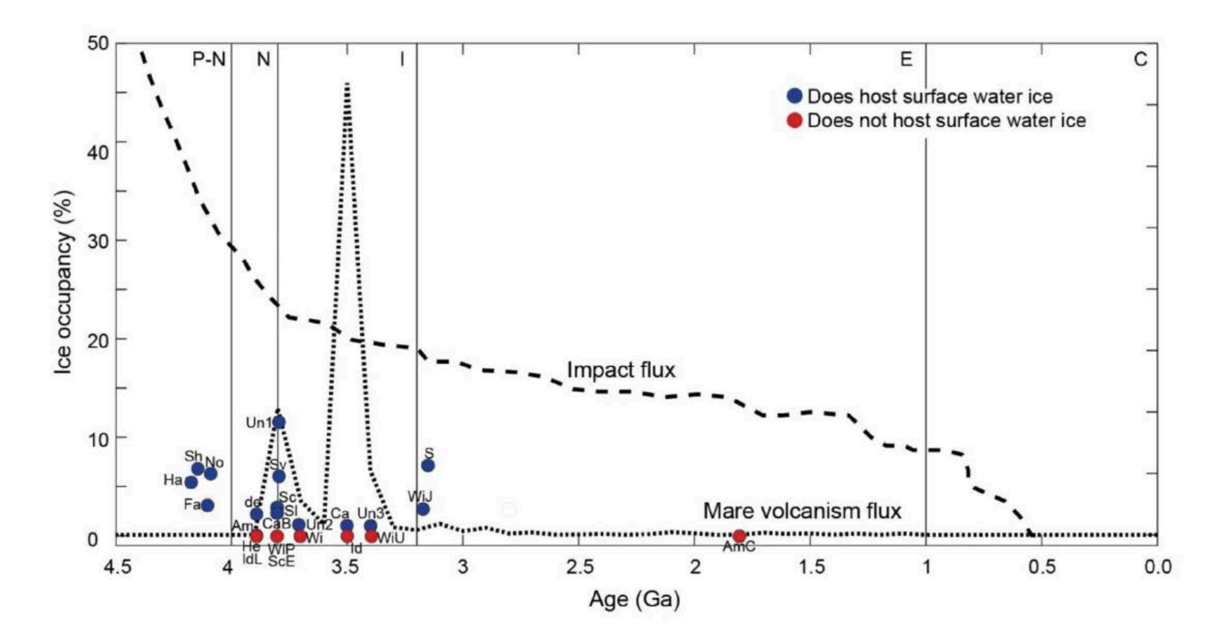
Siegler et al. (2016) Nature

Sources

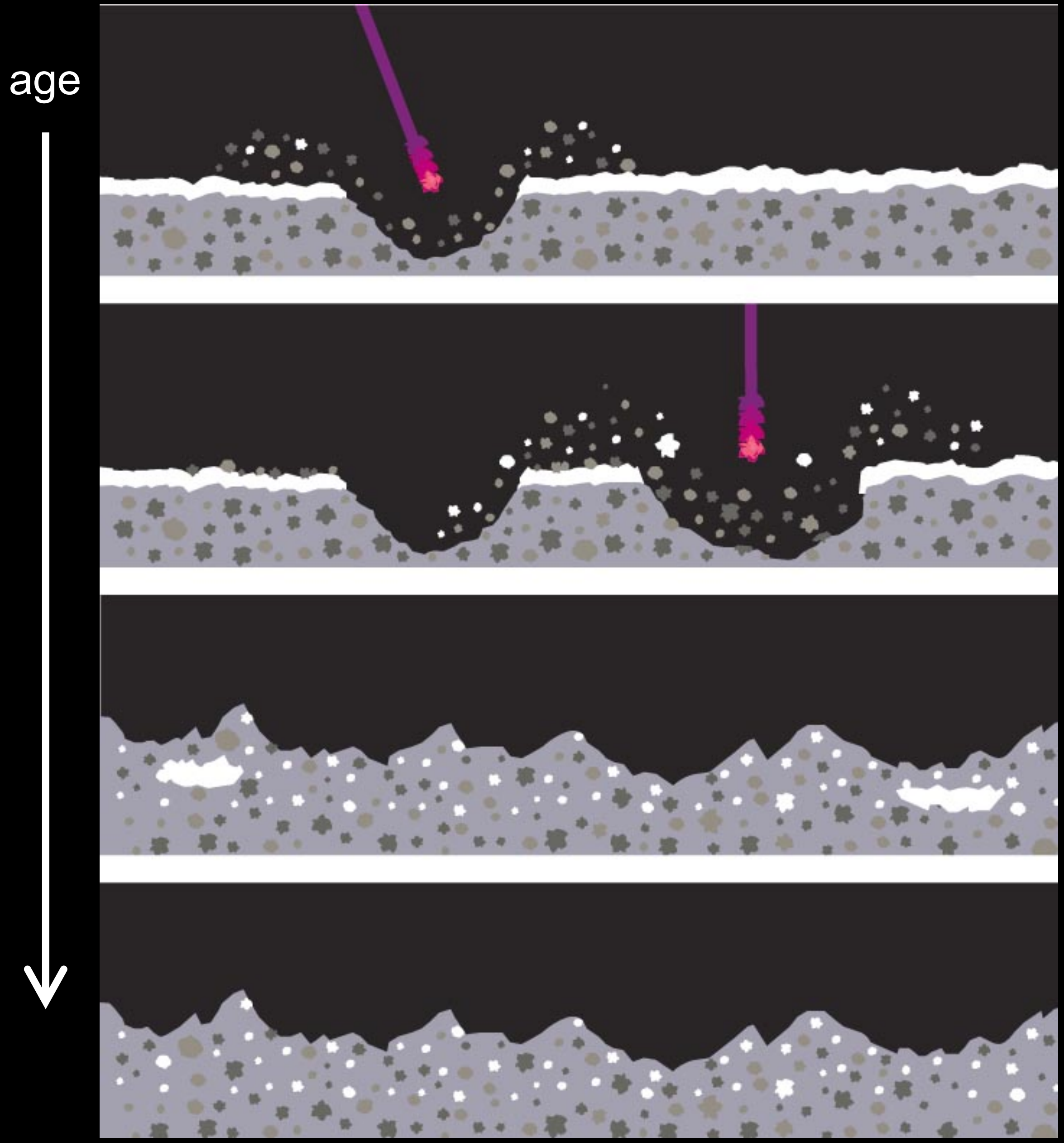
- More than just solar wind.
- Contributions still possible from:
  - Meteoroids.
  - Comets.
  - Volcanic outgassing.



Benna et al (2019) Nature Geoscience



Deutsch et al (2020) Icarus



After Vondrak and Crider, 2003

Redistribution Processes: 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.

Volatiles: Future Prospects

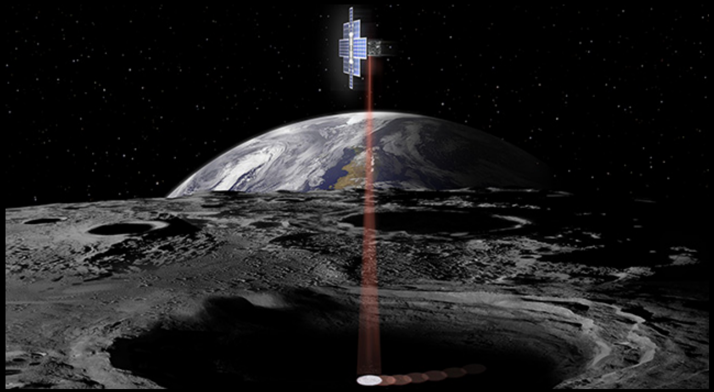
- Additional, dedicated lunar volatiles missions are needed:
  - Orbital.
  - Landed.
  - With exploration and science objectives.

- Leveraging multiple techniques is key:
  - Want information on surface content and volume content.
  - Spectral data and in situ identification are complementary.

- Understanding the system and processes is important:
  - Follow up on new information on sources.
  - Observe the redistribution process.
  - Loss processes are linked to present distribution.

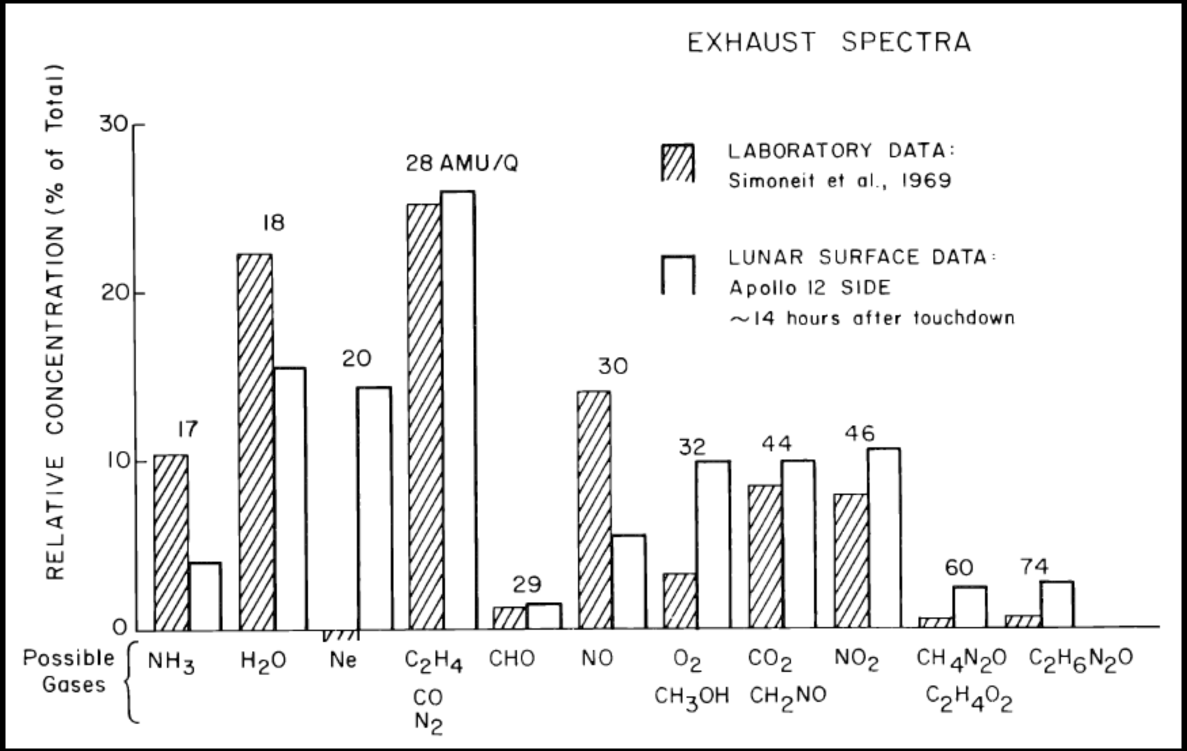
Volatiles: Future Prospects

- VIPER to provide in situ “ground truth” on composition, distribution, abundance, physical form.
  - Much anticipated!
  - Slated for 2023 launch.
  - Will probe volatile content both inside and outside of permanent shadowed regions.
- Cubesats:
  - Providing more information of surface veneer, surface frost, and hydrogen.
  - Will improve understanding of distribution and composition.



The Once and Future Lunar Exosphere

- **Almost any landed lunar mission will be an active volatile release experiment:**
  - Thruster firing during descent releases exhaust gases that may include H_2O, CO_2, NH_3, and others.
  - Well-recognized during the Apollo era (e.g., Milford & Pomilla, 1967; Aronowitz et al., 1968; Chang, 1969) and revisited since (e.g., Hurley et al., 2014, Shipley et al., 2014).
- This presents both a **scientific opportunity** to understand how volatiles interact with the lunar surface, and an **operational need** to understand how exhaust volatiles are redistributed, and how long they persist in the lunar environment.

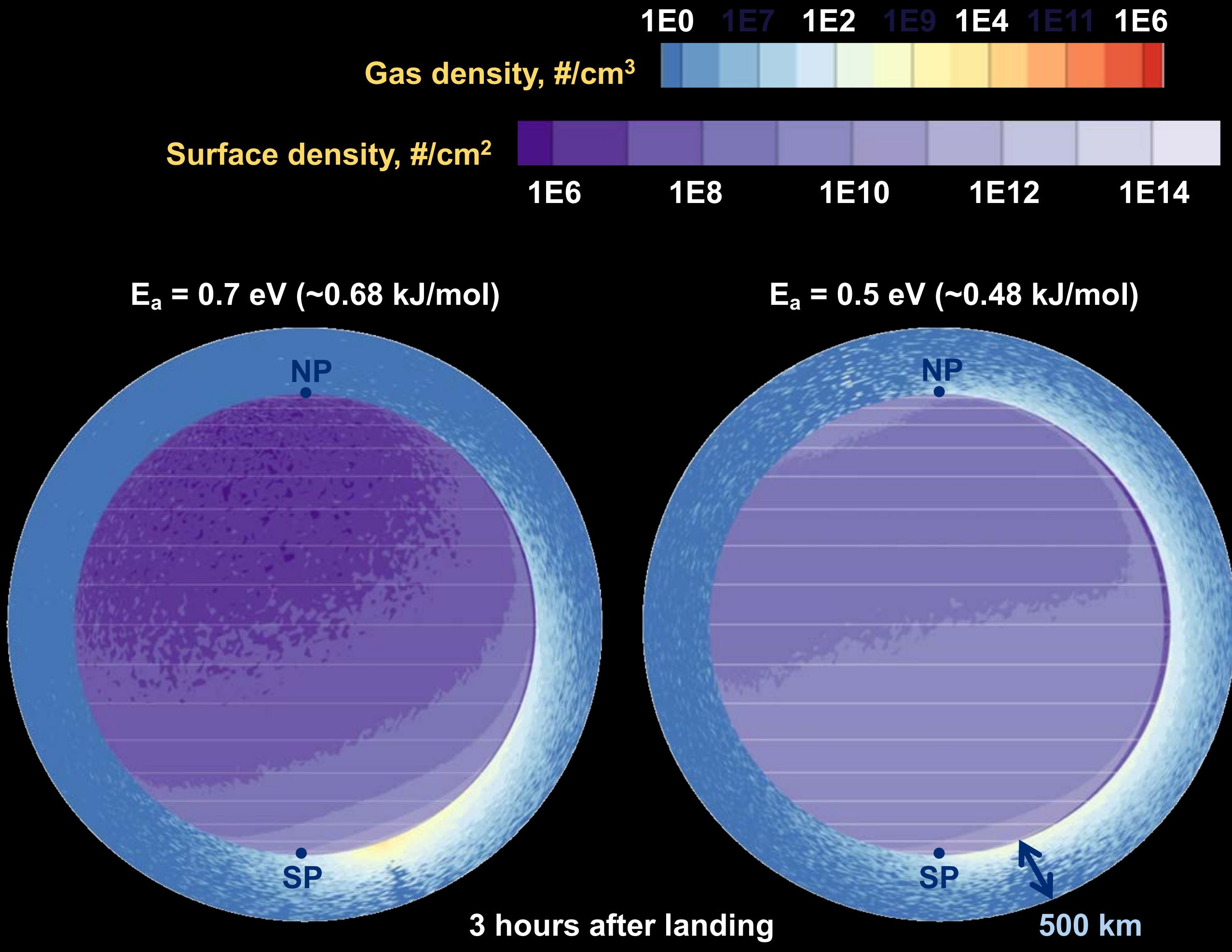


Mass spectra of Apollo Lunar Module exhaust gases, measured in the lab (shaded bars) and in the lunar exosphere (unshaded bars) 14 hours after the Apollo 12 landing (Freeman et al., 1972).

Modeling the Transport of Exhaust Volatiles

- We recently modeled the transport of water vapor released during a nominal high-latitude landing scenario:
  - Chang’e 3 class spacecraft: ~1200 kg dry mass, **~43 kg H_2O** (~30% of total exhaust mass).
  - **Early morning** landing at **70° S**.
  - **155 s** burn, spacecraft descends **~1.8 km**.

- Redistribution of exhaust gases is **global** and **sensitive to binding energy** (E_a), which determines how strongly water molecules adsorb with the lunar surface.

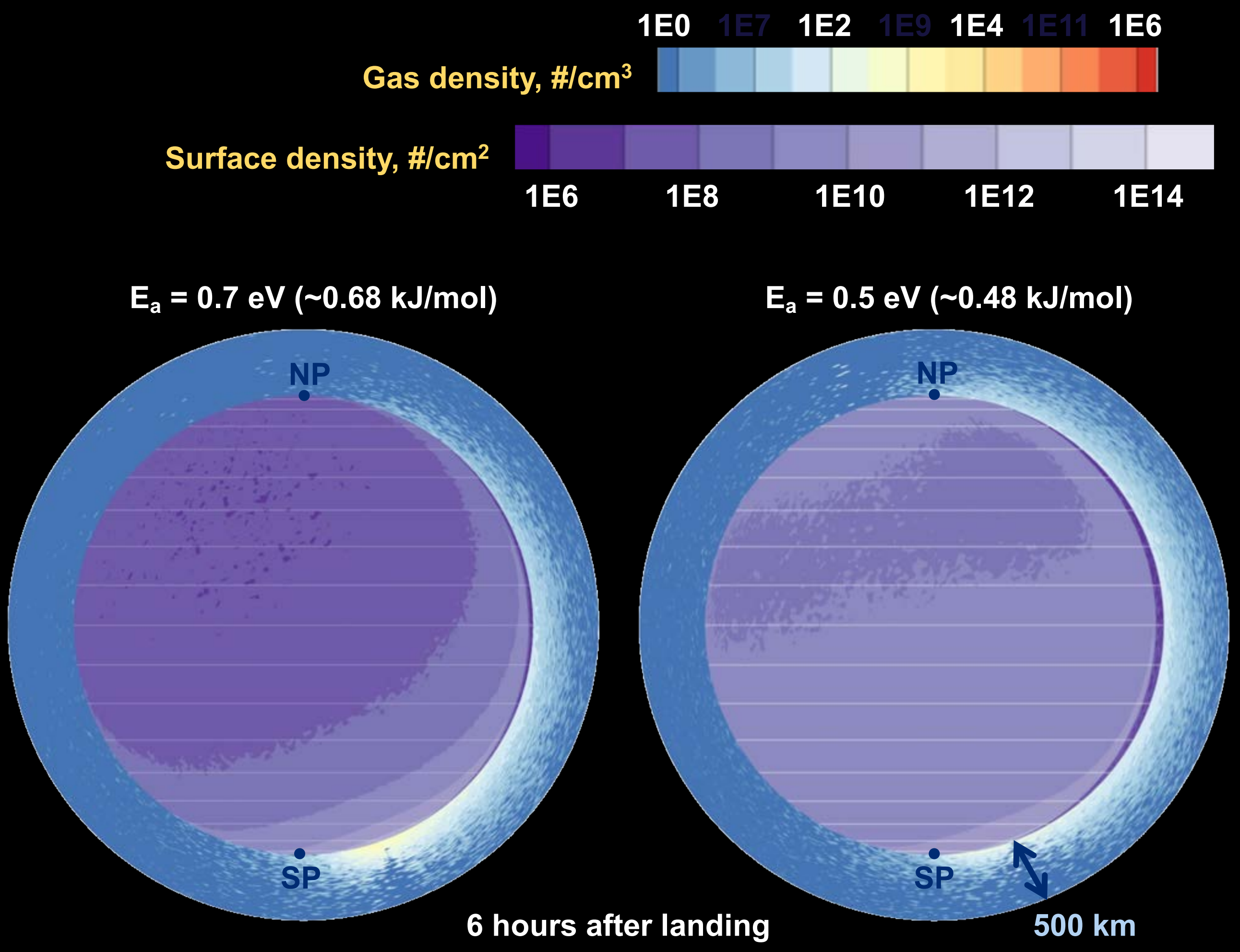


Prem, P., Hurley, D.M., Goldstein, D.B. and Varghese, P.L. (2020), JGR Planets (https://doi.org/10.1029/2020JE006464).

Modeling the Transport of Exhaust Volatiles

- We recently modeled the transport of water vapor released during a nominal high-latitude landing scenario:
  - Chang'e 3 class spacecraft: ~1200 kg dry mass, **~43 kg H_2O** (~30% of total exhaust mass).
  - **Early morning** landing at **70° S**.
  - **155 s** burn, spacecraft descends **~1.8 km**.

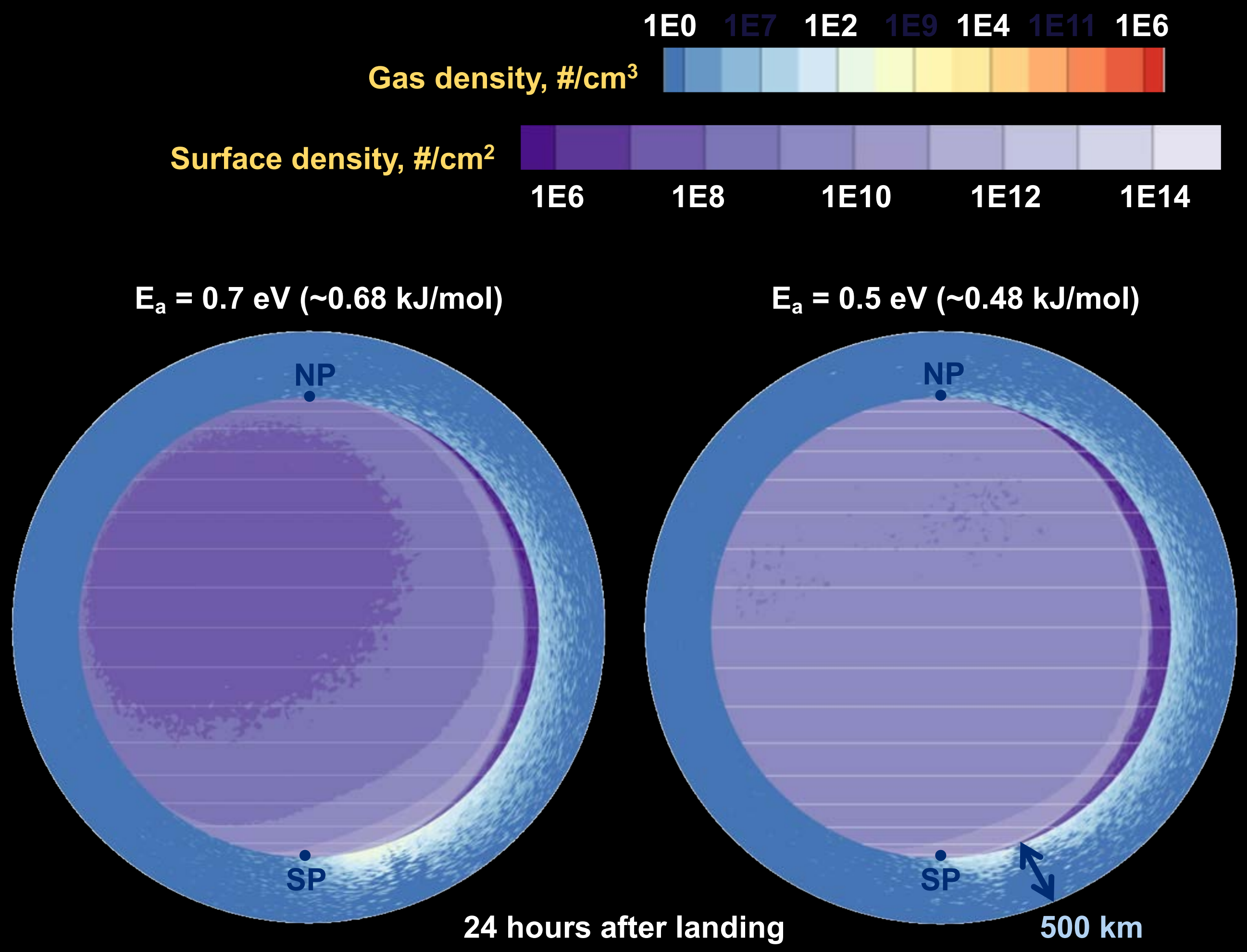
- Redistribution of exhaust gases is **global** and **sensitive to binding energy** (E_a), which determines how strongly water molecules adsorb with the lunar surface.



Prem, P., Hurley, D.M., Goldstein, D.B. and Varghese, P.L. (2020), JGR Planets (https://doi.org/10.1029/2020JE006464).

Modeling the Transport of Exhaust Volatiles

- We recently modeled the transport of water vapor released during a nominal high-latitude landing scenario:
  - Chang'e 3 class spacecraft: ~1200 kg dry mass, **~43 kg H_2O** (~30% of total exhaust mass).
  - **Early morning** landing at **70° S**.
  - **155 s** burn, spacecraft descends **~1.8 km**.
- Redistribution of exhaust gases is **global** and **sensitive to binding energy** (E_a), which determines how strongly water molecules adsorb with the lunar surface.



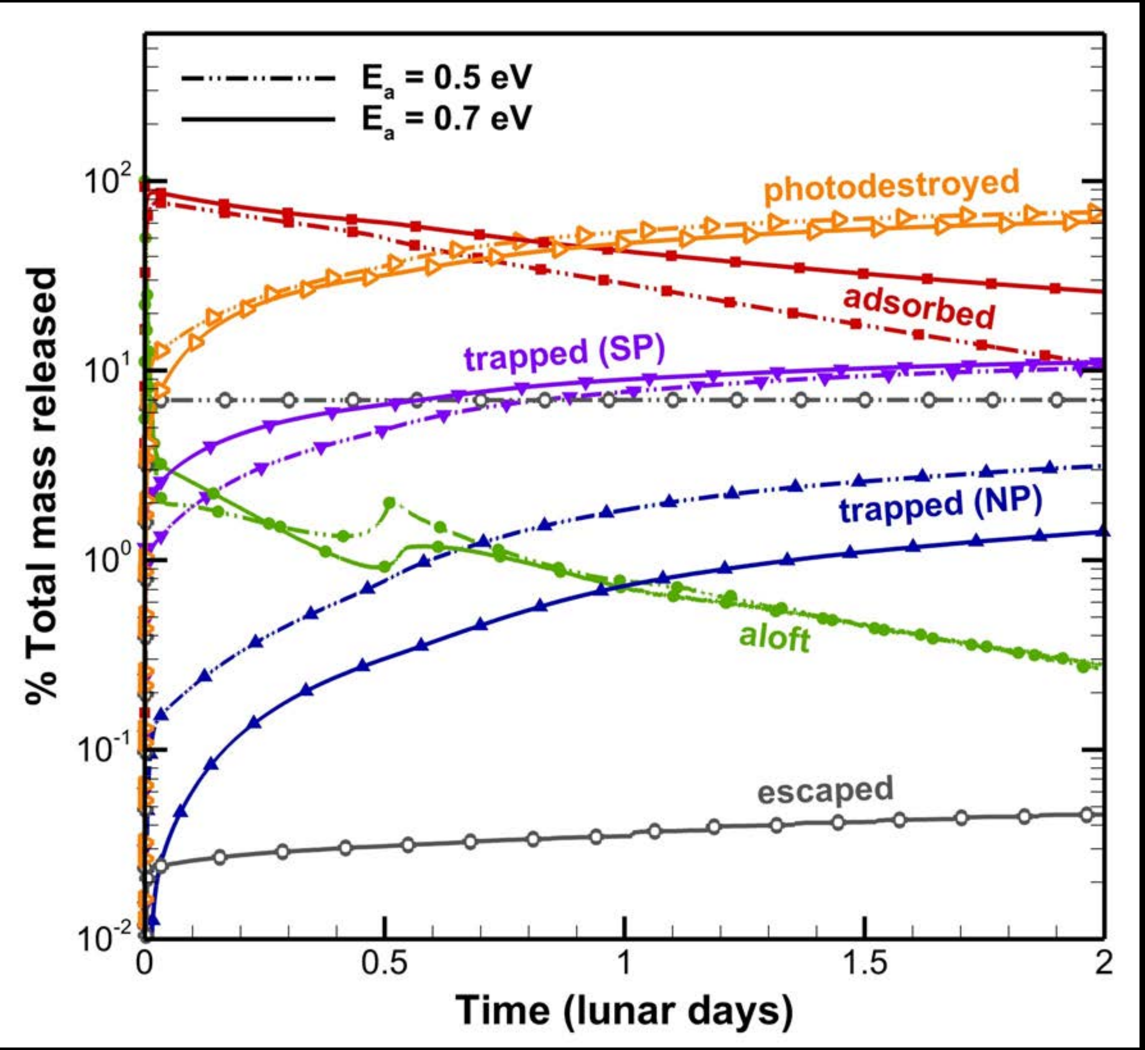
Prem, P., Hurley, D.M., Goldstein, D.B. and Varghese, P.L. (2020), JGR Planets (https://doi.org/10.1029/2020JE006464).

Long-term Transport, Deposition and Loss

- **Two lunar days** after landing, **~10–30%** exhaust water vapor persists in the lunar environment. Most of this water is adsorbed to the night side surface.

- Photolysis is the major modeled loss process.

- **Both north and south polar cold traps** accumulate water (~20% exhaust is cold-trapped), **directly** and **through transport**.



Perspectives on Exhaust Volatiles

- Persistence of exhaust volatiles in the lunar environment is likely to scale with lander **mass** and **proximity to polar regions**. Human landing systems currently under development are anticipated to burn between 10^3 to 10^6 kg of O_2 + H_2 or CH_4.

- There are **key gaps** in our understanding of:
  - How volatiles interact with the lunar surface.
  - Ongoing and past physical and chemical processes operating in the polar microenvironment.
  - Pre-existing volatile composition, abundance and distribution.

- There is likely a tradeoff between light, widespread contamination vs. heavier, localized contamination.

- Contamination by exhaust may be surficial, but so too are several processes of scientific interest and most remote-sensing datasets (which remain to be ground-truthed).

- Water is one of **several potential exhaust species** that have a range of surface residence times at polar temperatures and photolytic lifetimes.

Looking Back and Looking Ahead

- The lunar poles are unlike previous lunar landing sites, but a look back at previous scientific measurements may be instructive when planning for the impact of spacecraft on their operational environments:

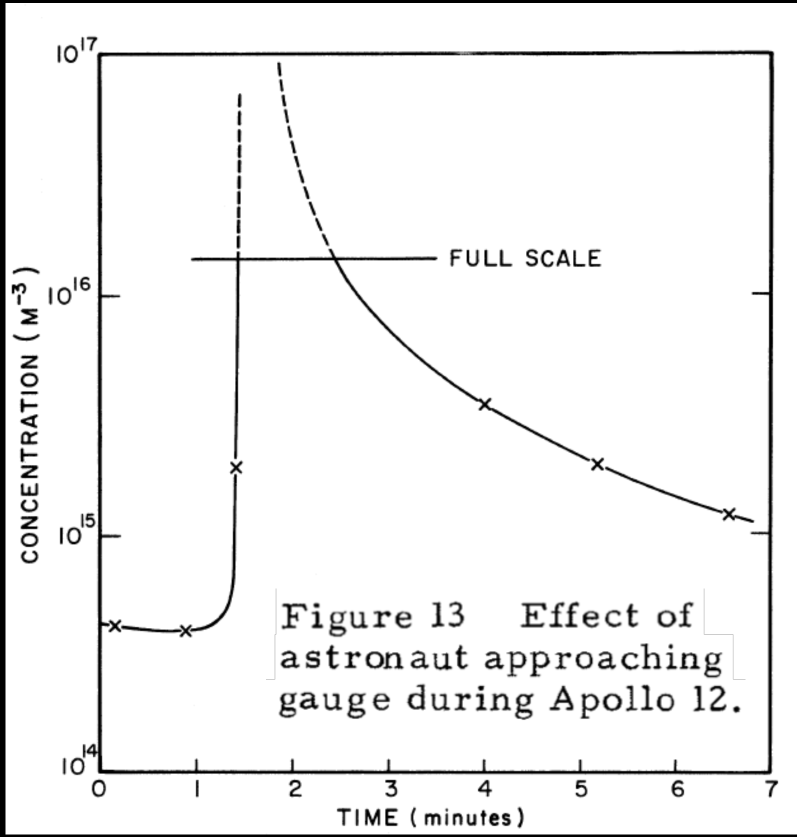
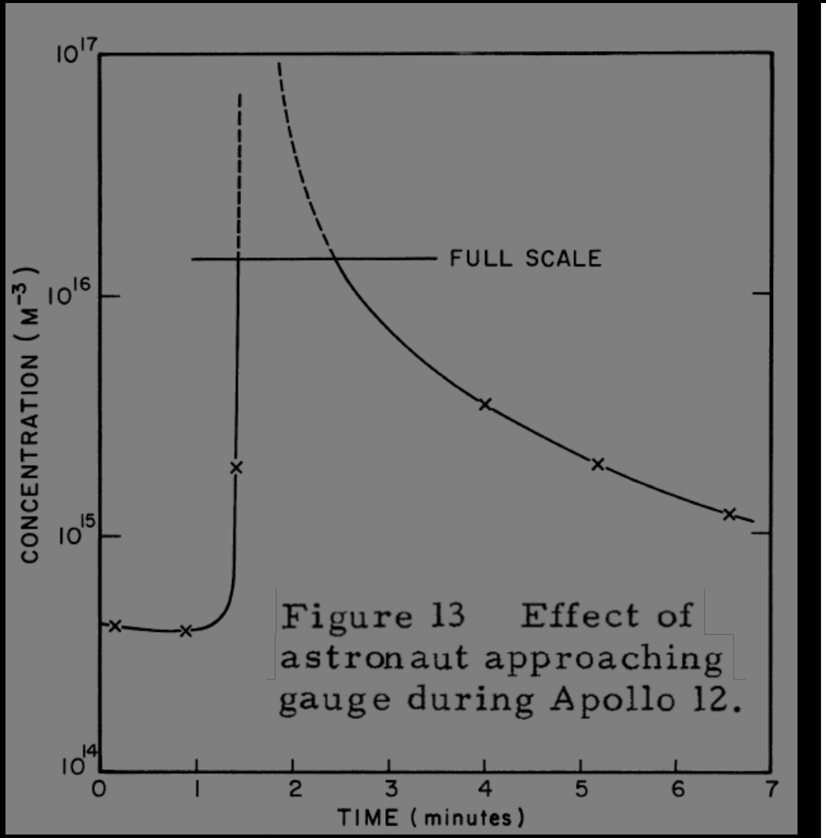


Figure 13 Effect of astronaut approaching gauge during Apollo 12.

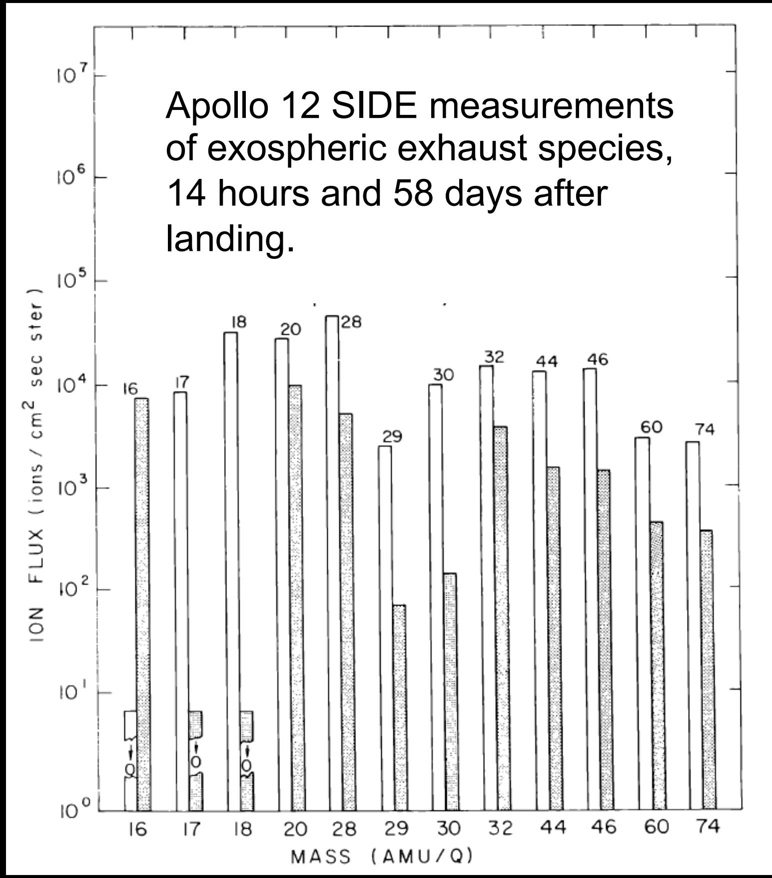
from the Final Report for Cold Cathode Gauge Experiment (Johnson et al., 1974)

Looking Back and Looking Ahead

- The lunar poles are unlike previous lunar landing sites, but a look back at previous scientific measurements may be instructive when planning for the impact of spacecraft on their operational environments:



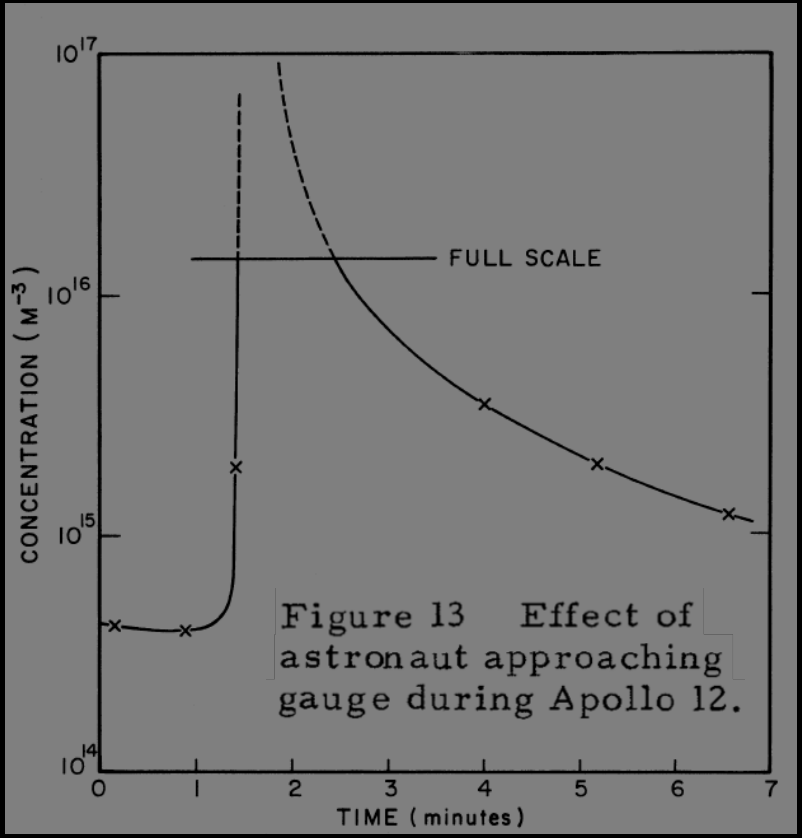
from the Final Report for Cold Cathode Gauge Experiment (Johnson et al., 1974)



Freeman et al., 1972

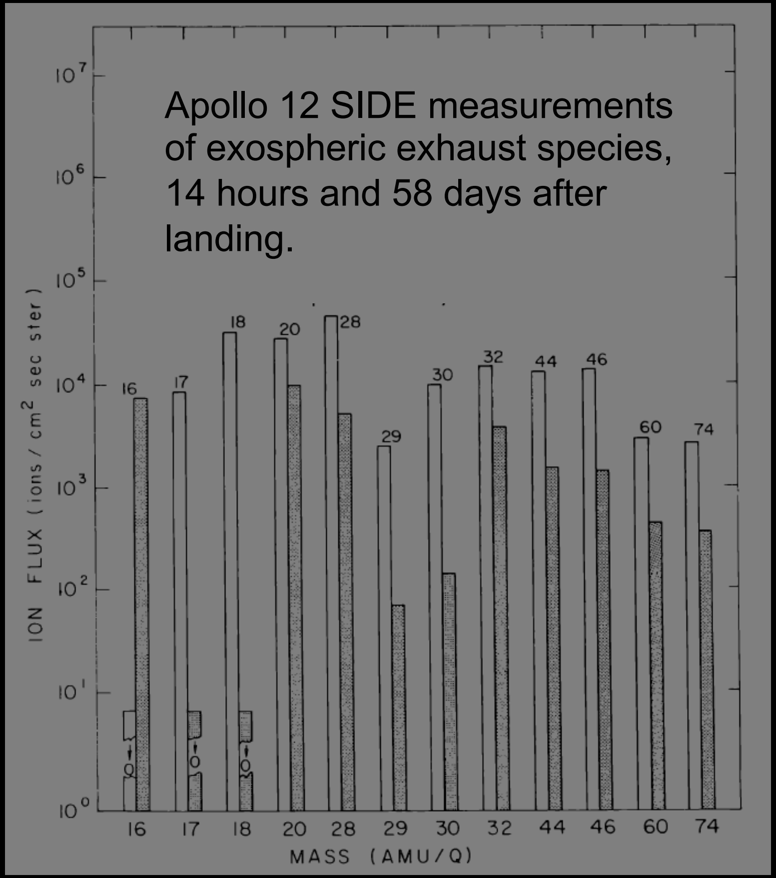
Looking Back and Looking Ahead

- The lunar poles are unlike previous lunar landing sites, but a look back at previous scientific measurements may be instructive when planning for the impact of spacecraft on their operational environments:



from the Final Report for Cold Cathode Gauge Experiment (Johnson et al., 1974)

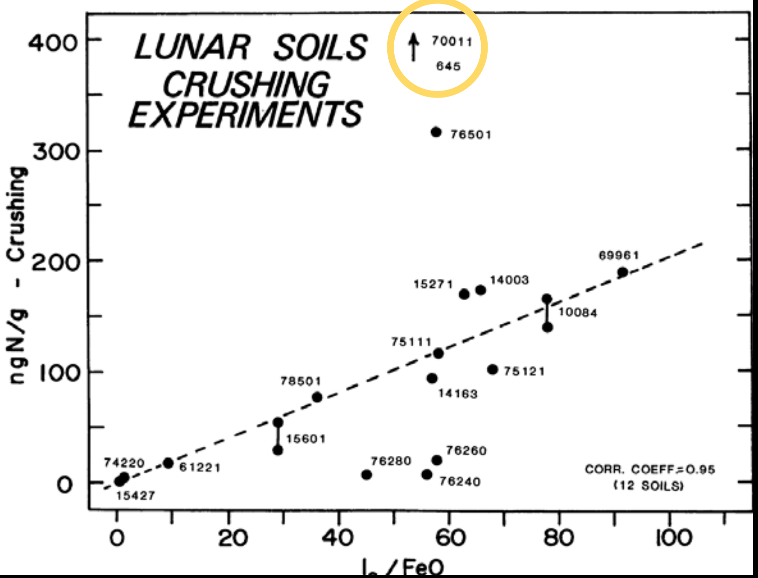
Apollo 12 SIDE measurements of exospheric exhaust species, 14 hours and 58 days after landing.



Freeman et al., 1972

Lunar soils, nitrogen content vs. maturity (Gibson & Andrawes, 1978)

70011 (collected beneath lunar module)



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 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.

Conclusions

- Important open questions include:
  - Sources.
  - Age.
  - Retention.
  - Redistribution.
  - Ongoing activity.
  - Ground truthing of remote sensing data.
- Mobility and subsurface access improve the ability to access volatiles in lunar PSRs .
- The act of exploring the Moon impacts the polar environment and needs to be considered in interpreting results.

JOHNS HOPKINS

APPLIED PHYSICS LABORATORY