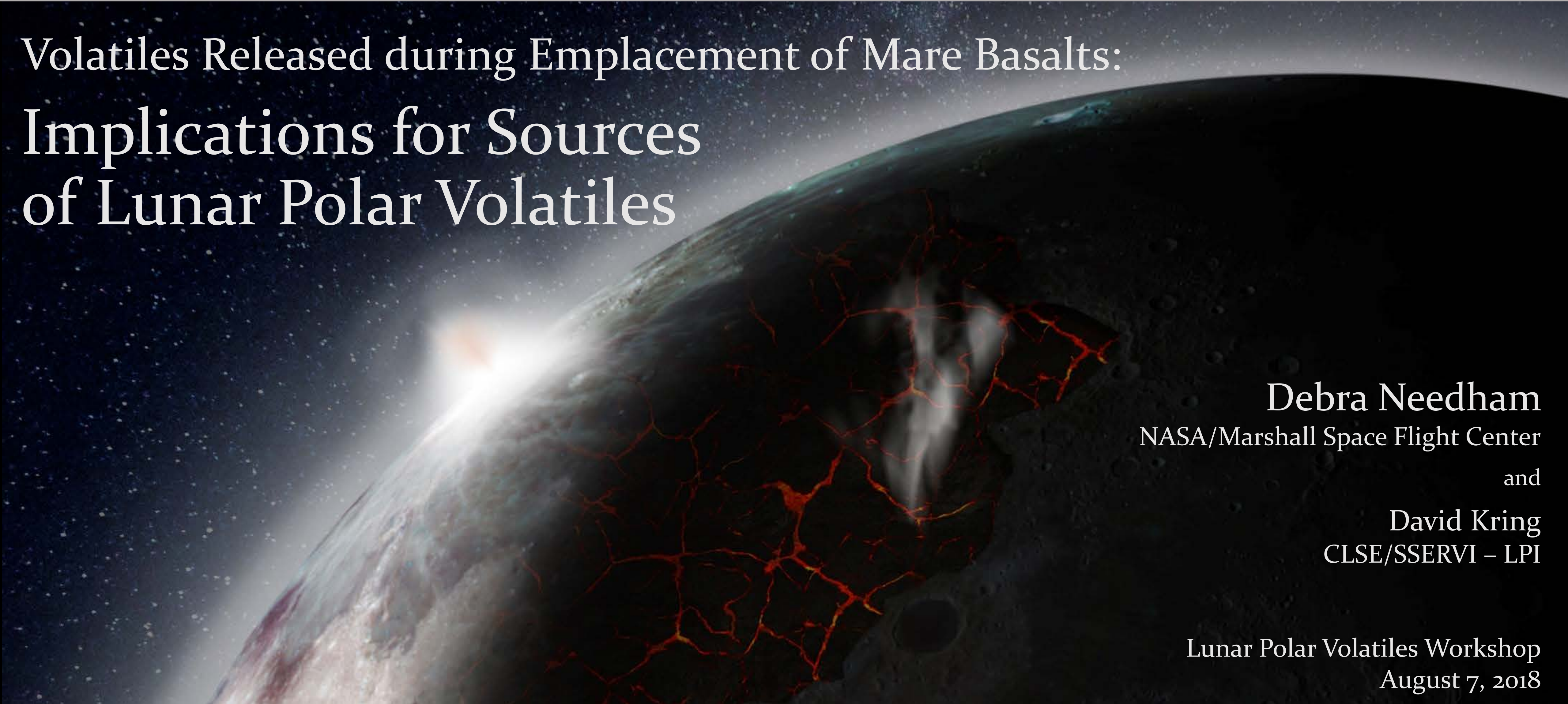


Volatiles Released during Emplacement of Mare Basalts:

Implications for Sources of Lunar Polar Volatiles

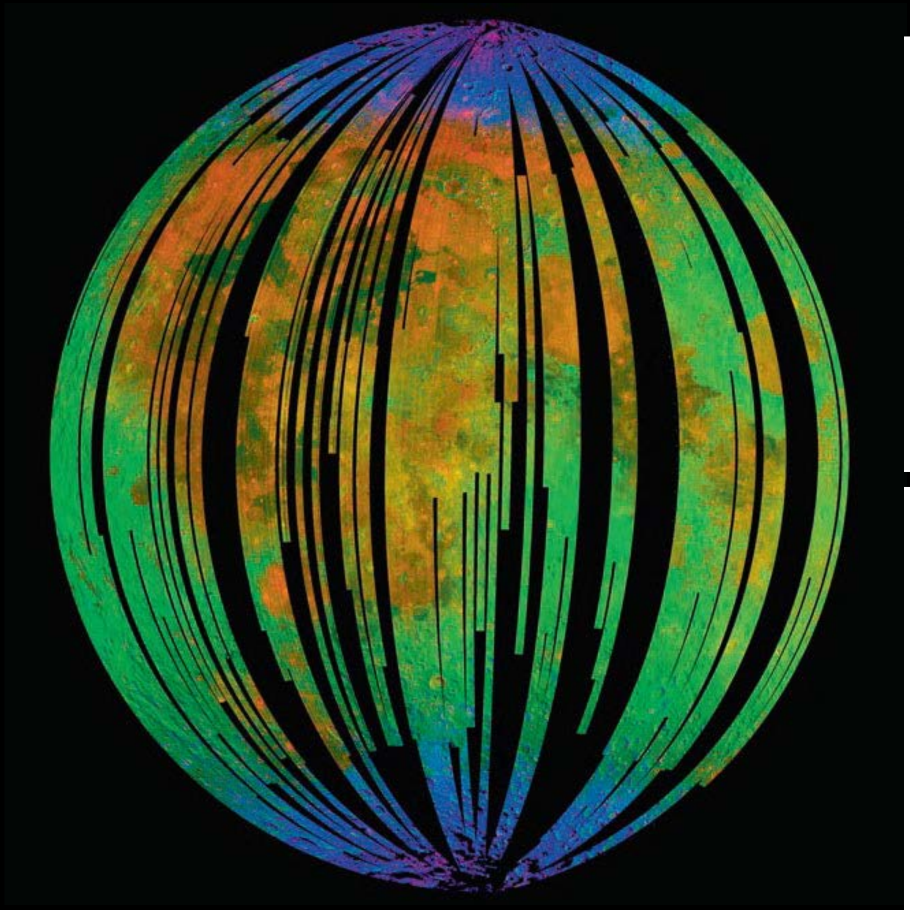
Debra Needham
NASA/Marshall Space Flight Center

and

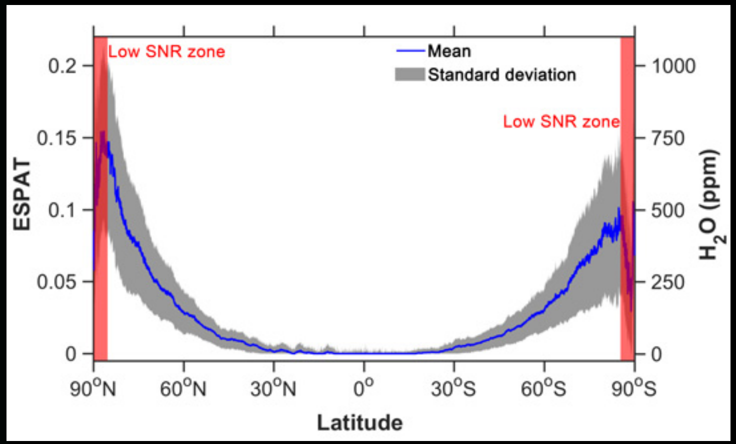
David Kring
CLSE/SSERVI – LPI

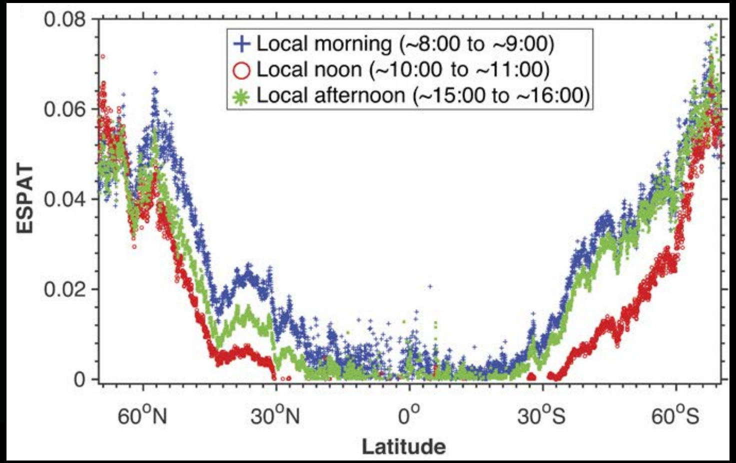
Lunar Polar Volatiles Workshop
August 7, 2018

Recent Water Detections from Orbit

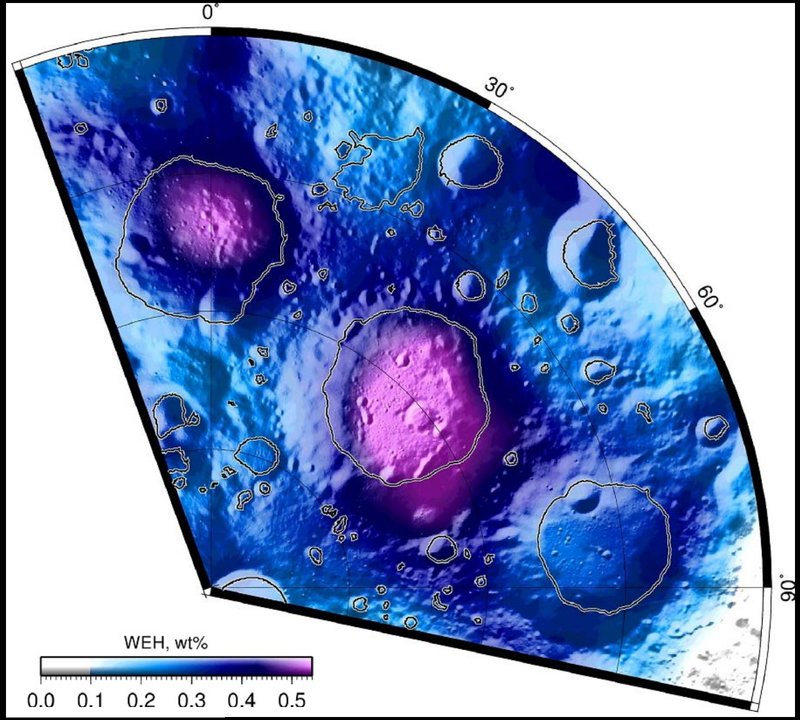


Moon Mineralogy Mapper detection of OH/H_2O at lunar poles (blue/purple); Pieters et al., 2009.



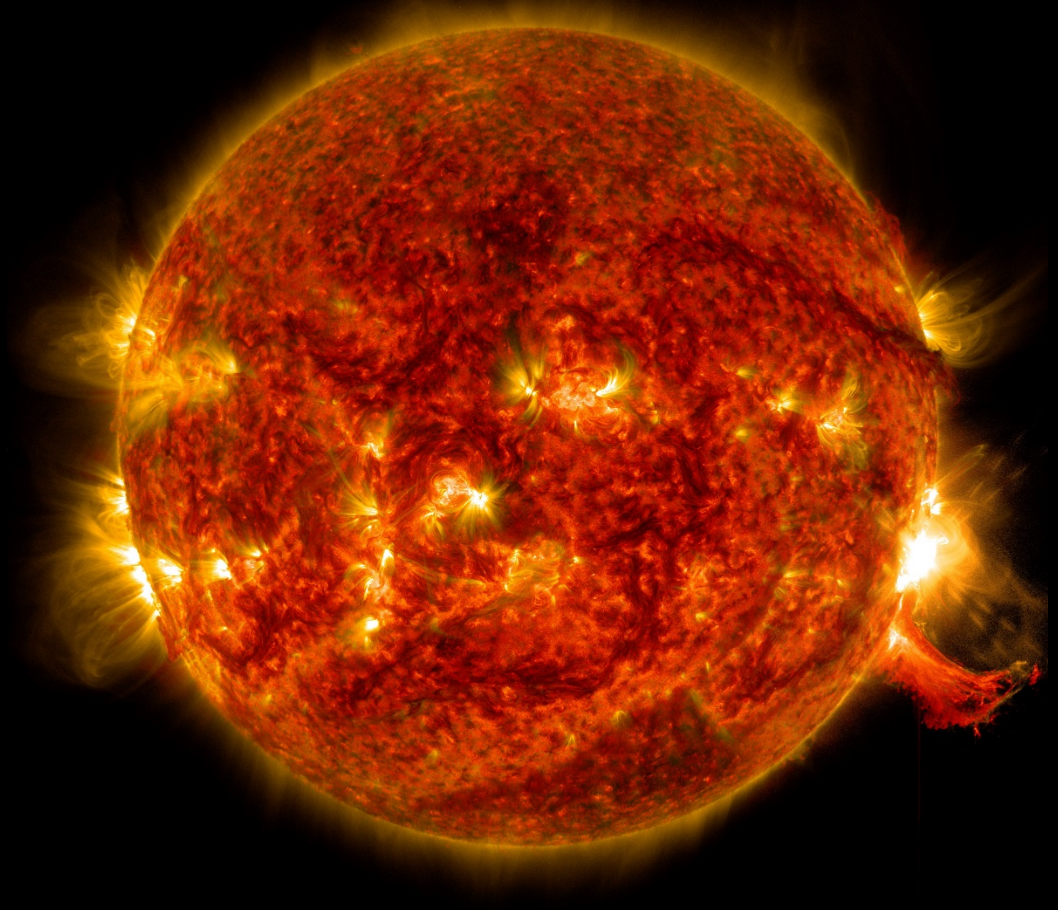


OH/H_2O variability by latitude and day from M^3; Li and Milliken, 2017.

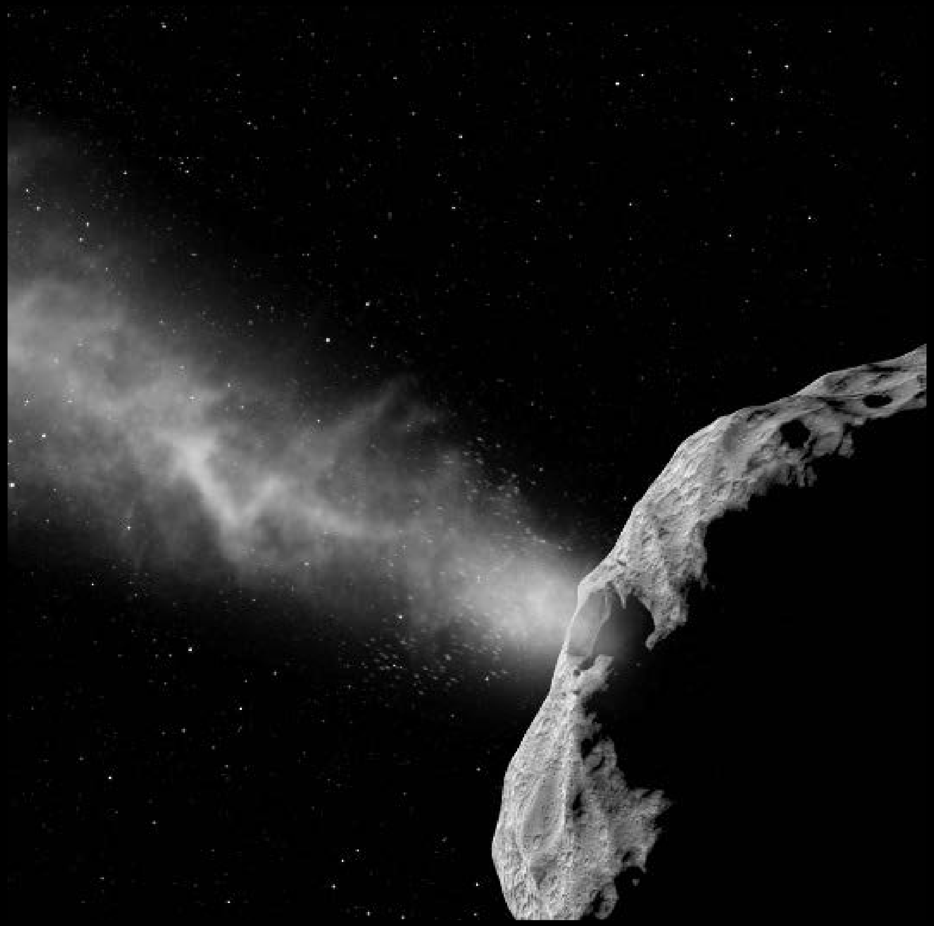


LEND detection of water equivalent H via neutron suppression at lunar poles; Sanin et al., 2017.

Identified Sources for Lunar Volatiles

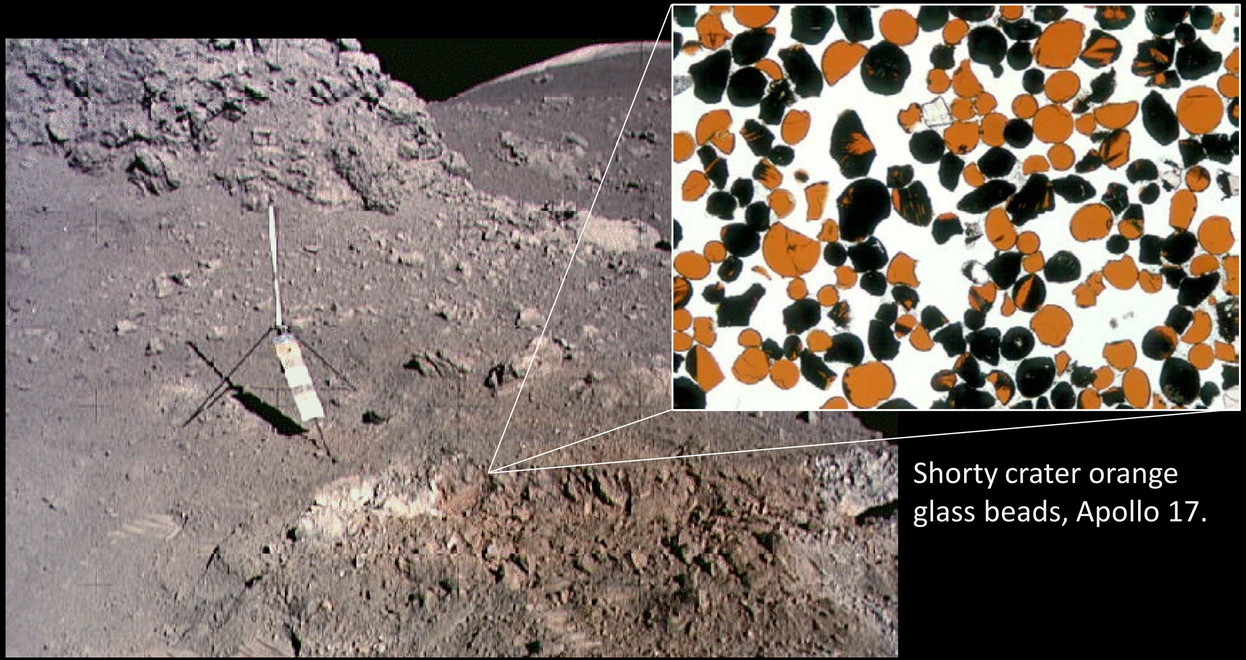


Solar wind-delivered hydrogen trapped in the Moon's PSRs?

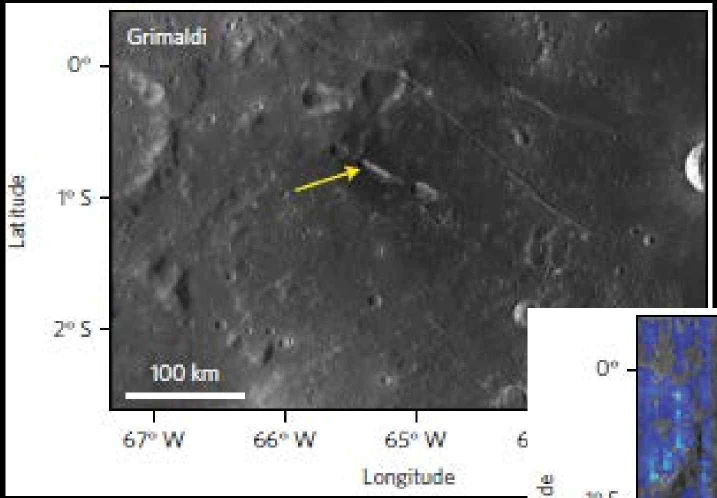


Water delivered by asteroid and comet impacts on the Moon?

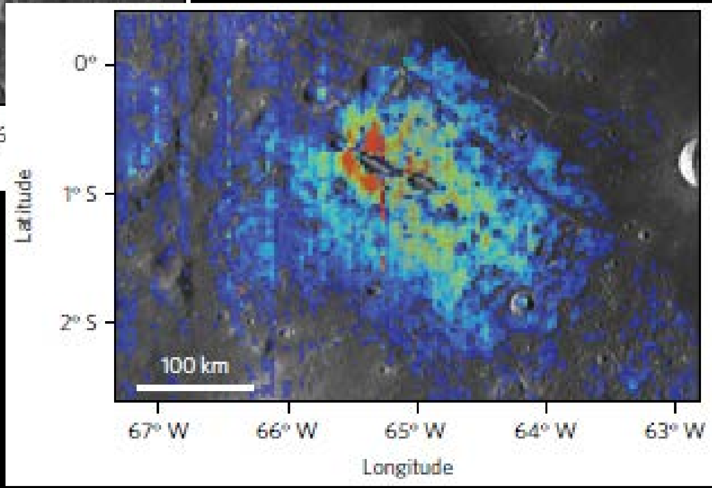
Another Type of Lunar Water



Shorty crater orange glass beads, Apollo 17.



Pyroclastic deposit at Grimaldi as identified from Lunar Reconnaissance Orbiter Camera and Moon Mineralogy Mapper.



Water content observed on the lunar surface, ranging from <0.005% (blue) to >0.03% (red); (Milliken and Li, 2017).

Significance of a Volcanic Source for the Lunar Polar Volatiles

1. Lunar Mare Production Function
   - Volume of mare
   - Age of emplacement
2. Volatile Mass Production Function
   - Lunar mare volatile distributions.
3. Atmosphere Pressure, Duration
4. Final Volatile Sink

LROC WAC mosaic

Lunar Mare Volume

- Volume of mare in lunar basins:

Table 1: Total volume of mare in lunar basins

Basin	Total Area (km^2)	Ave. Thickness (m)	Volume (km^3)	Thickness Reference
Crisium	156,103	2,940	458,943	Williams and Zuber 1998
Grimaldi	15,359	3,460	53,142	Williams and Zuber 1998
Humorum	101,554	3,610	366,611	Williams and Zuber 1998
Imbrium	1,010,400	5,240	5,294,497	Williams and Zuber 1998
Nectaris	64,277	840	53,993	Williams and Zuber 1998
Orientale	75,975	88	13,294	Whitten et al 2011
Oceanus Procellarum	1,757,799	325	571,285	Hörz 1978
Serenitatis	342,716	4,300	1,473,679	Williams and Zuber 1998
Smythii	28,075	1,280	35,937	Williams and Zuber 1998
South Pole - Aitken	206,430	Varied	153,240	Yingst and Head 1997
Tranquillitatis	371,257	350	129,940	Hörz 1978

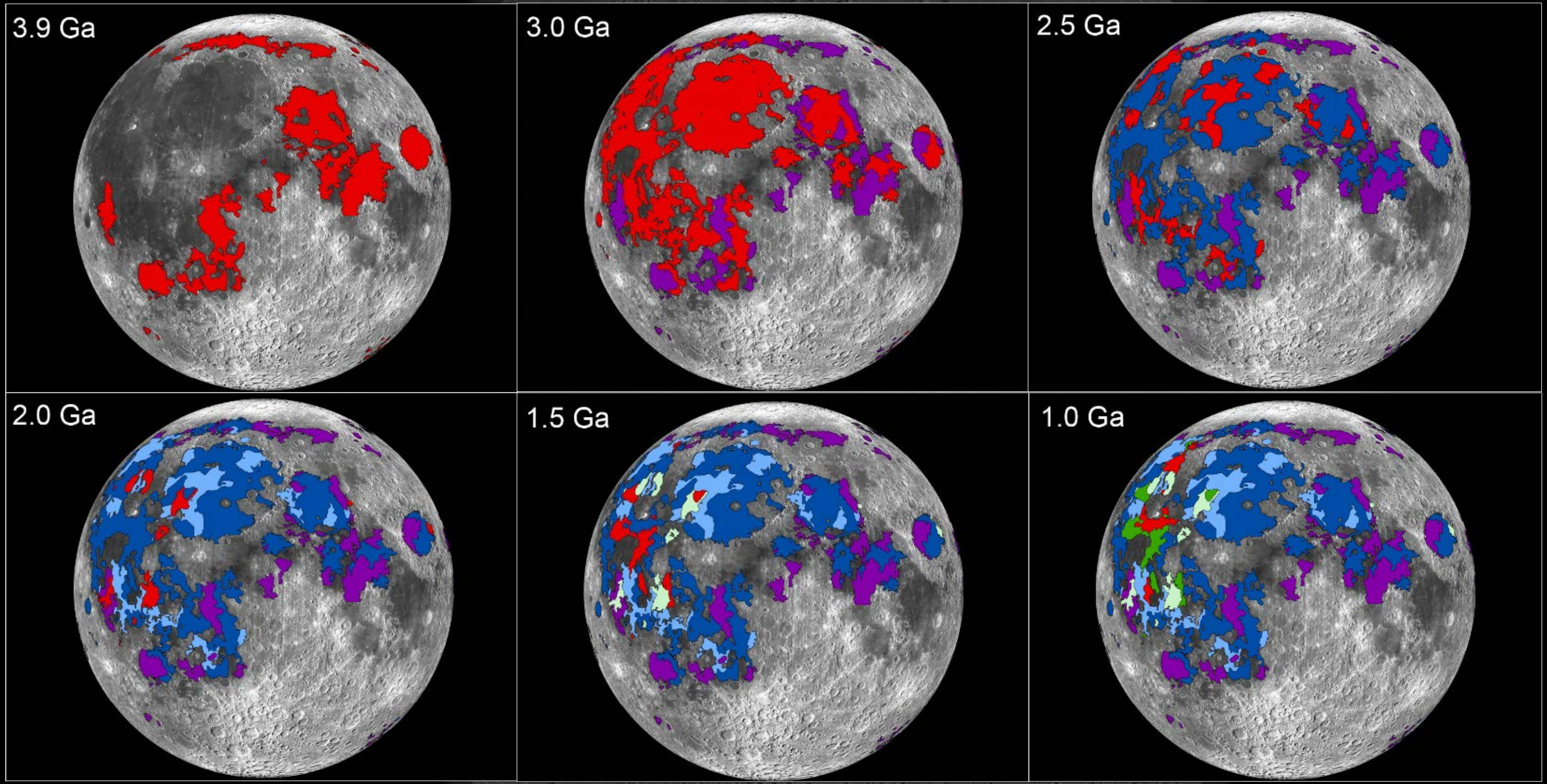
From Needham and Kring, 2017, *EPSL*.

Total volume of mare: ~9×10^6 km^3, similar to previous estimates.

(1×10^7 km^3, Head and Wilson, 1992)

Timing of Mare Emplacement

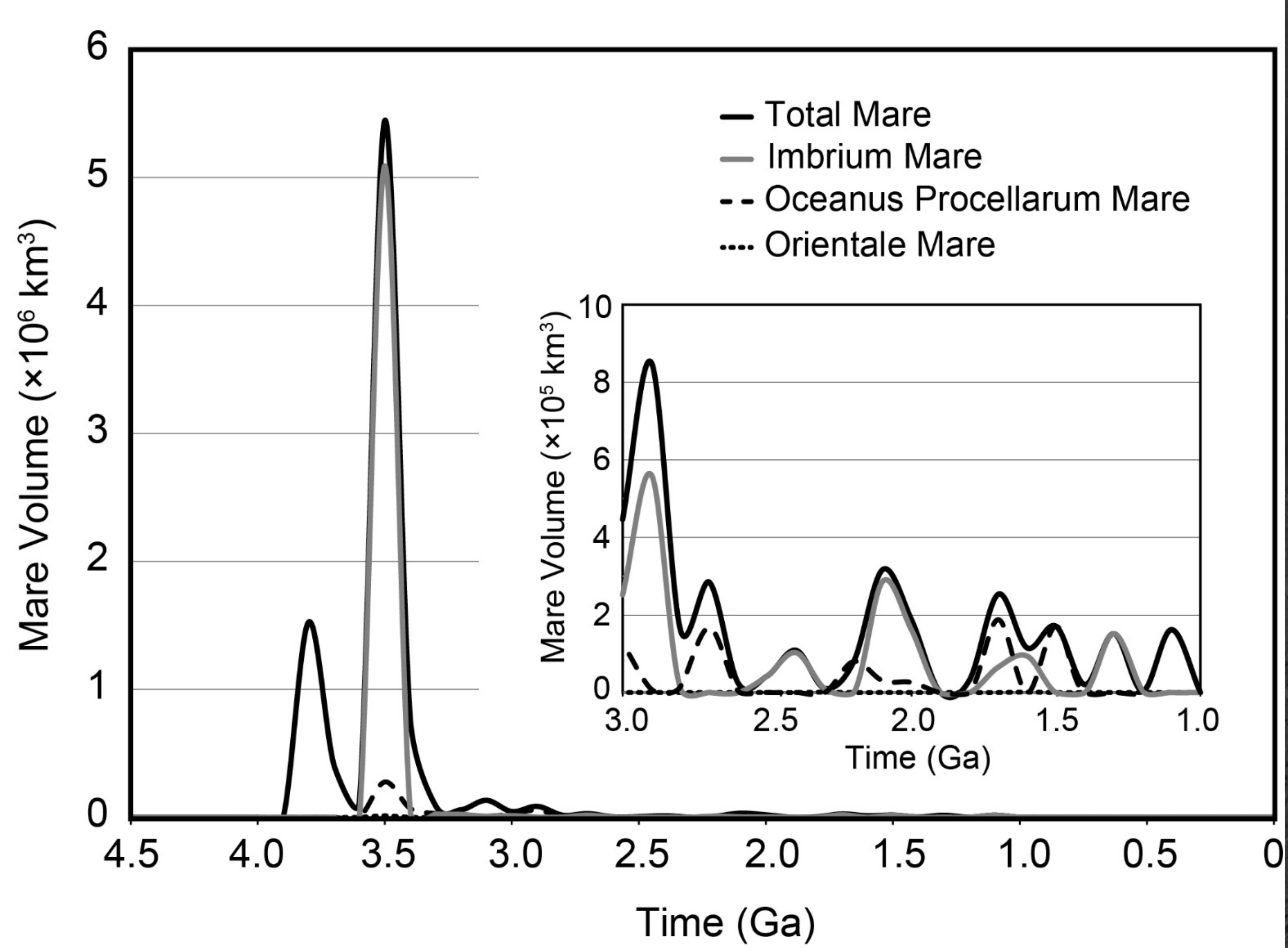
- Area, thickness of each mapped unit *(Hiesinger et al., 2011; Whitten et al., 2011)*.
- Age of each mapped unit from crater counting *(Hiesinger et al., 2011; Whitten et al., 2011)*.
- Remaining mare volume emplaced at time of oldest surface unit.



Based on data presented in Hiesinger et al., 2011; Whitten et al., 2011

Needham and Kring, 2017, *EPSL*.

Volume of erupted basalts as a function of time



Needham and Kring, 2017, *EPSL*.

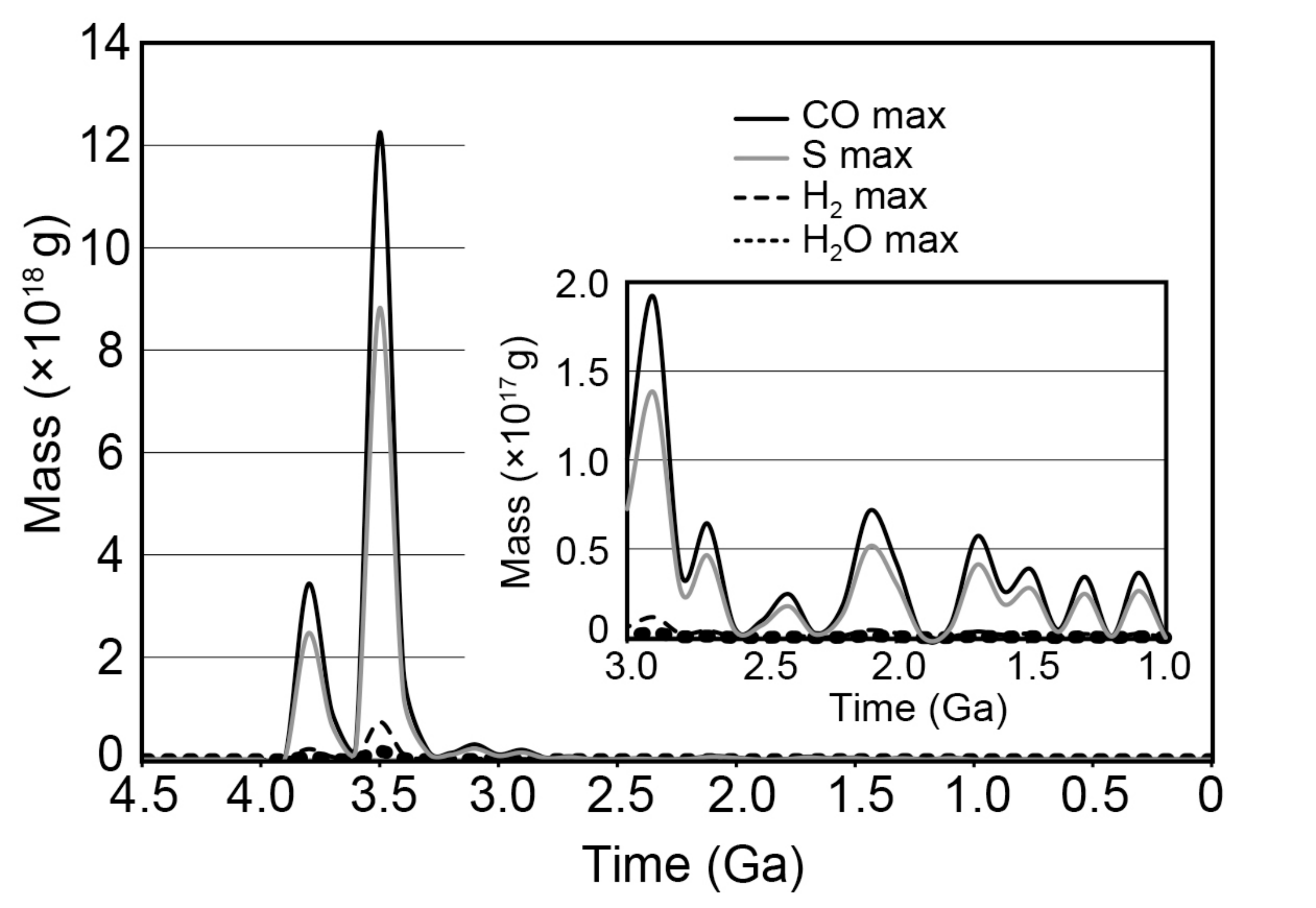
Mass of Released Mare Volatiles

- Lava density: 3000 kg/m^3
  - Calculate total mass of mare.
- Mare volatile measurements from literature
  - Calculate mass of each released volatile.

Mare Volatiles	Min (ppm)	Max (ppm)	Released (%)	Min (ppm)	Max (ppm)	Reference
CO	80	750	100	80	750	Sato 1979
H_2O	2	10	90	1.8	9	Robinson and Taylor 2014; Elkins-Tanton and Grove 2011
H_2	0.007	45	100	0.007	45	McCubbin et al., 2010
S	200	600	90	180	540	Shearer et al., 2006

From Needham and Kring, 2017, *EPSL*.

Volatile mass released from all mare eruptions



assuming max mare volatile content

Needham and Kring, 2017, *EPSL*.

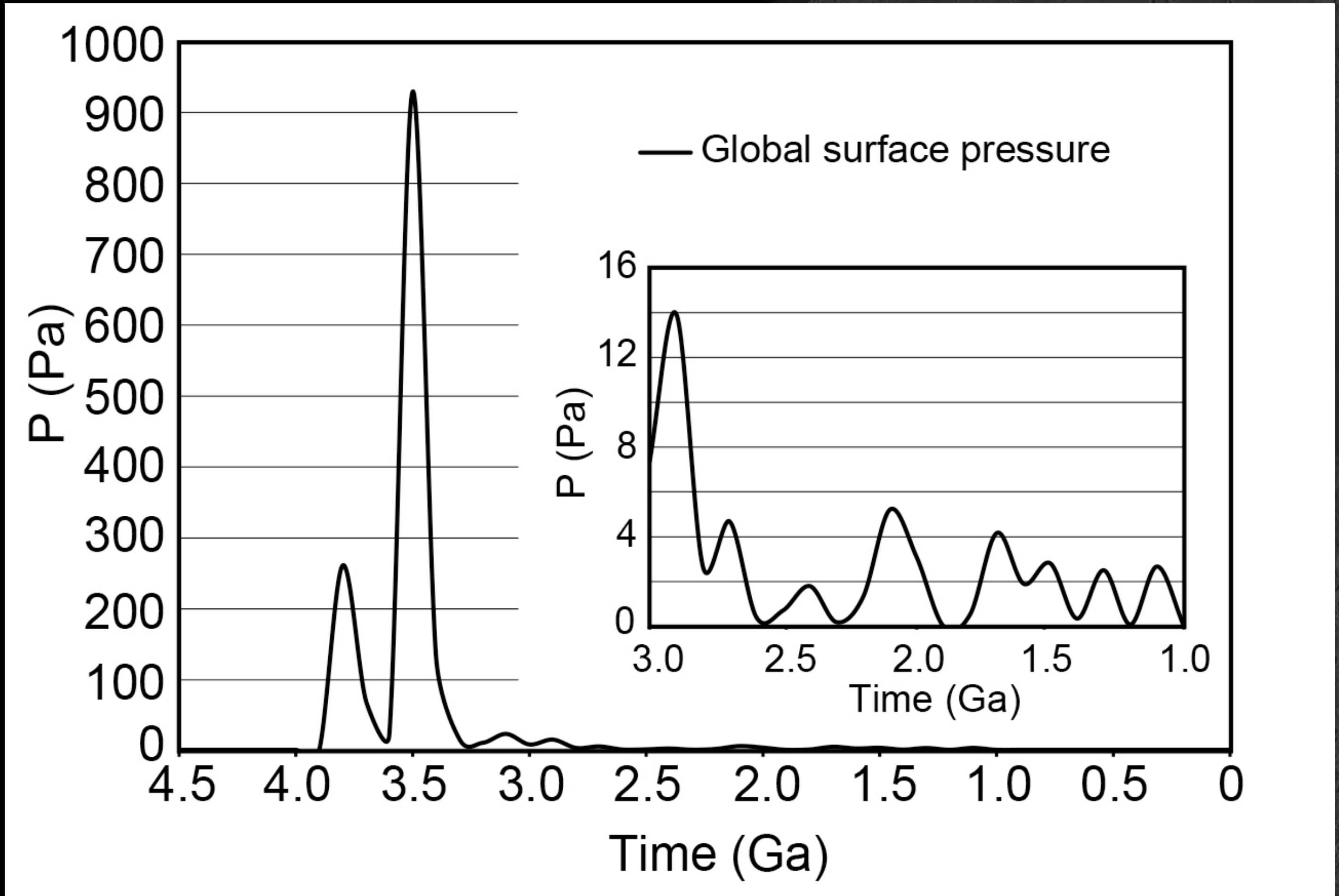
Atmospheric Pressure resulting from Volcanically Released Volatiles

- Total mass released as a function of time.

$$P_{surf} = \frac{mg}{A}$$

- Distributed over whole lunar surface.

Atmospheric Pressure resulting from Volcanically Released Volatiles



Needham and Kring, 2017, *EPSL*.

Implications for a Lunar Atmosphere

- Surface Pressure
  - At peak, ~1000 Pa (~0.01 atm).
    - ~1% of Earth's current surface pressure.
    - ~1.5 times greater than Mars' current surface pressure.

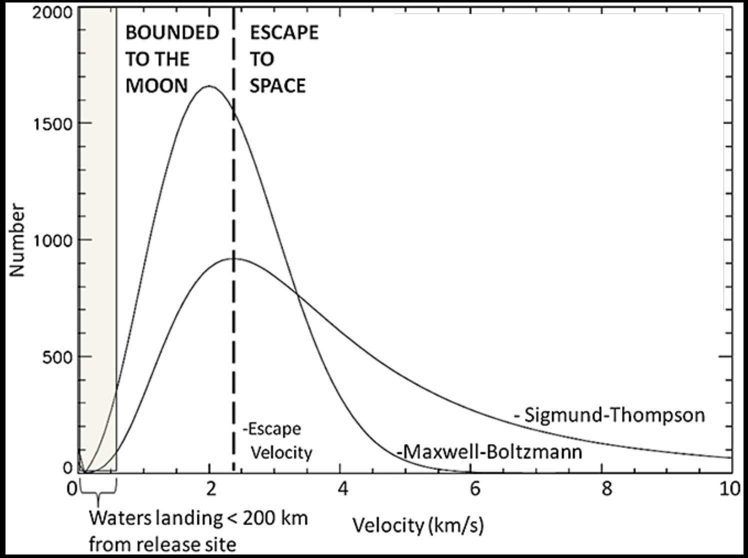
- Scale Height of ancient lunar atmosphere: $\frac{KT}{mg}$
    - At Noon: ranges from ~60 km (S) to 1000 km (H_2).
    - At Midnight: ranges from ~15 km (S) to 250 km (H_2).

Implications for a Lunar Atmosphere

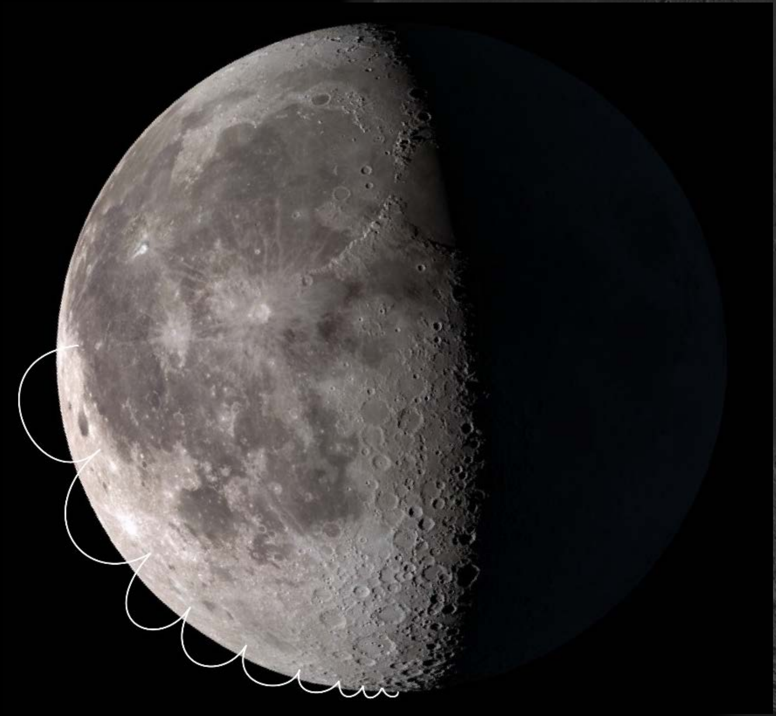
- Duration of Lunar Atmosphere
  - Loss rate controlled by particle interactions.
    - Total atmospheric mass exceeds 10^{11} g (*Vondrak*, 1974), -> 10^4 g s^{-1}
      - Peak volcanic activity (~3.5 Ga), total mass is 10^{16} kg.
        - Volatile effusion rate > 10^7 g s^{-1}. (Wilson and Head, 1980)
      - Resulting atmosphere may have required ~70 Ma to dissipate.

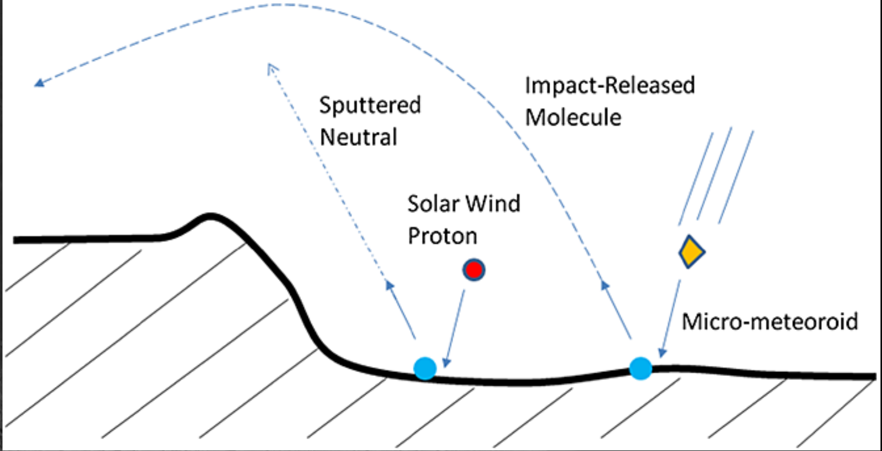
Implications for a Volcanic Source for Lunar Volatiles

- Sink of Lunar Atmospheric Volatiles:
  - If 0.1% of vented mare water (~10^{17} g) is trapped in Permanently Shadowed Regions, volcanically-derived volatiles could account for all water in PSRs (10^{14} g, *Eke et al.*, 2009).



Released volatiles lost to space vs. bounded to the Moon; Farrell et al., 2015.

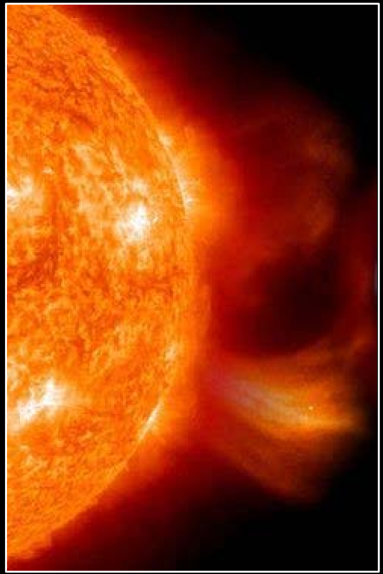




Releasing volatiles via sputtering and impact vaporization processes; Farrell et al., 2015.

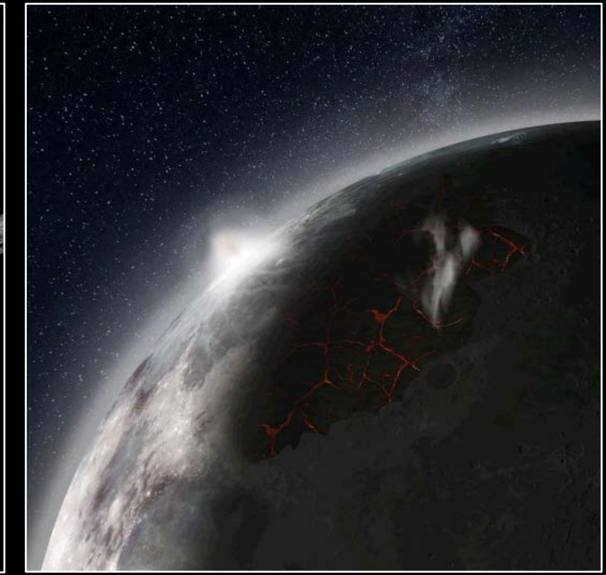
Hypotheses for Distribution of Polar Lunar Volatiles

- The source of volatiles can affect how these deposits are distributed and how accessible they are as resources.

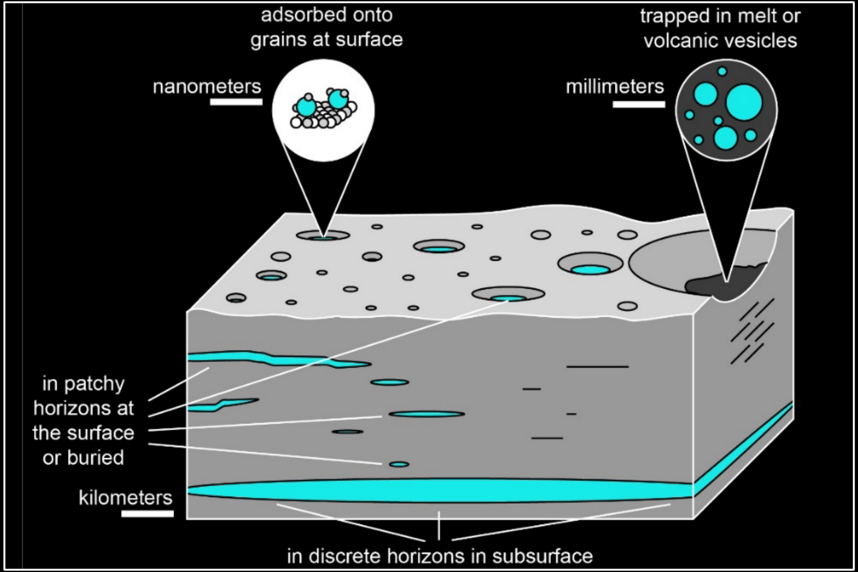


Solar wind-delivered hydrogen trapped in the Moon's PSRs.

Water delivered by asteroid and comet impacts on the Moon.

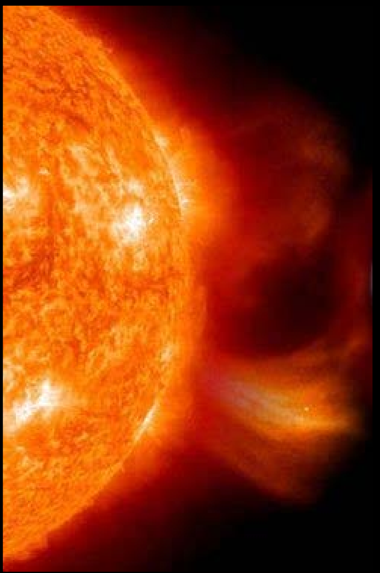


Water-building components erupted during volcanic eruptions.



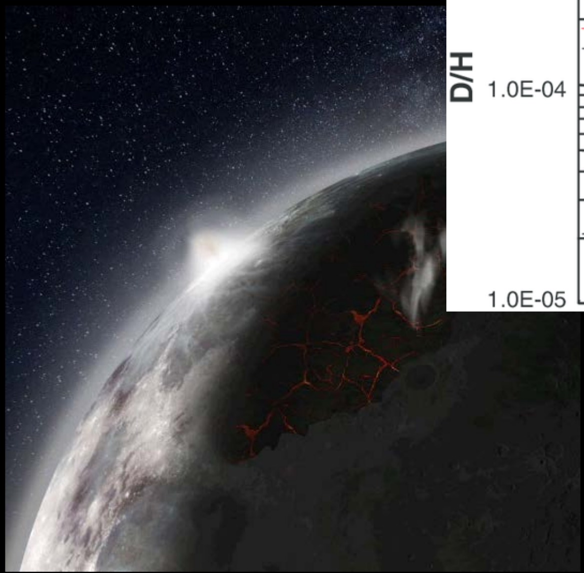
Implications for a Mission Prospecting for Lunar Volatiles

- The source of volatiles can affect the composition of these volatile deposits.

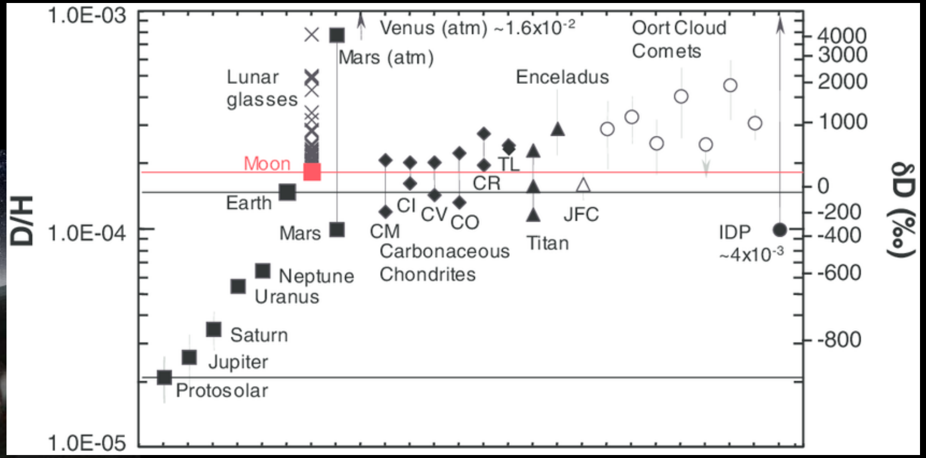


Solar wind-delivered hydrogen trapped in the Moon's PSRs.

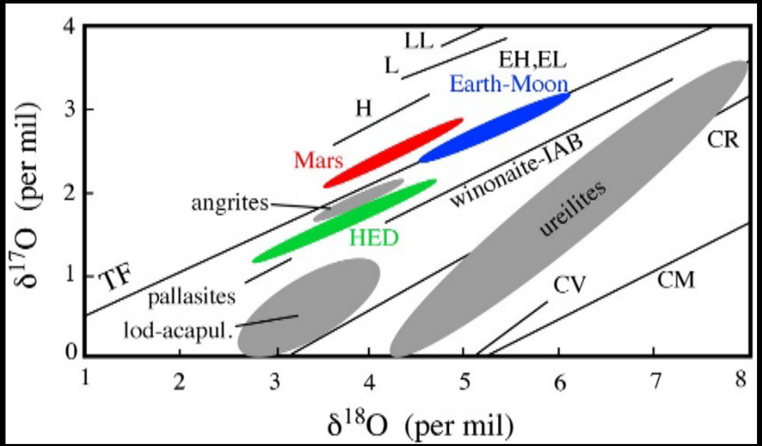
Water delivered by asteroid and comet impacts on the Moon.



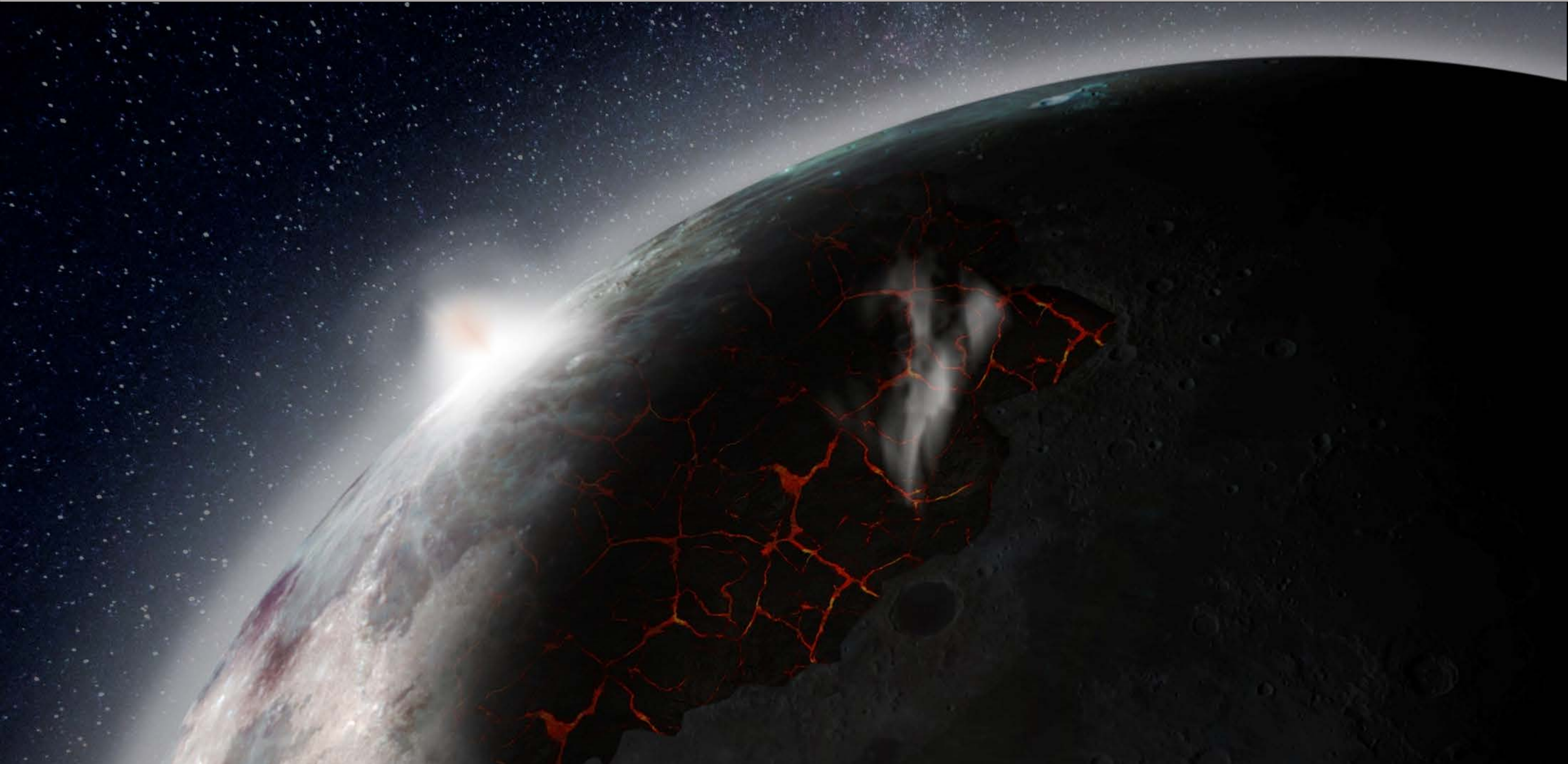
Water-building components erupted during volcanic eruptions.



D/H isotopes across the Solar System, from Saal et al., 2013 and references therein.



Oxygen isotopes across the Solar System from Righter and O'Brien, 2007 and refs. therein.



The Current Lunar Atmosphere

- Detected via Apollo 14, 15 (*e.g.*, *Johnson et al.*, 1972; *Stern*, 1999 and references therein)
  - Night Pressure: ~1.6 × 10^{-13} atm
  - Day Pressure: ~1.6 × 10^{-15} atm
  - Ar, CH_4, He, CO, CO_2, N_2, Rn
- Surface Boundary Exosphere with various sources (*Stern*, 1999):
  - Solar Wind Impingement
  - Thermal, Sputtering, Chemical
  - Meteoritic Delivery
  - Outgassing of Internal Volatiles


Lunar ALSEP deployed during Apollo 12.

- Enhanced impact and volcanic activity >3 Gyr may have enabled development of more substantial collisional lunar atmosphere.