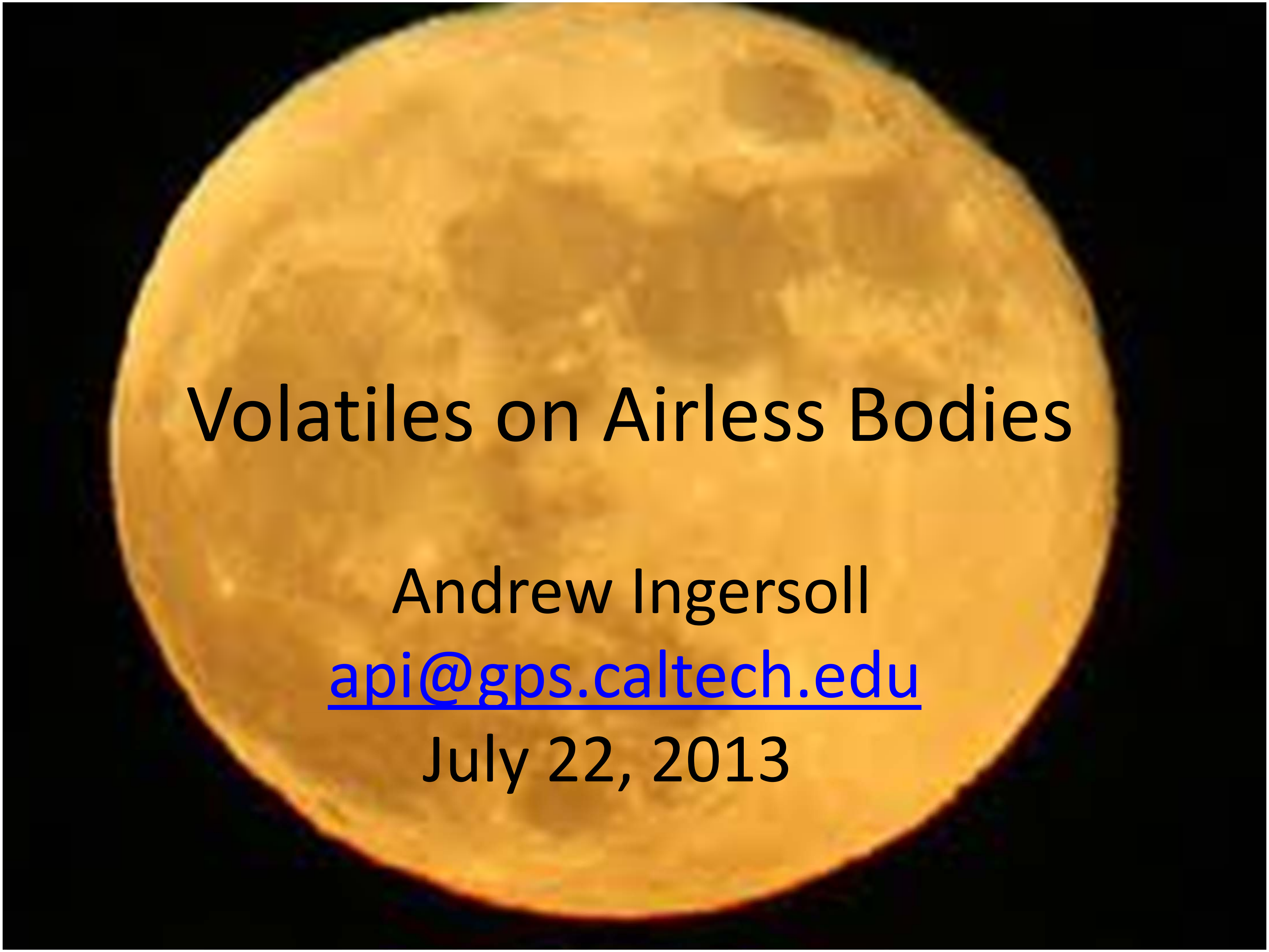

Volatiles on Airless Bodies

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Lunar Volatiles: An Outline in Matrix Form

Sources of volatiles	**Comets & asteroids**	**Moon's Interior**	**Solar wind**
Volatiles delivered	H_2O, CO, CO_2, H_2S, organics	hydrated minerals	H^+ + O^-, all elements
Recorded history	comets, asteroids	lunar water, outgassing	solar activity, cosmic rays
Volatiles as resources	astronaut life support	structures	power & propulsion
Basic physics	cold trapping	OH in mantle	mineral alteration
Competing processes, loss of record	Sublimation, solar UV, sputtering	exogenic vs. endogenic sources	degradation vs. preservation by burial

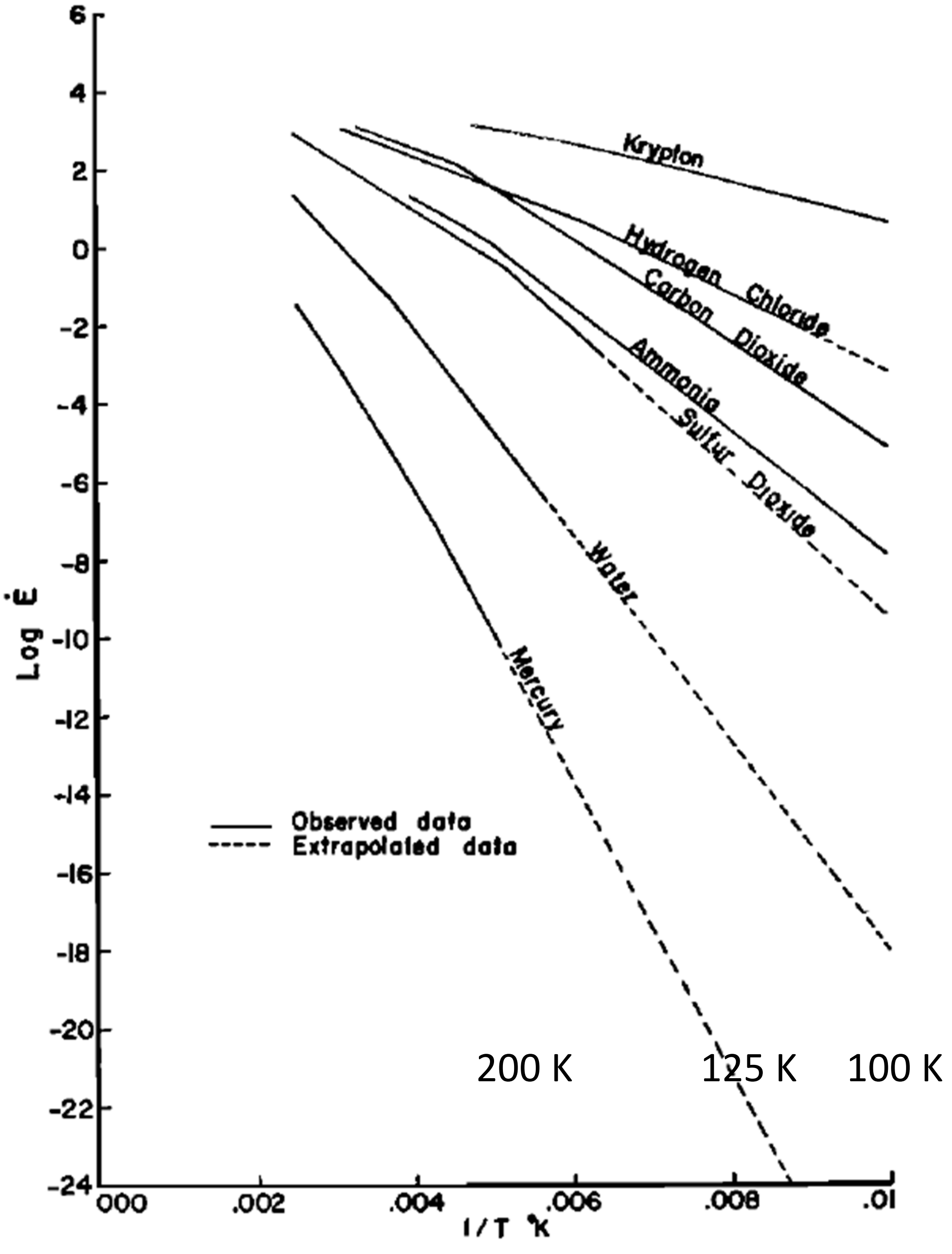
Watson et al. (1961)

$\dot{E}$ (g cm^2 s^{-1}) vs. 1/T (K)

4.56 x 10^9 yr = 1.44 x 10^{17} s

$$E = p\sqrt{\frac{\mu}{2\pi RT}}$$

James Jeans: The
Dynamical Theory of
Gases (1904)



200 K 125 K 100 K

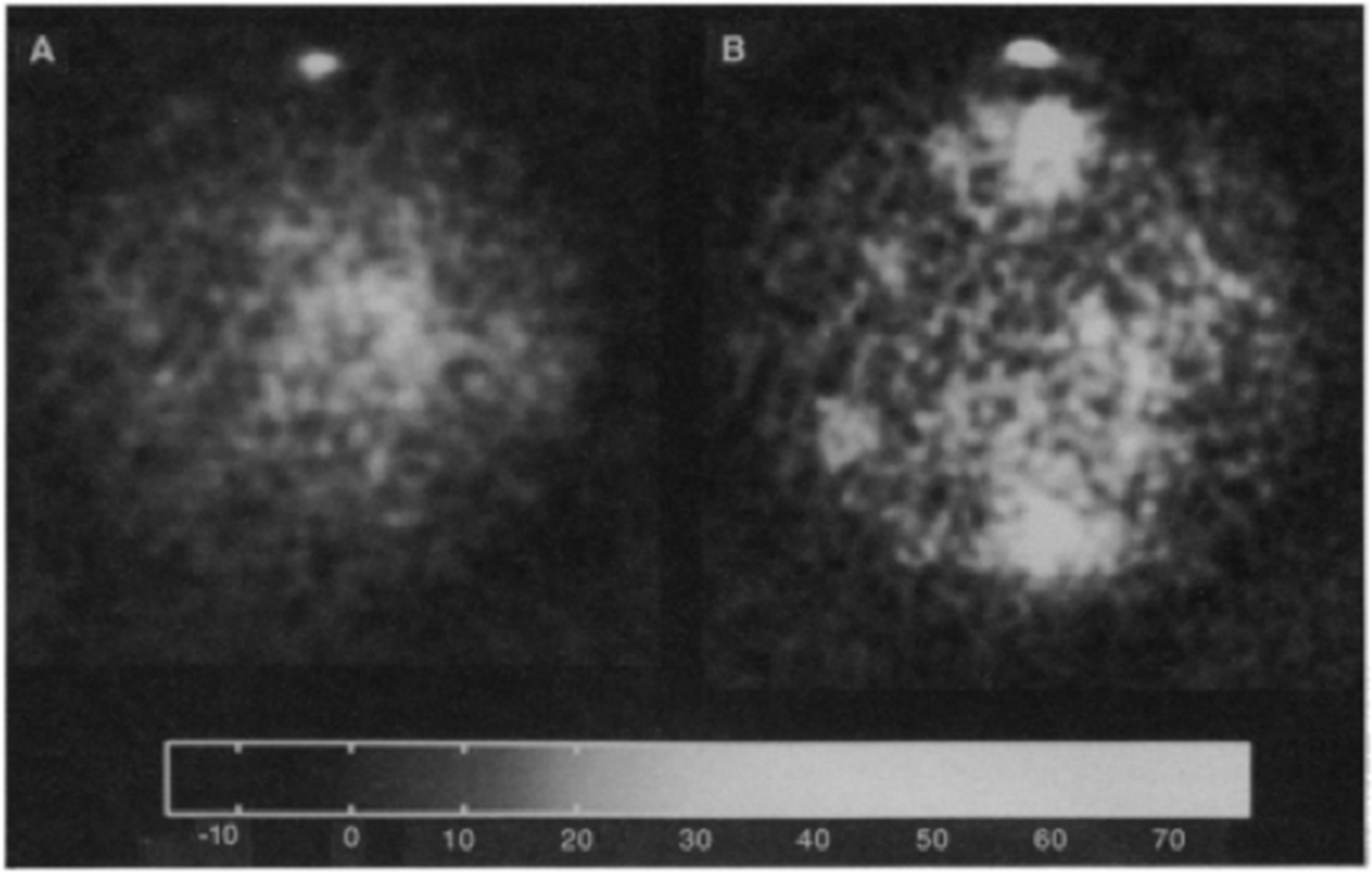


Fig. 1. Goldstone/VLA SS, or "depolarized," radar images of the Mercury disk for (**A**) 8 August 1991 and (**B**) 23 August 1991. North is at the top. Scale, radar reflectivity × 10^{-3} (see Eq. 1).

Goldstone/VLA depolarized radar images of Mercury. From Slade et al. (1992).

Paige et al. (1992): Mercury

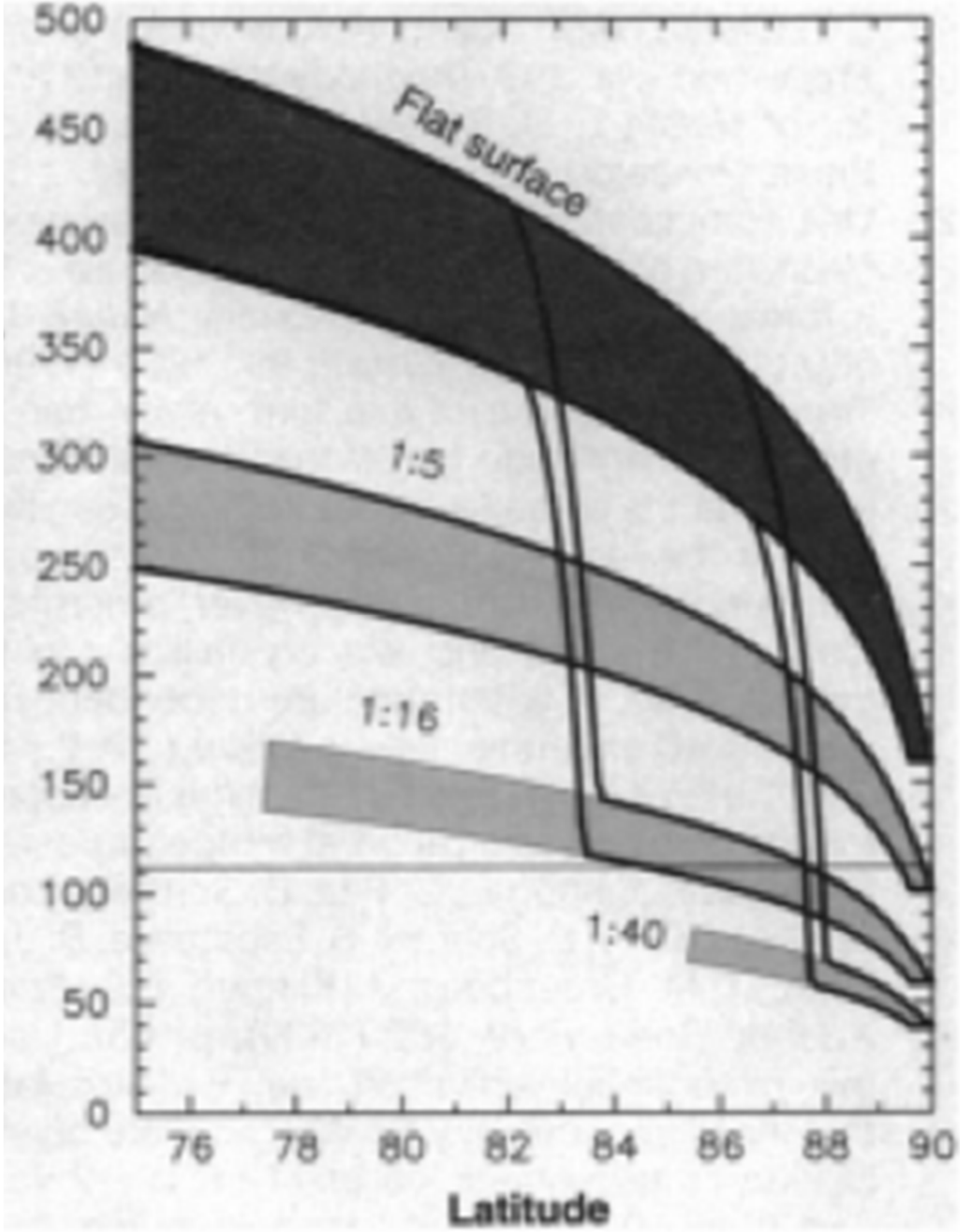
Biannual maximum surface temperature vs. latitude for craters of depth to diameter ratios of 1:5, 1:16, and 1:40.

The line at T = 112 K corresponds to an evaporation rate of 1 m/b.y.

Ingersoll et al. (1992): Spherical bowl-shaped craters:

$$\sigma T^4 = F_{abs}(1 + A/\varepsilon)(2d/D)^2$$

$$F_{abs} = F_0 \sin i (1 - A)$$



Butler (1997)

Random walk with MB velocity distribution with H_2O molecules uniformly spread over the surface.

T = lifetime against photo-dissociation and photo-Ionization.

$\tau(10^4\ \mathrm{s})$	$n_{stable}(\%)$
3.3	21
6.7	34
13.0	50

Lower curve: Probability of a single molecule reaching a stable cold trap vs. latitude (my interpretation of Butler's Figure 5).

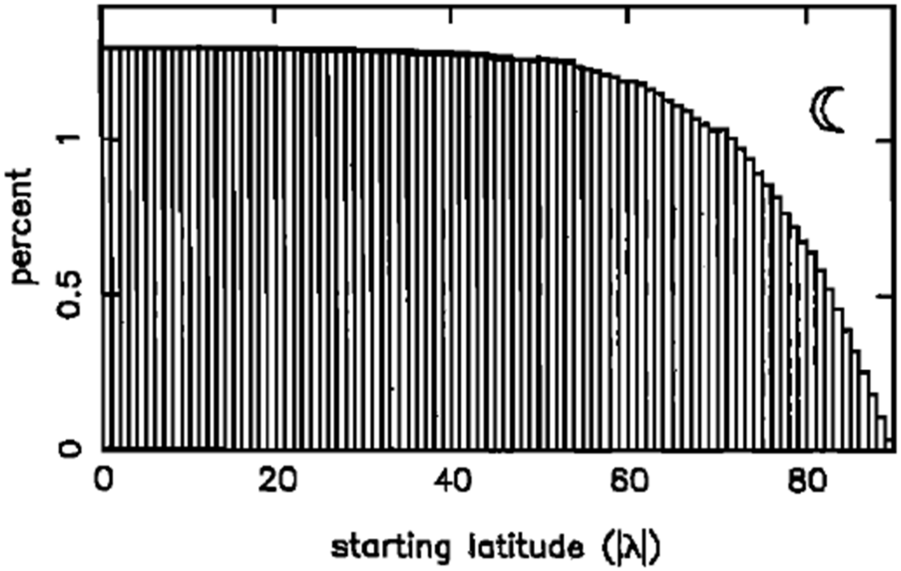
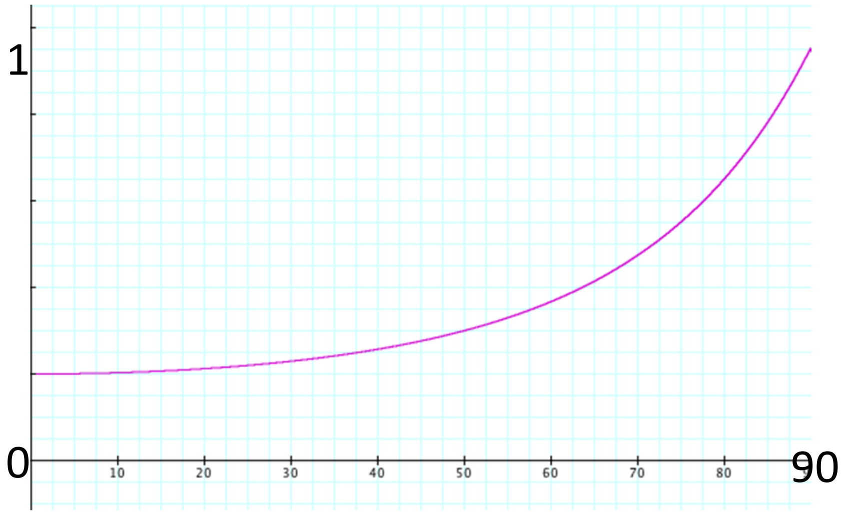


Figure 5. Histogram of the starting latitude of molecules which eventually became stable in the nominal Mercury and Moon simulations, showing that equatorial molecules may become stable.



Moses (1999): Mercury

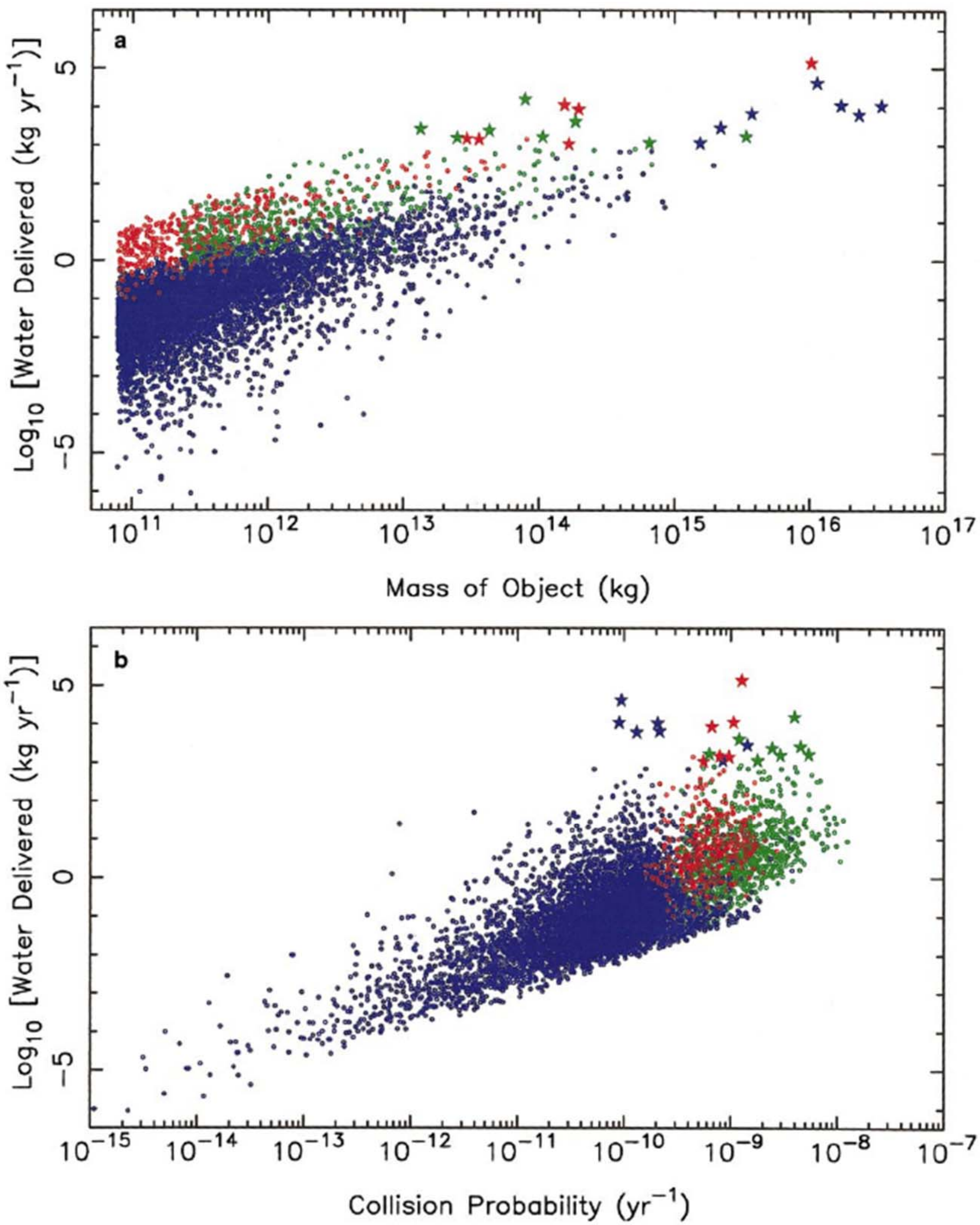
Monte Carlo results
for 3 kinds of impactors

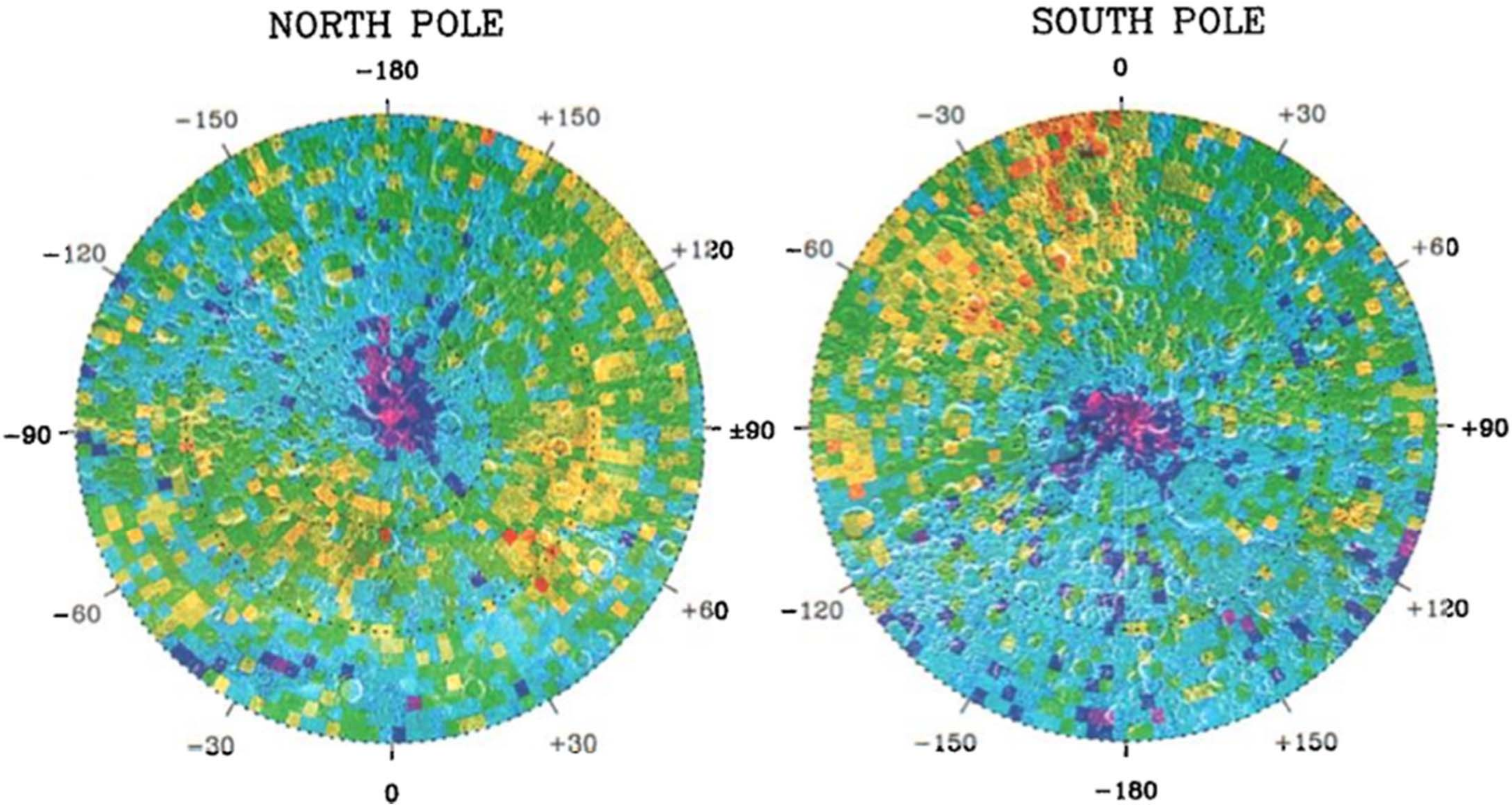
Asteroids in green
0.04-2 x 10^{17} g over 3.5 b.y.

Jupiter-family comets in red
Halley-type comets in blue
0.03-20 x 10^{17} g over 3.5 b.y.

Micrometeoroids (IDPs)
0.3-6 x 10^{17} g over 3.5 b.y.

Observations of poles:
Mercury: 0.6-6 x 10^{17} g
Moon: 2 x 10^{15} g





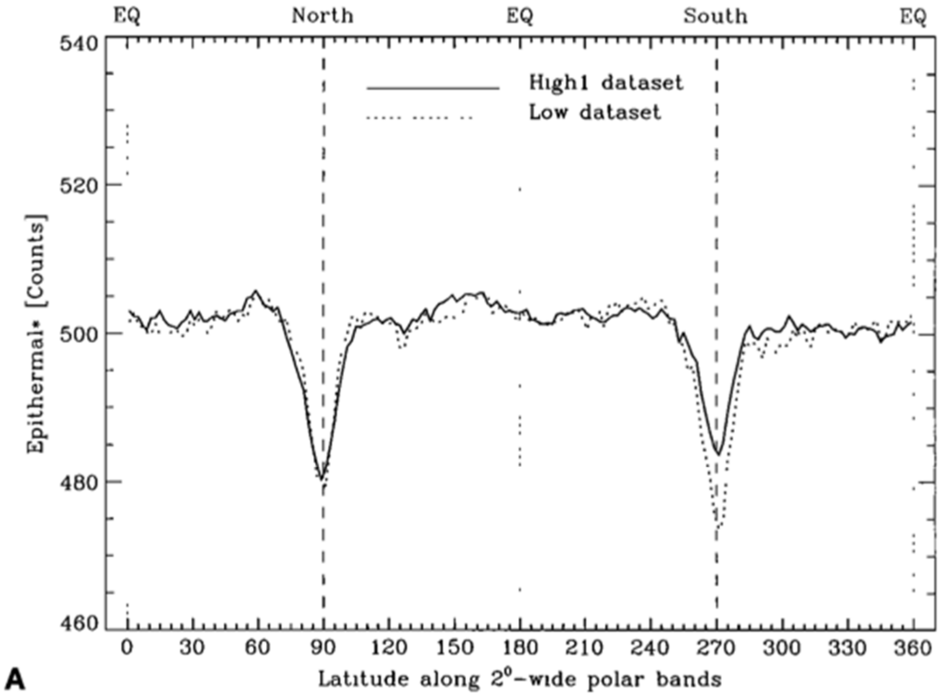
Moon: Absorption of epithermal neutrons poleward of ±45°. Purple color indicates the presence of hydrogen, either H_2O or OH. From Feldman et al. (2000).

A. Epithermal neutrons
B. Fast neutrons

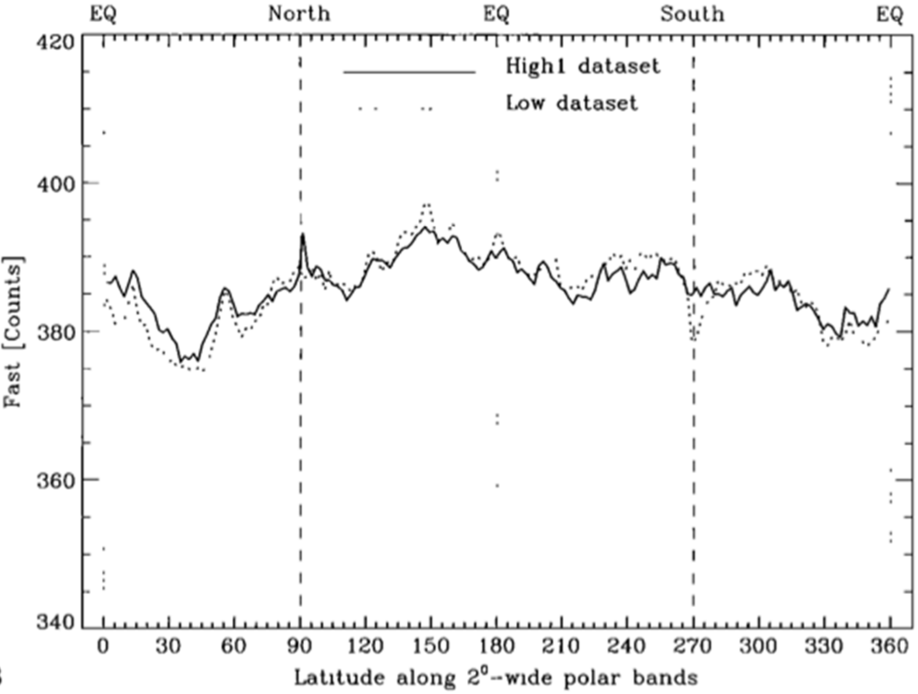
Low counting rates indicate absorption by hydrogen. Fast neutrons are more sensitive to elements beside H.

The polar deposits are estimated to be 1.5 ±0.8% by mass of water ice. Any deposits of pure water ice must be at least 1 m below the surface.

From Feldman et al. (2000)
2 x 10^{15} g ice at lunar poles

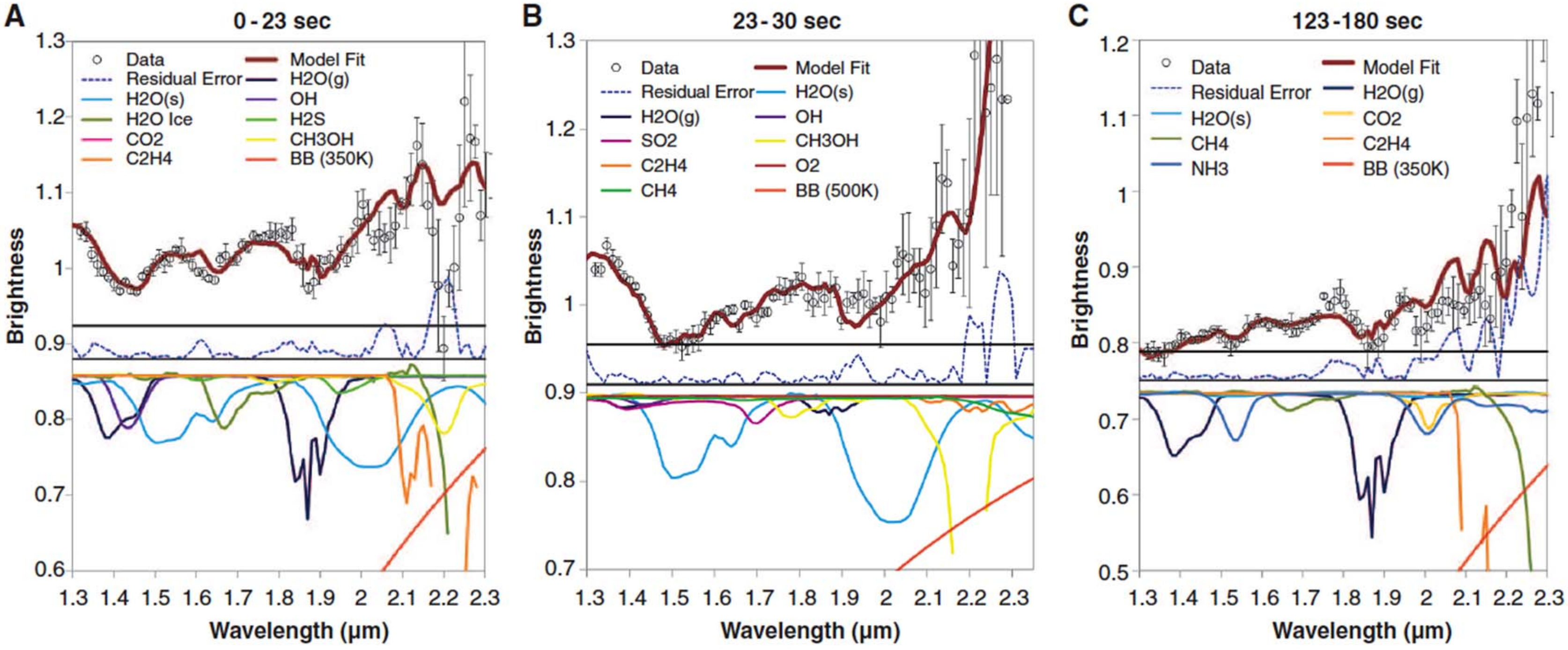


A



B

Colaprete et al. (2010): Moon. LCROSS ejecta plume

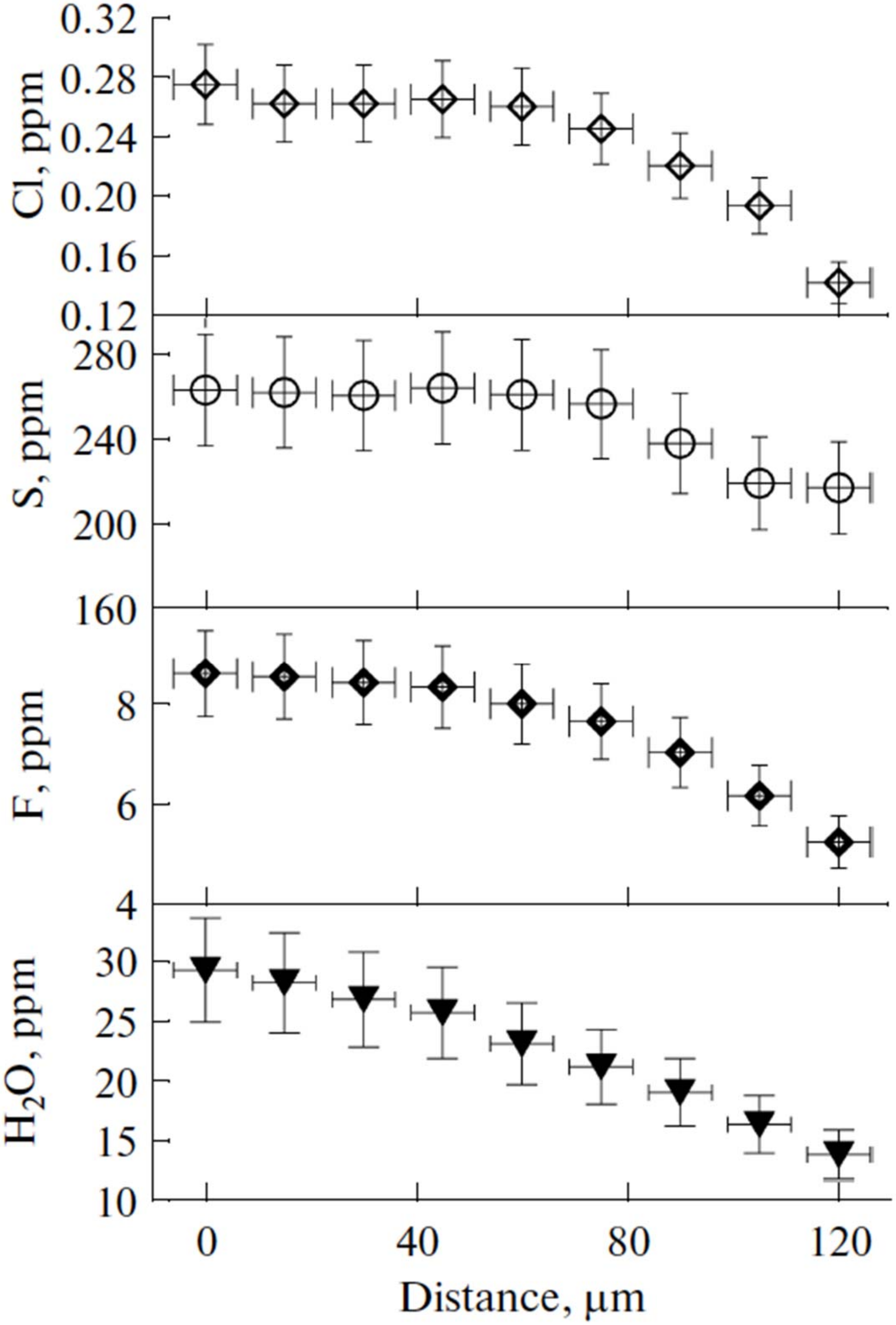


Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$*
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

Volatile content of lunar glass beads vs. distance from the center.

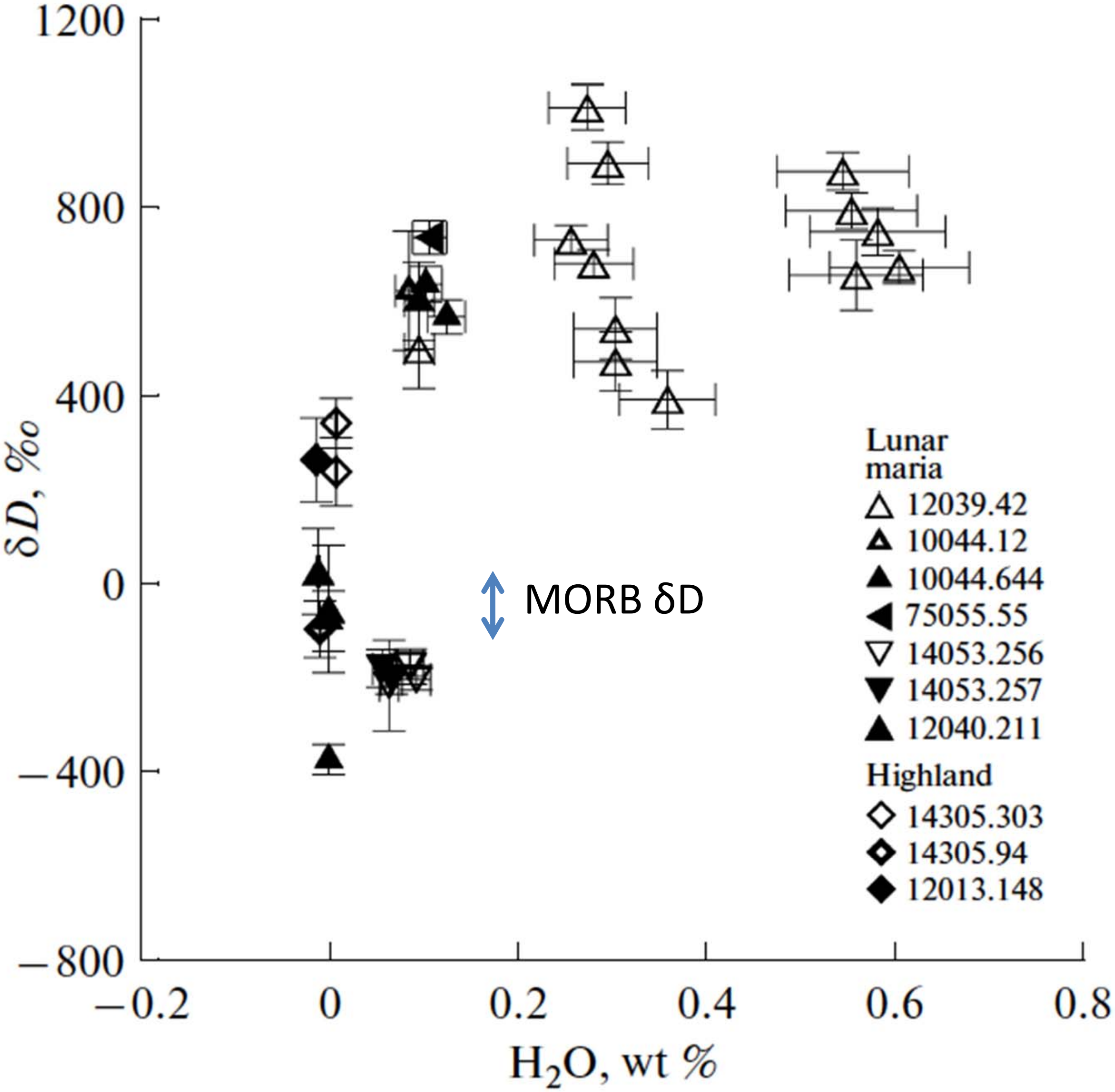
Terrestrial contamination and solar wind implantation would have ***increased*** with distance from the center.

Redrawn by Basilevsky et al. (2012) from data by Saal (2008).



From Basilevsky
et al. (2012).

Apatite = calcium
phosphate with F,
which is sometimes
replaced by Cl or OH.



↕ MORB δD

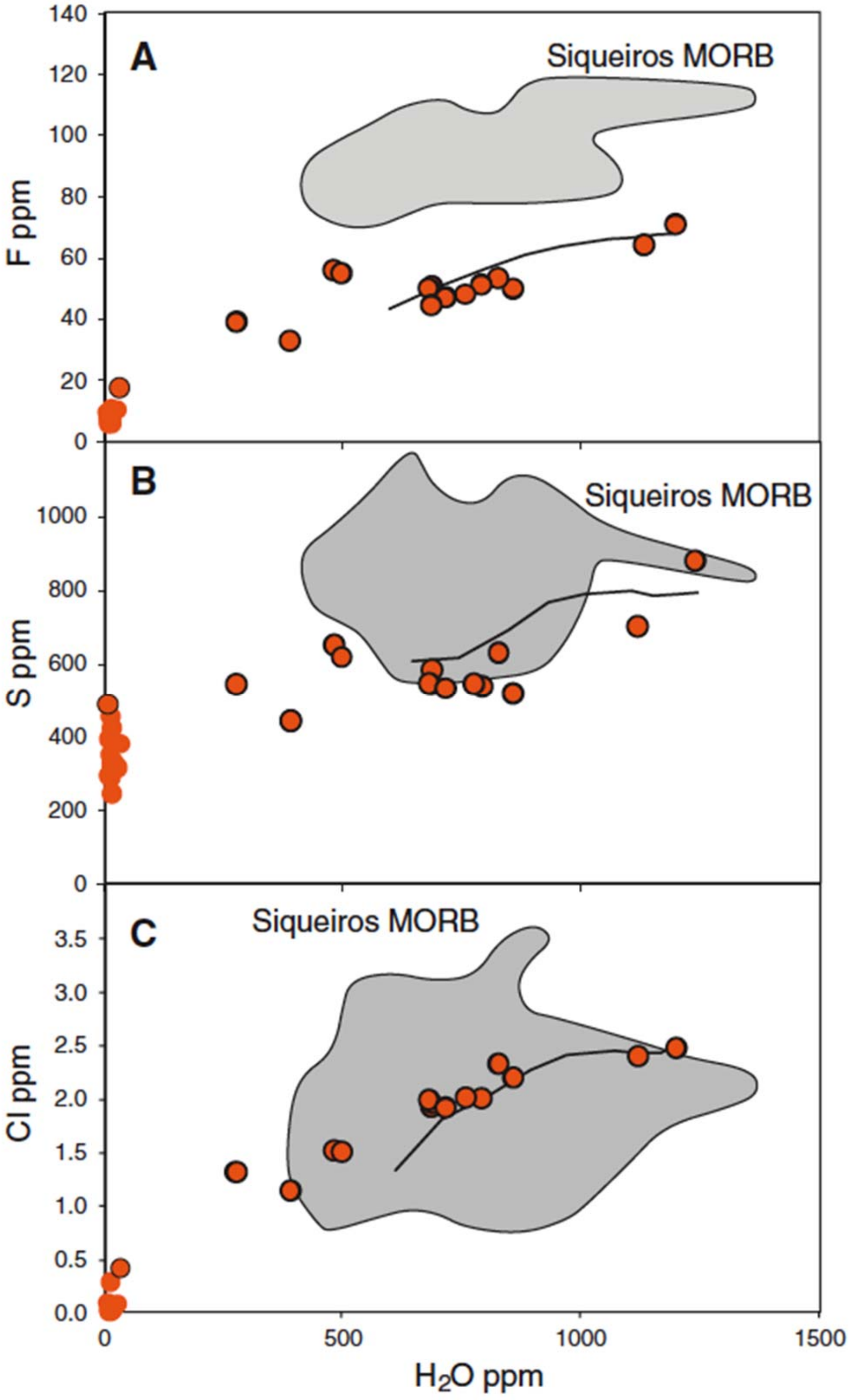
Fig. 3. Hydroxyl contents (in H_2O equivalent) and σ*D* of lunar apatites (built from the data of Table 7 in *Supplementary Materials* to (Greenwood et al., 2011a)).

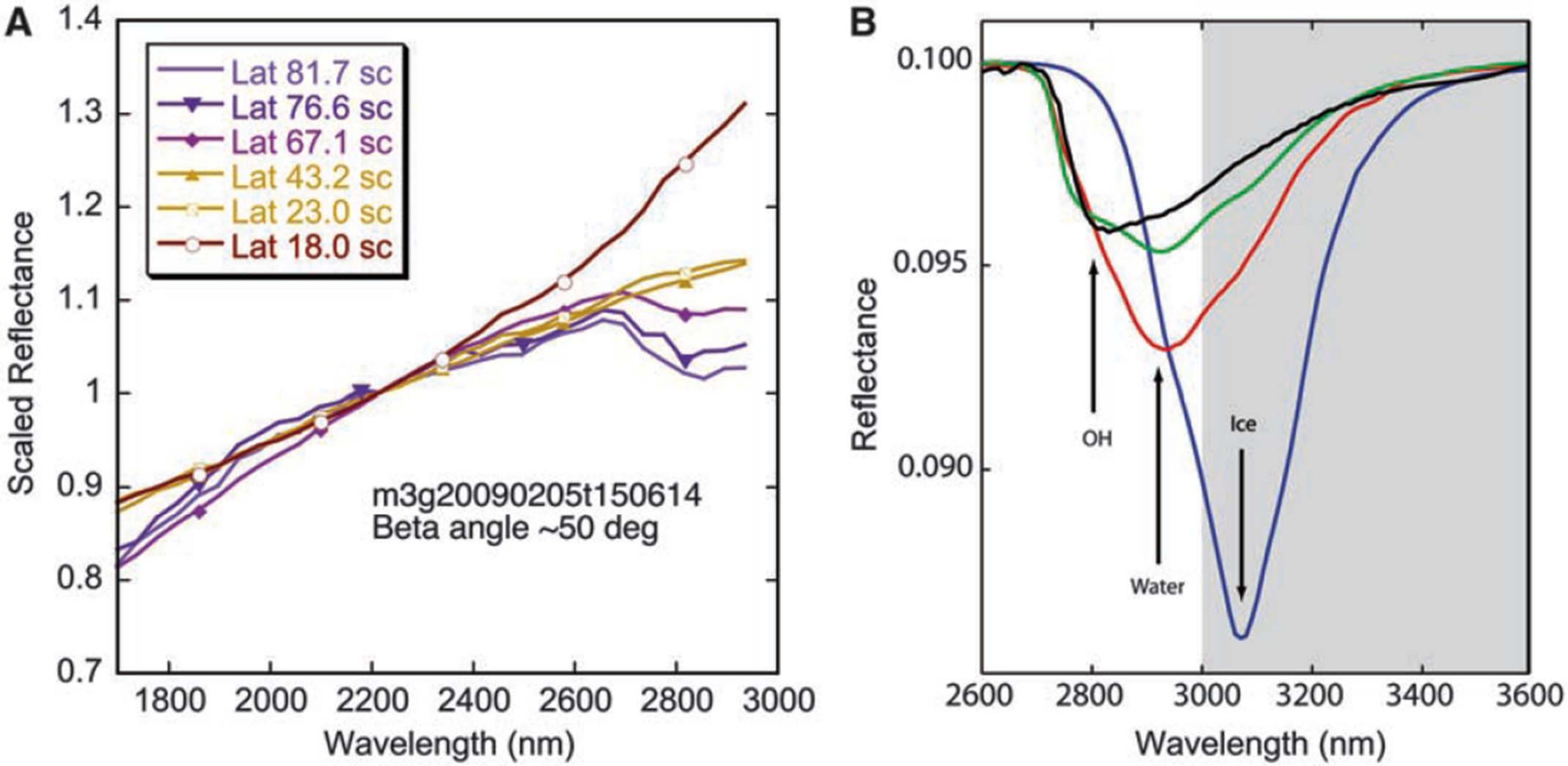
Volatiles in lunar melt Inclusions from Hauri et al. (2011).

Orange circles with dark outlines are from the inclusions. Orange circles without outline are from the matrix in which the inclusions are imbedded.

Implies volatiles were not entirely lost during the lunar-forming giant impact.

Degassing may have contributed to polar volatile inventory



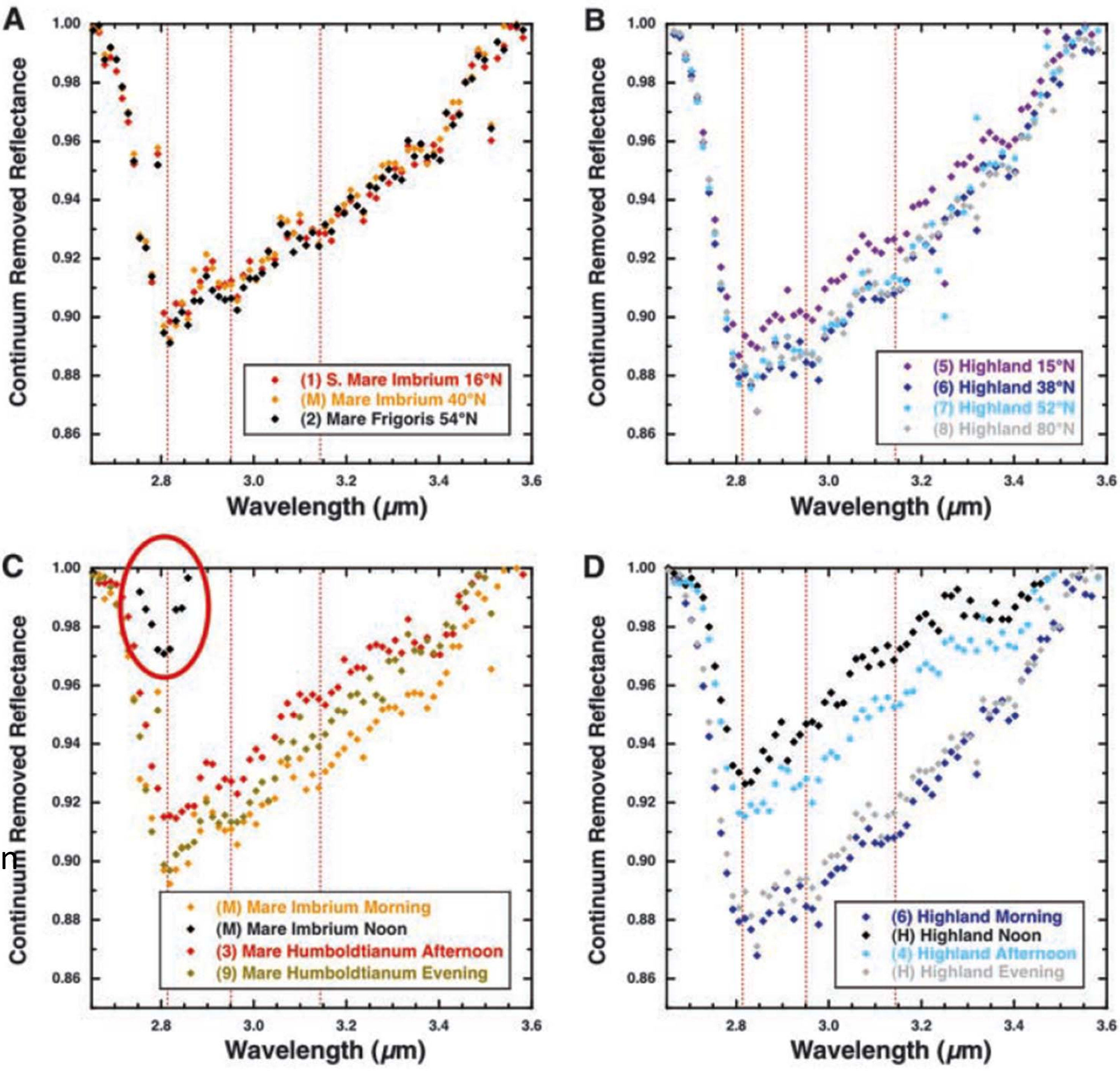


Pieters (2009). 2.8-3.0 µm absorption bands of water are stronger at high latitudes

Sunshine et al. (200): diurnal cycles in 3 μm water band.

Higher position on the graph (noon time) means less water.

Water is on the grain surfaces, Is produced by solar wind, and evaporates when T is high (noon).



Solar wind particle flux
3 x 10^8 cm^{-2} s^{-1} .

Assume it impacts the lunar disk for 3.5 b.y. and produces one H_2O for every 2 particles (100% efficiency, no losses).

Total mass = 4.7 x 10^{19} g.

100 x (asteroids + comets)
10,000 x (polar ice observed)

J. Aerosp. Eng. 2013.26:5-17.

Sanders and Larsen (2013): In Situ Resource Utilization

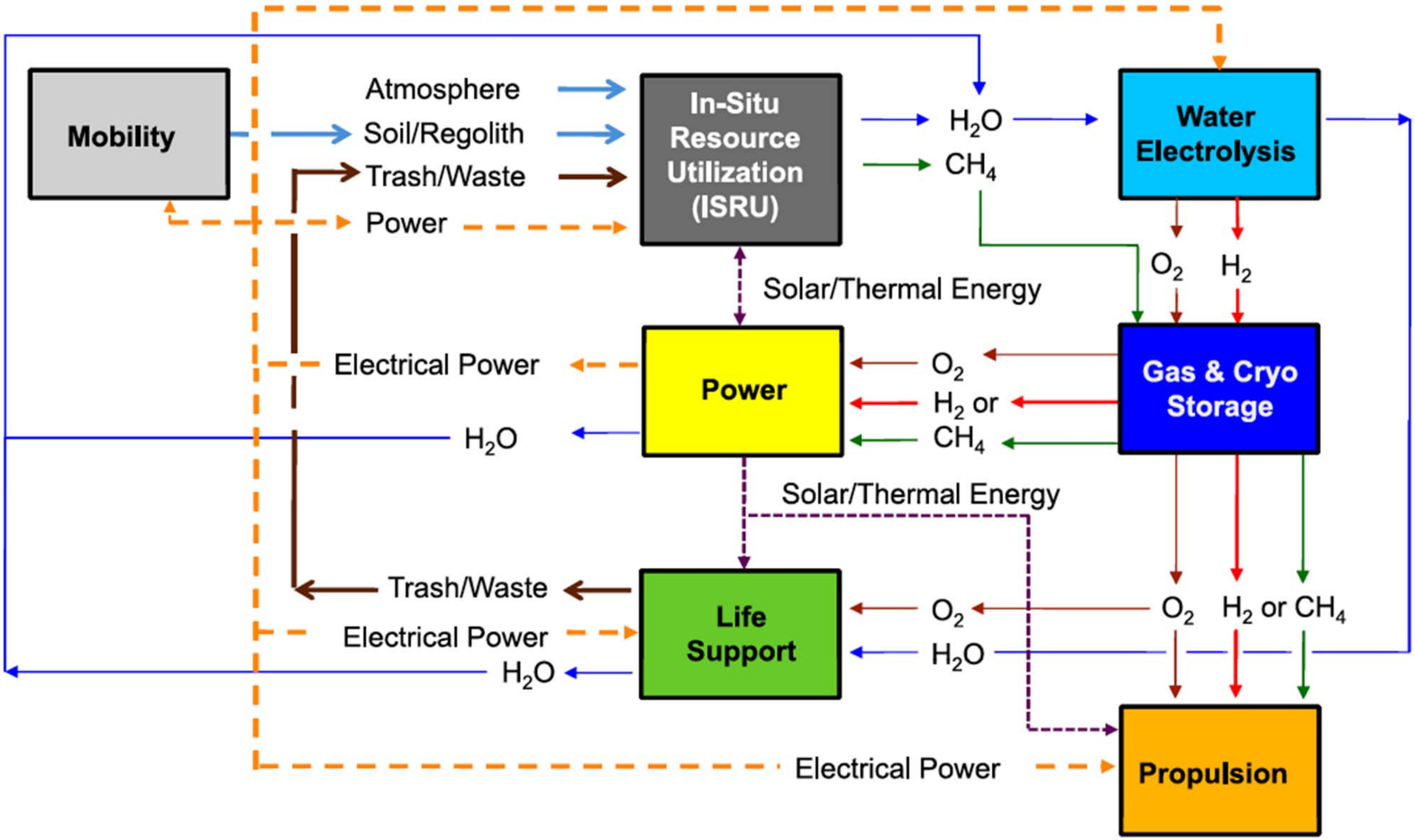


Fig. 2. Integrated ISRU-power-propulsion-life support fluid and energy cycles

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