In Situ Formation of Molecular Water on Mercury.

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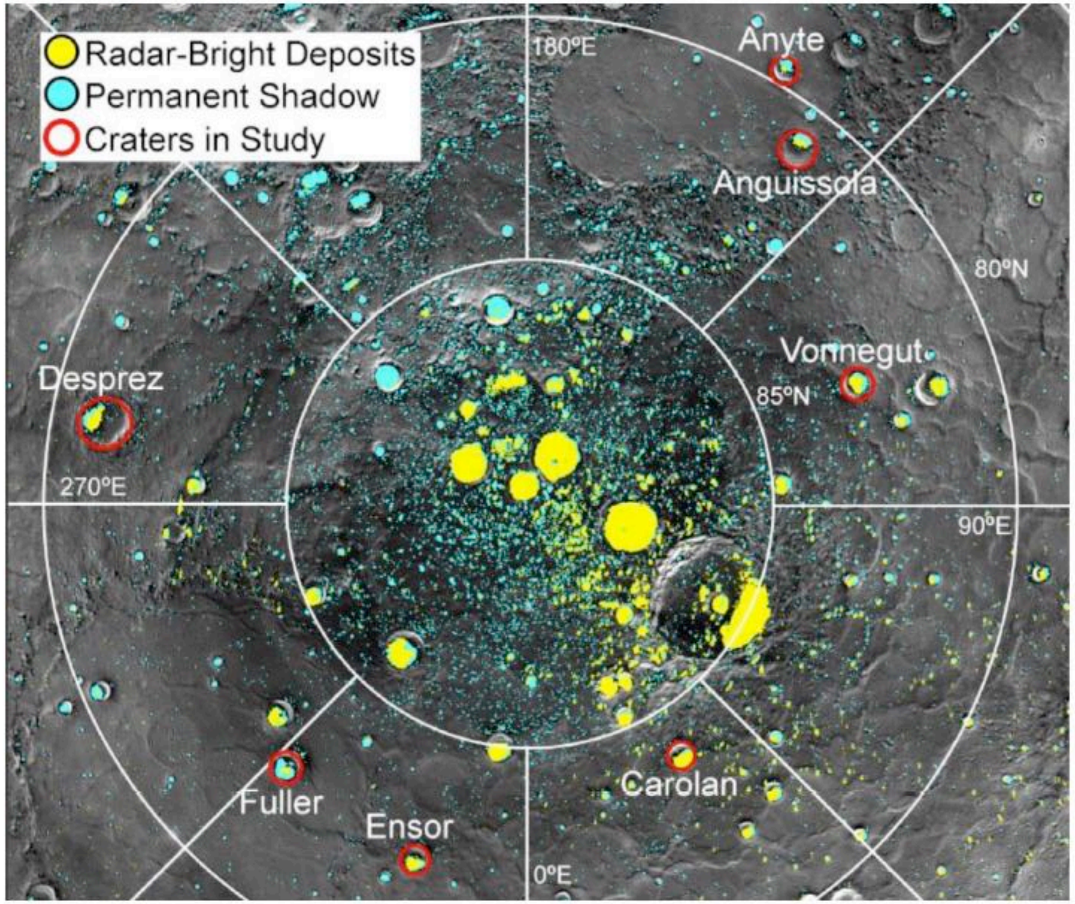
Water Detection on Mercury

- Ground based radar observations of Mercury have yielded maps of bright and depolarizing features near the poles[1, 2].
- Subsequent radar measurements isolated these abnormalities to the permanently shadowed regions (PSRs)[3]. These radar anomalies were attributed to the presence of frozen water ice.
- Following these observations were seminal papers based on the neutron spectrometer[4] and the Mercury Laser Altimeter (MLA)[5].



1. Slade, *Science* 258, 635-640 (1992). 2. Harmon, *Science* 258, 640-643 (1992). 3. Harmon, *Icarus* 211, 37-50 (2011). 4. D. J. Lawrence, *Science* 339, 292-296 (2013). 5. G. A. Neumann, *Science* 339, 296-300 (2013).

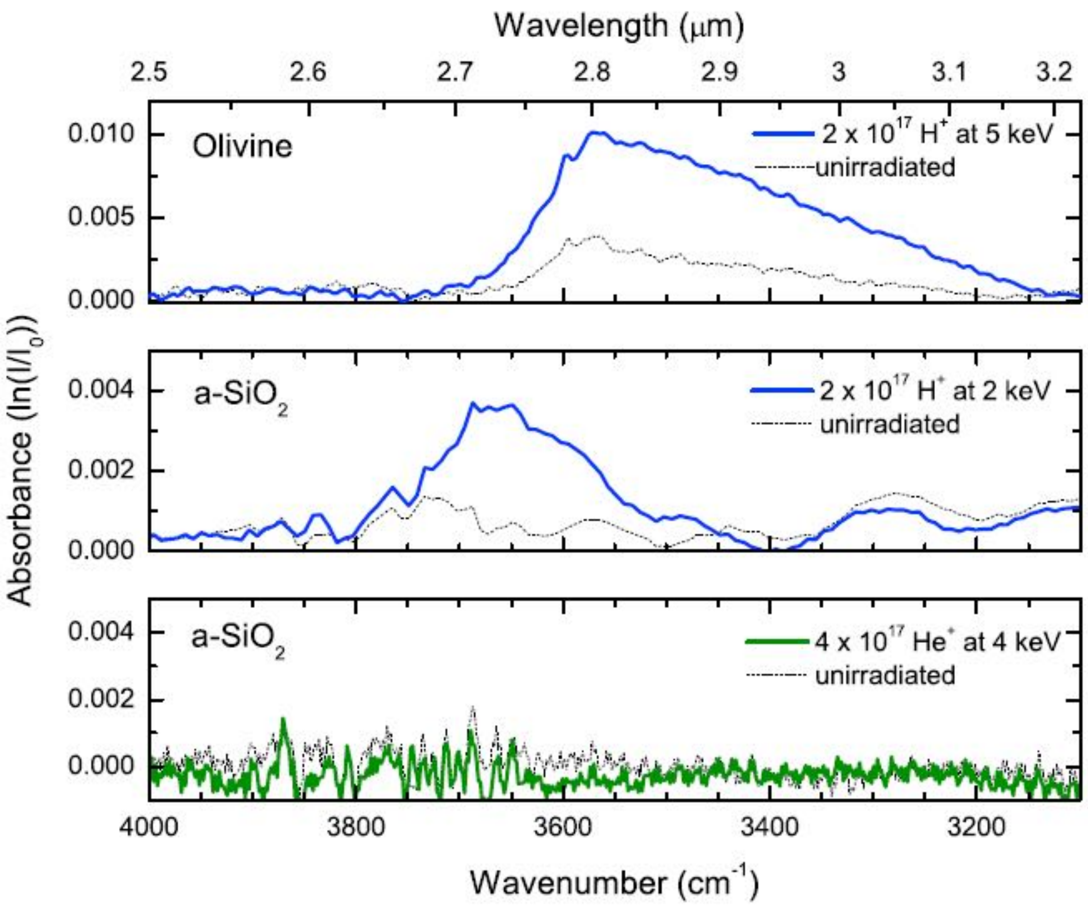
How did water get on the Mercury?

- Most common accepted answer is delivery of via meteorites and interplanetary dust particles[1]
  - Mercury intercepts 12 tons/day of meteoroids[2,3] and the energy input is high given the > 3 km/sec impact velocities, meteoroid-driven water production could also be an additional source of water, particularly on the nightside.
  - Delivery **CANNOT** explain the total amount, without invoking an abnormal large strike!
- *However, we postulate an* ***additional*** *source term: Solar Wind Induced Formation*[4]
  - *Implantation of keV* H^+
  - *Diffusion*
  - *Recombinative desorption*

[1]D. J. Lawrence, *Science* **339**, 292-296 (2013), [2]P. Pokorný, *ApJ* **863**, 31 (2018), [3]P. Pokorný *JGR Planets* **124**, 752– 778 (2019), [4]B. M. Jones, GRL **45**, 10,959-910,967, (2018).

Solar wind implantation makes hydroxyl, not water directly!

$MO + H^+ \rightarrow MOH$



Schaible M., *JGR Planets*, **2014,** 119(9)

Bragg peak indicates clearly defined stopping depth. Proton range is 10 - 30 nm.

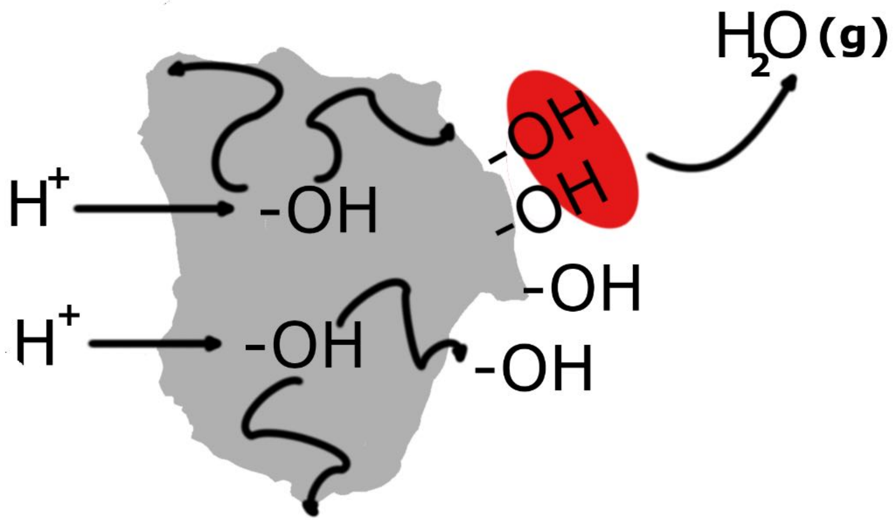
A thin shell of hydrogen accumulates as chemically bonded OH

For olivine saturated number density is ~10^{17} cm^2 and optical feature is BROAD.

Diffusion

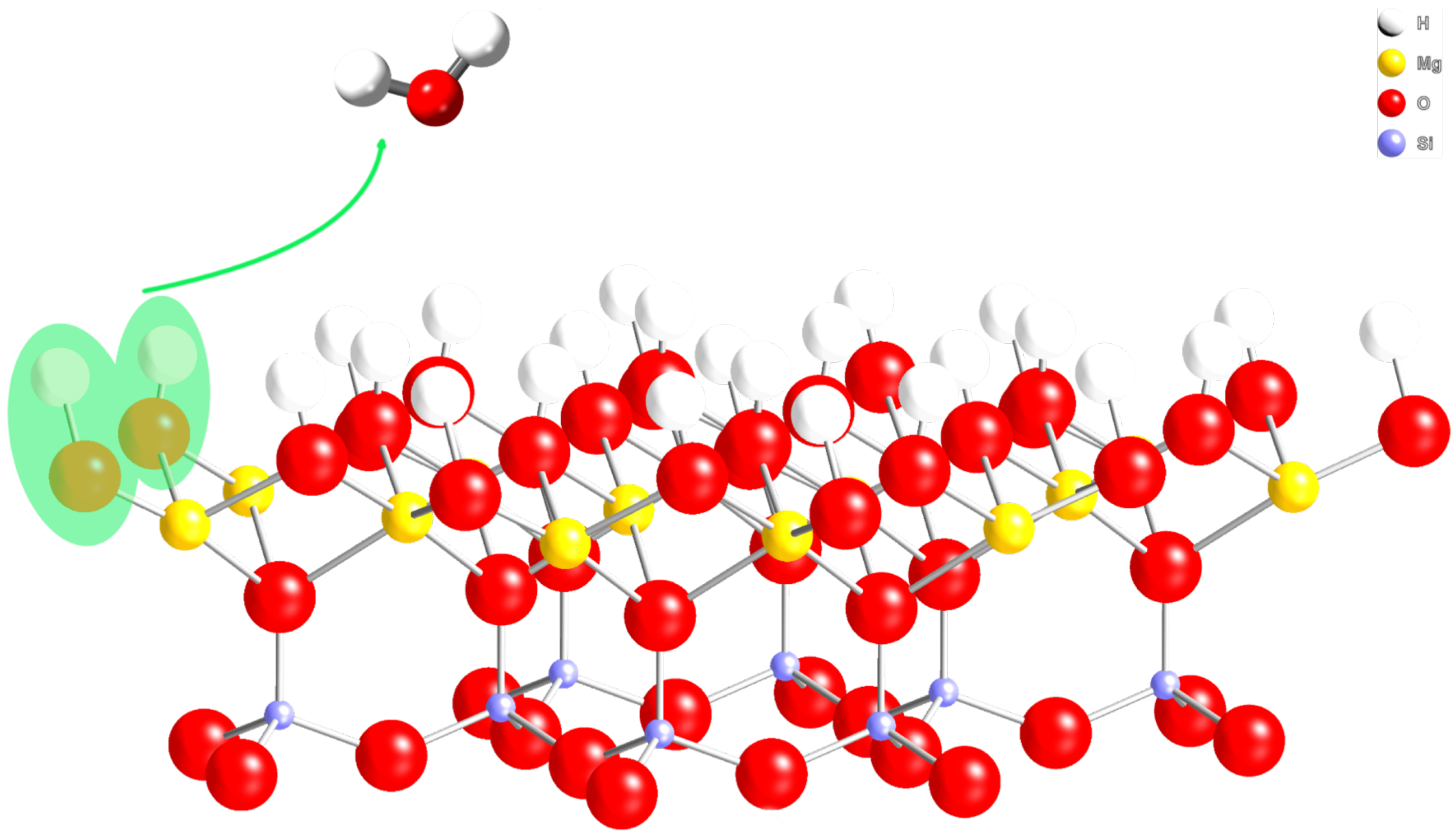
$$W(x,t)dx = \frac{1}{\sqrt{4\pi Dt}} e^{\left(\frac{-x^2}{4Dt}\right)} dx$$

- Analytical solution to 1D diffusion
- Penetration Depth of 10 nm
- Activated Diffusion Constant
- Spherical Grain Size of 60 um
- Only surficial OH sites were considered available for recombinative desorption

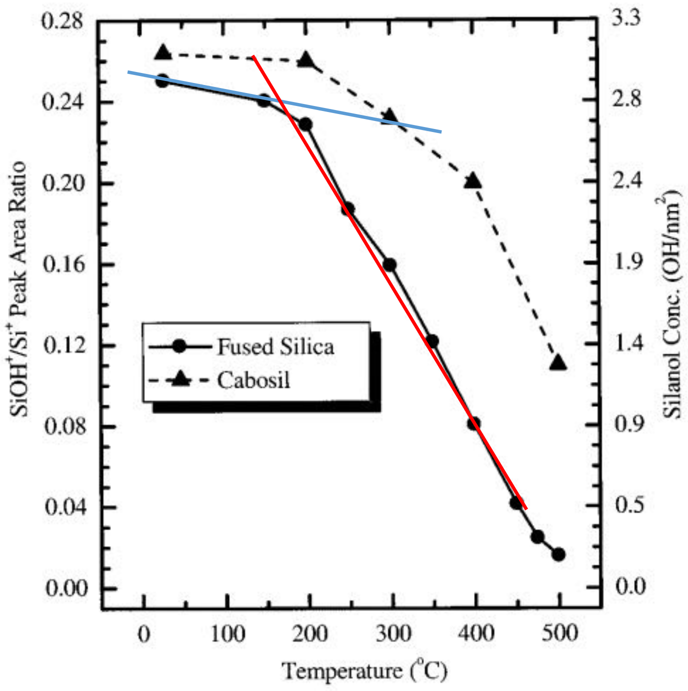


How to make water?

Recombinative Desorption (AKA Associative Desorption)

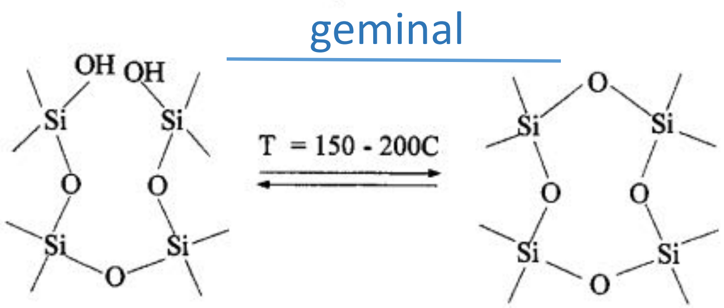


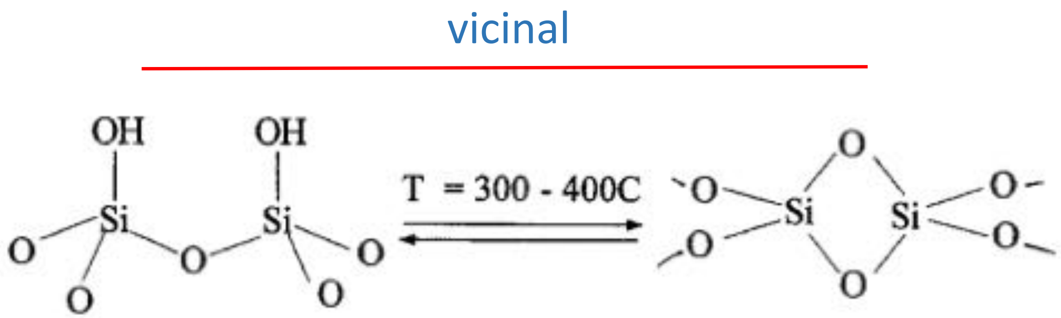
Recombinative desorption **kinetics of hydroxyl "defects"**



Temperature dependence of dehydroxylation (to form water) from <u>hydroxyl defects.</u>

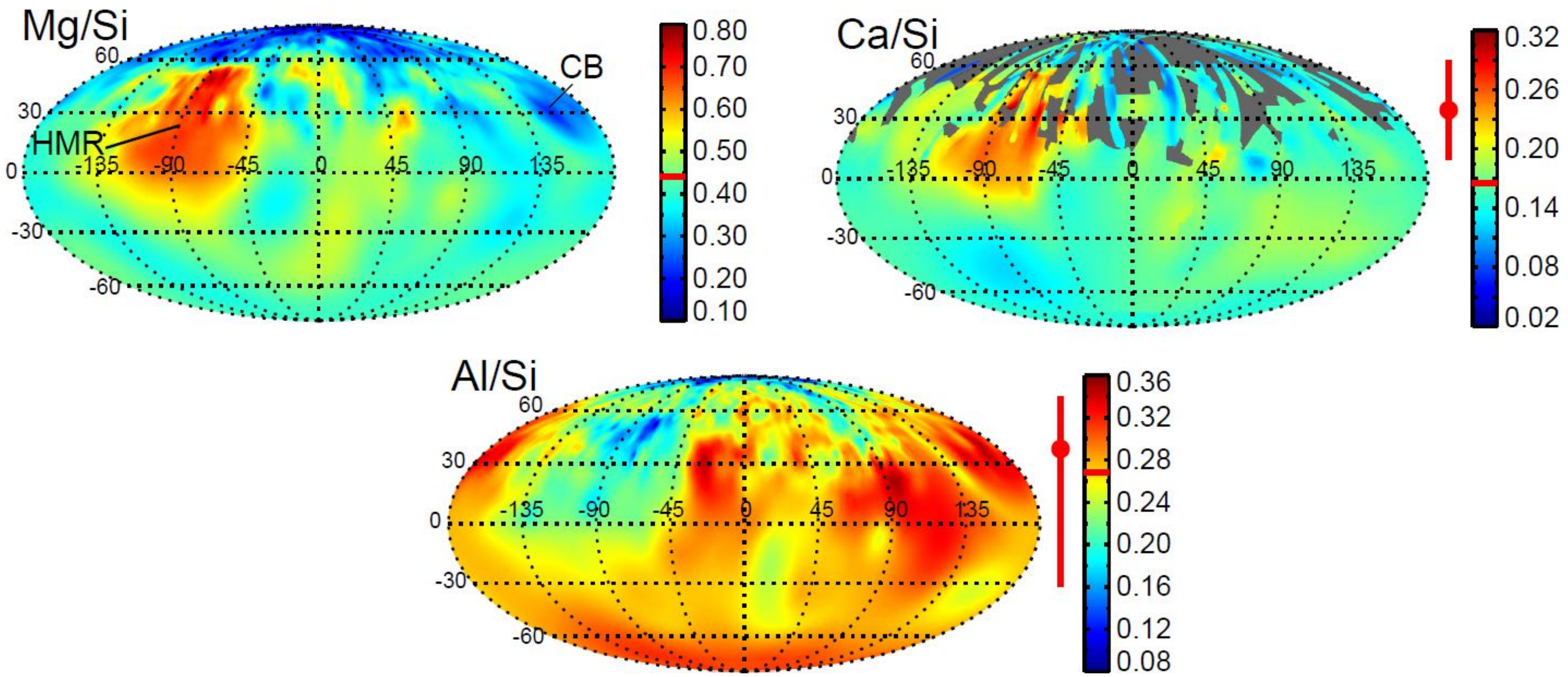
Two temp regimes for dehydroxylation based on stability of Si-OH structures.





<u>**Activation energy will depend on chemical "make-up" and be COVERAGE dependent.**</u> Changing a Si to Al, Mg, Ca, Fe, Ti all shift this to lower temps and lower binding energies.

Surface of Mercury



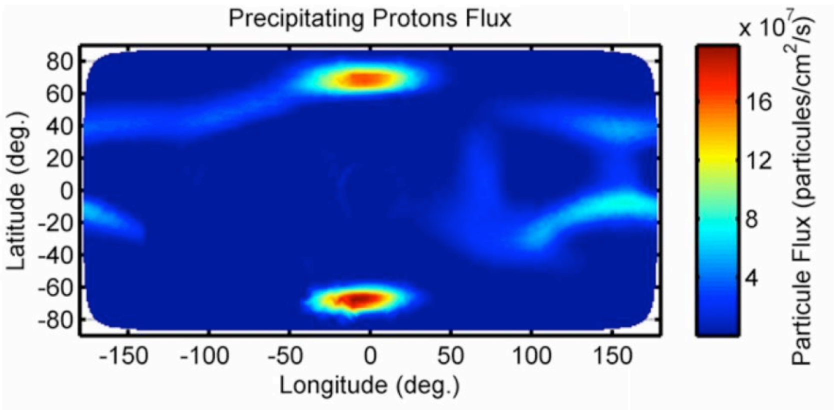
The surface of Mercury is assumed to consist entirely of four metal oxides; SiO_2, Al_2O_3, MgO, and CaO with SiO_2 assumed to have a uniform coverage of 55%.

From here, a linear combination of the rates at each latitude and longitude was calculated based on their respective RD activation energies (E_a) and prefactors (ν) of each hydrated metal oxide:

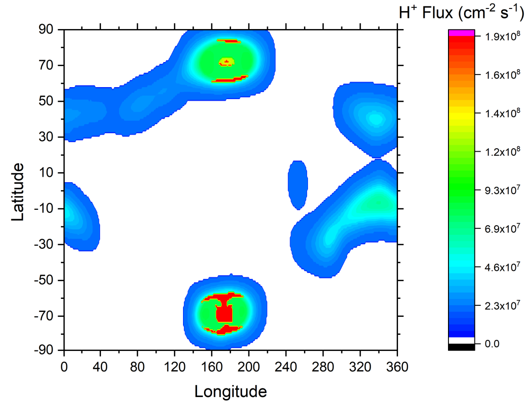
All of these metal oxides have an onset temperature well below the peak dayside temperature of Mercury

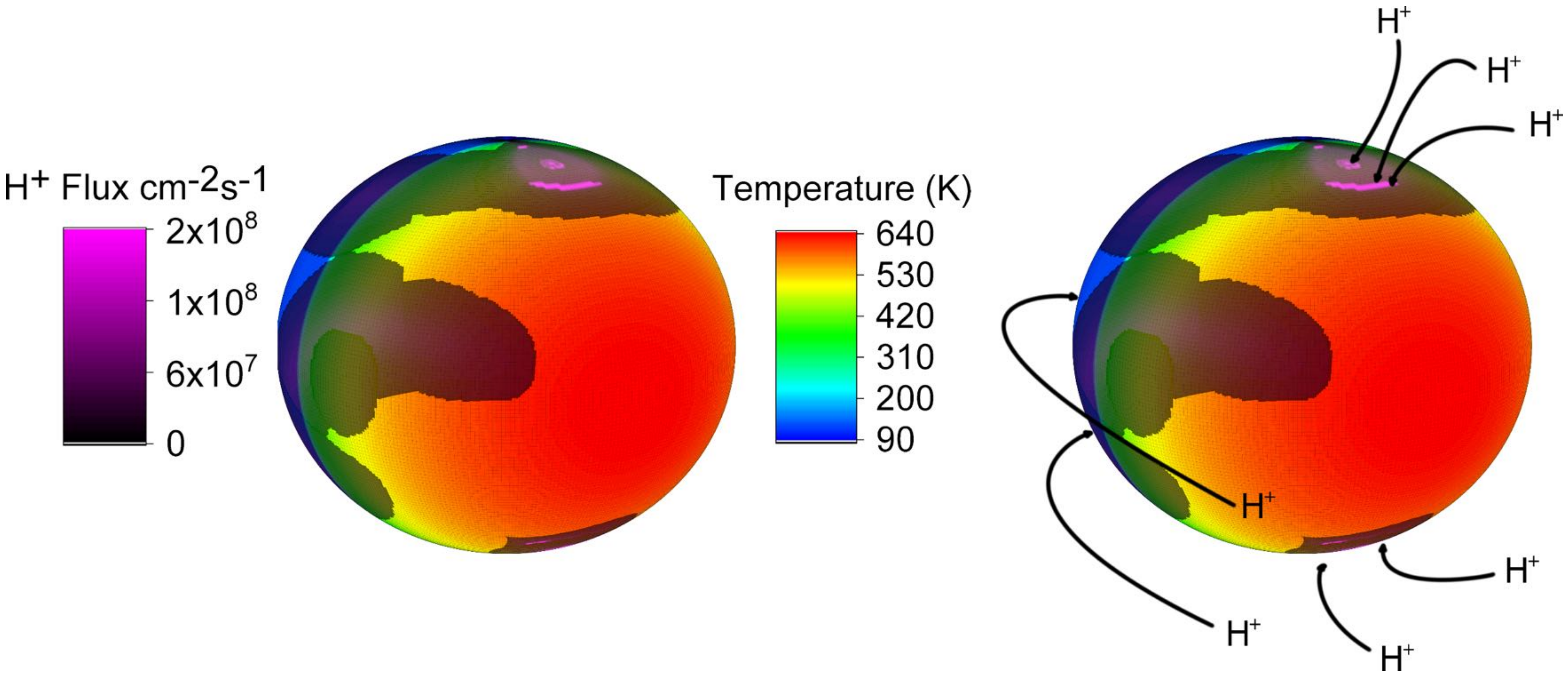
Mineral	Activation Energy	Prefactor	Onset Temperature
SiO_2	100 kJ mol^{-1}	4.9×10^{7} s^{-1}	600 K
Al_2O_3	96 kJ mol^{-1}	1.0×10^{13} s^{-1}	350 K
TiO_2	75 kJ mol^{-1}	4.9×10^{10} s^{-1}	250 K
MgO	63 kJ mol^{-1}	1.0×10^{13} s^{-1}	250 K
CaO	87 kJ mol^{-1}	1.0×10^{13} s^{-1}	300 K

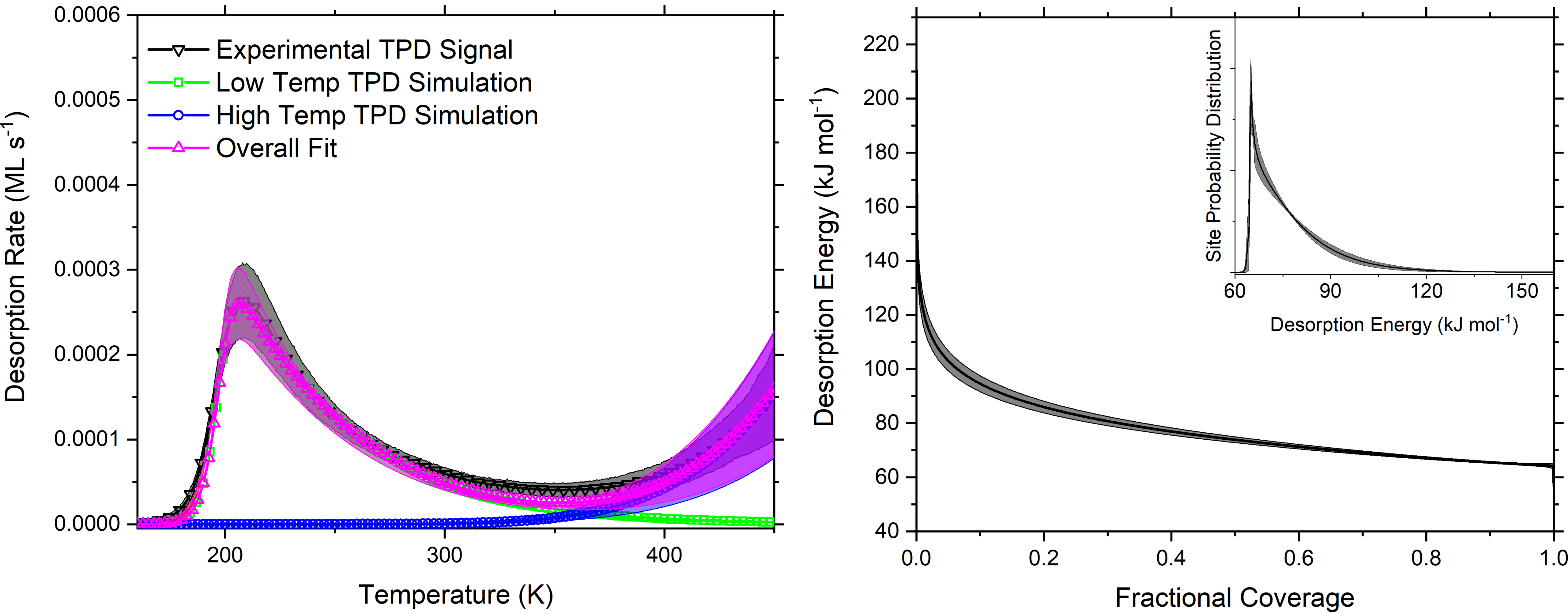
Polanyi-Wigner Equation, $\frac{d\theta}{dt} = \nu\theta^2 e^{\left(\frac{-Ea}{RT}\right)}$



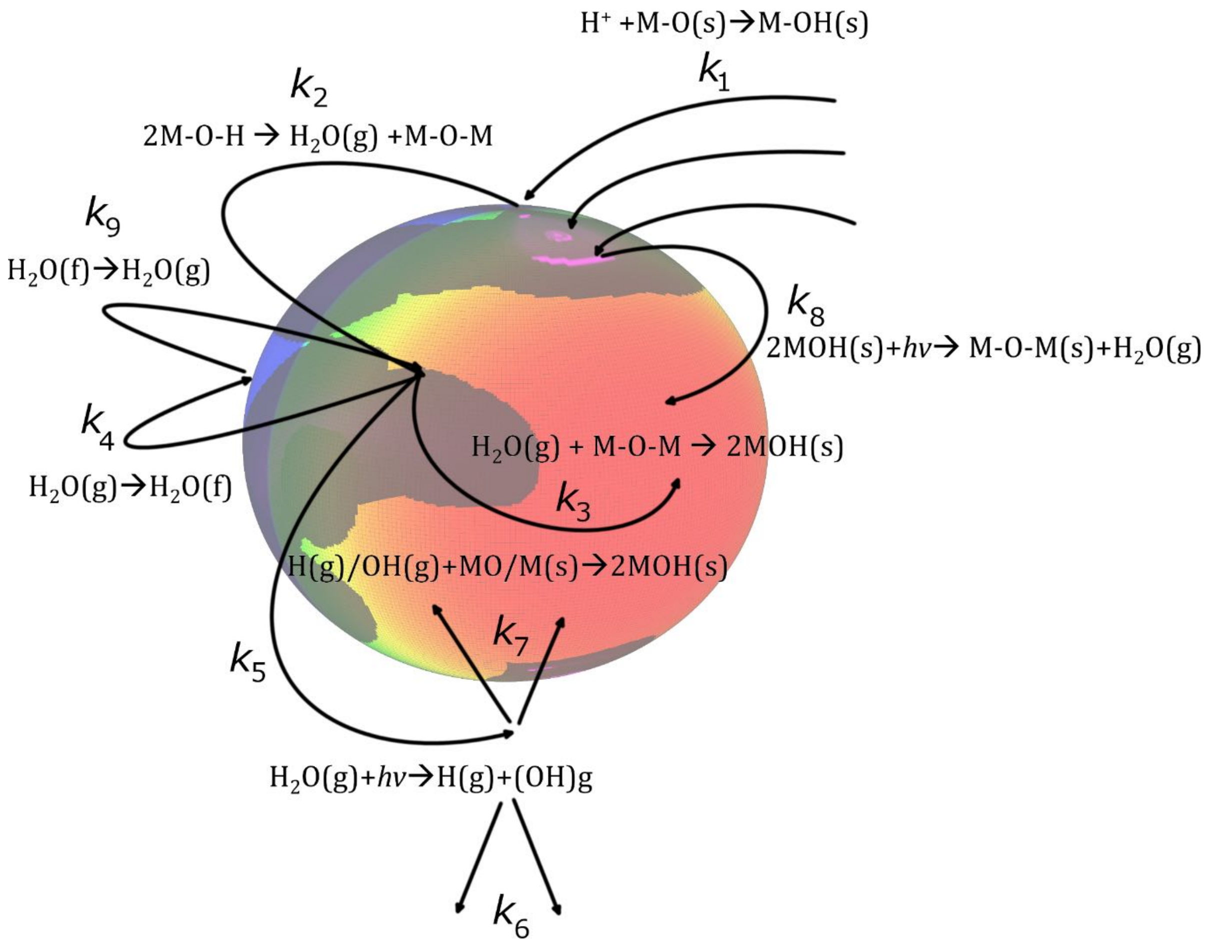
Benna, M., Icarus **2010**.







H_2O desorption data from Lunar Mare (Apollo sample 10084) after deliberate exposure to water vapor.



$$\frac{d[MO]}{dt} = -k_1(1-[MO])$$

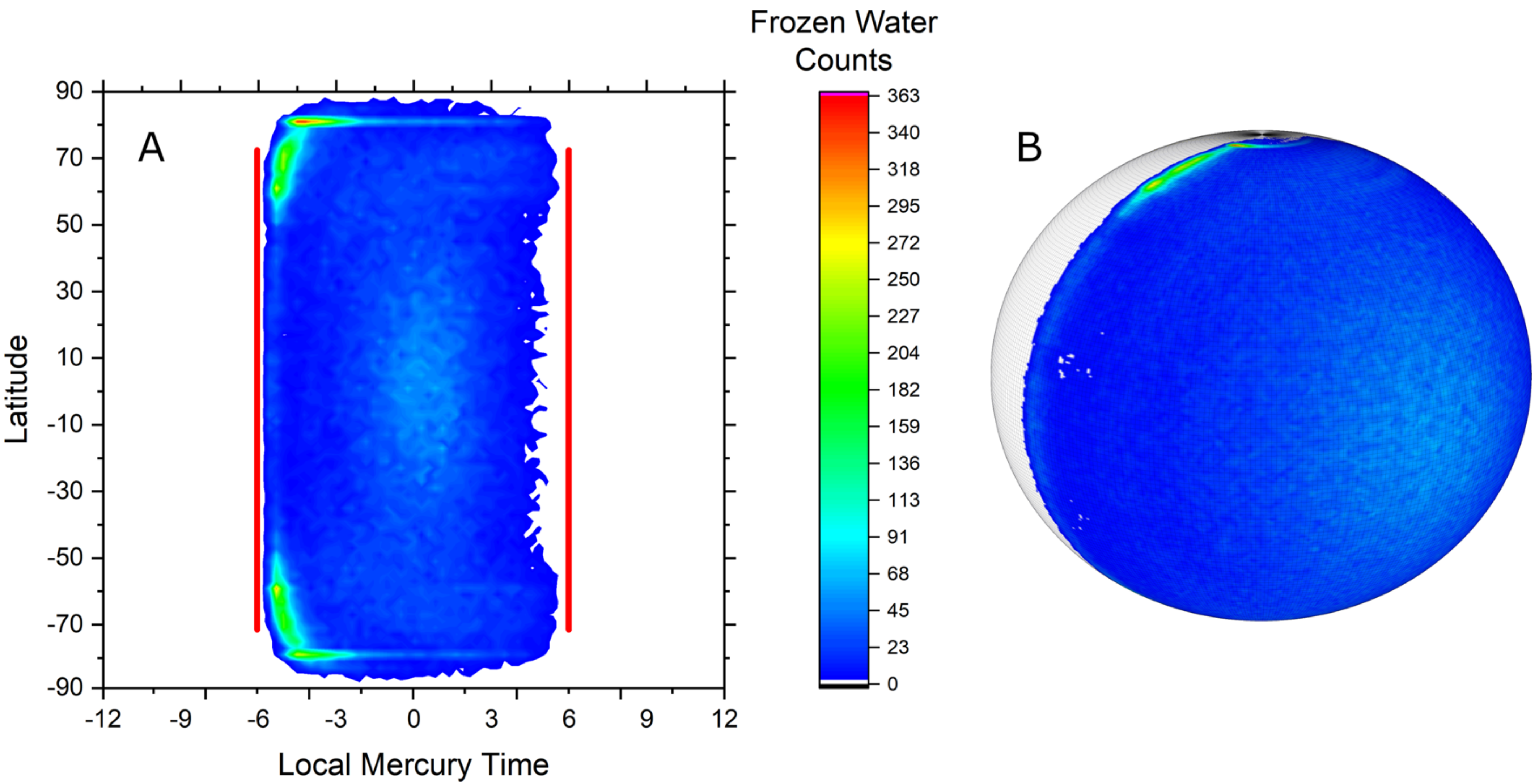
$$\frac{d[MOH]}{dt} = k_1(1-[MO]) - k_2[MOH]^2 + k_3(1-[MOH])^2[H_2O]_g + 2k_7(1-[MOH])[OH]_g - k_8[MOH]^2$$

$$\frac{d[H_2O]_g}{dt} = k_2[MOH]^2 - k_3(1-[MOH])^2[H_2O]_g + k_8[MOH]^2 - k_5[H_2O]_g - k_4(1-[MOH])[H_2O]_g + k_9[H_2O]_s$$

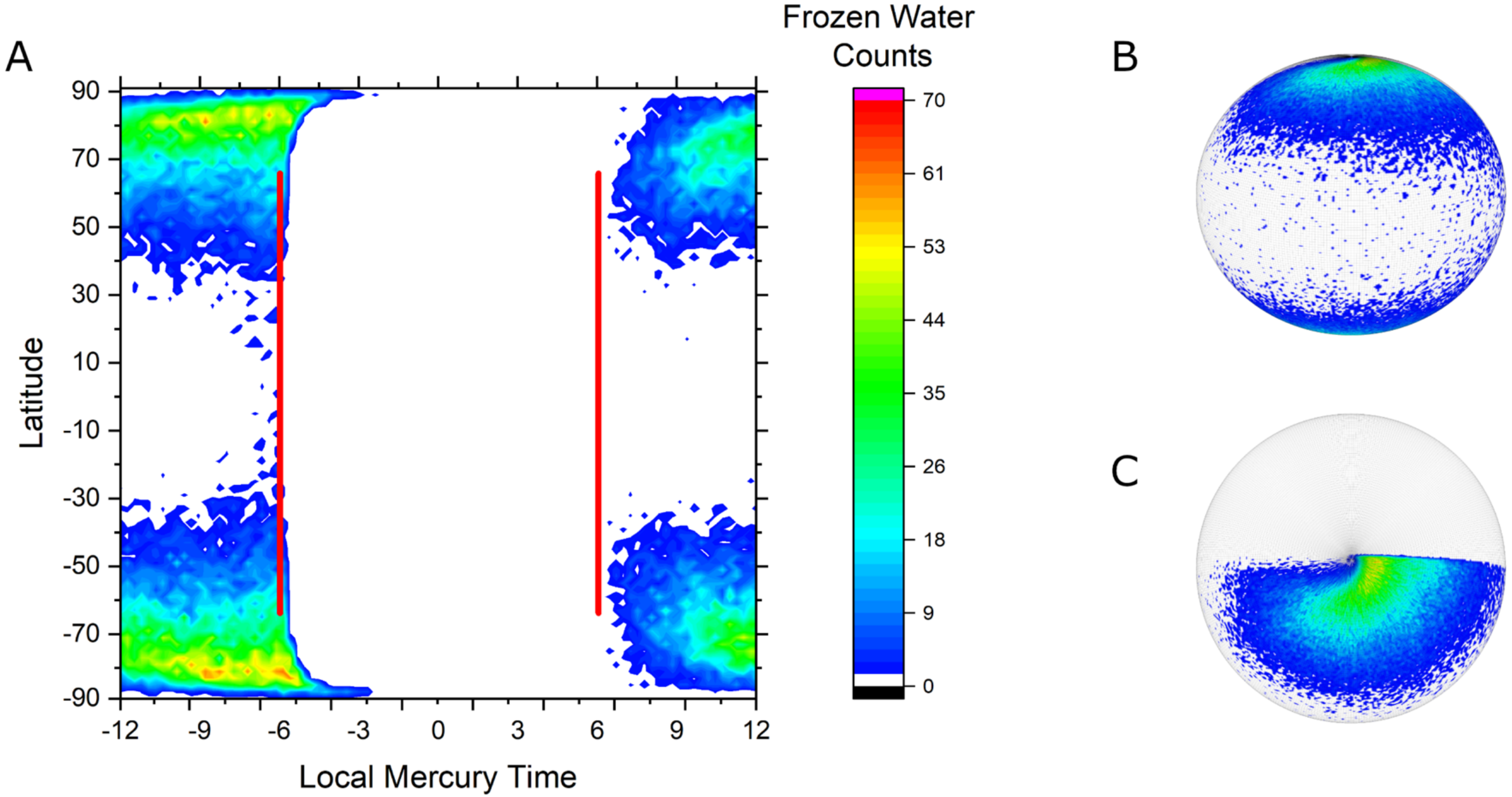
$$\frac{d[OH]_g}{dt} = k_5[H_2O]_g - k_7(1-[MOH])[OH]_g - k_6[OH]_g$$

$$\frac{d[H]_g}{dt} = k_5[H_2O]_g - k_7(1-[MOH])[H]_g - k_6[H]_g$$

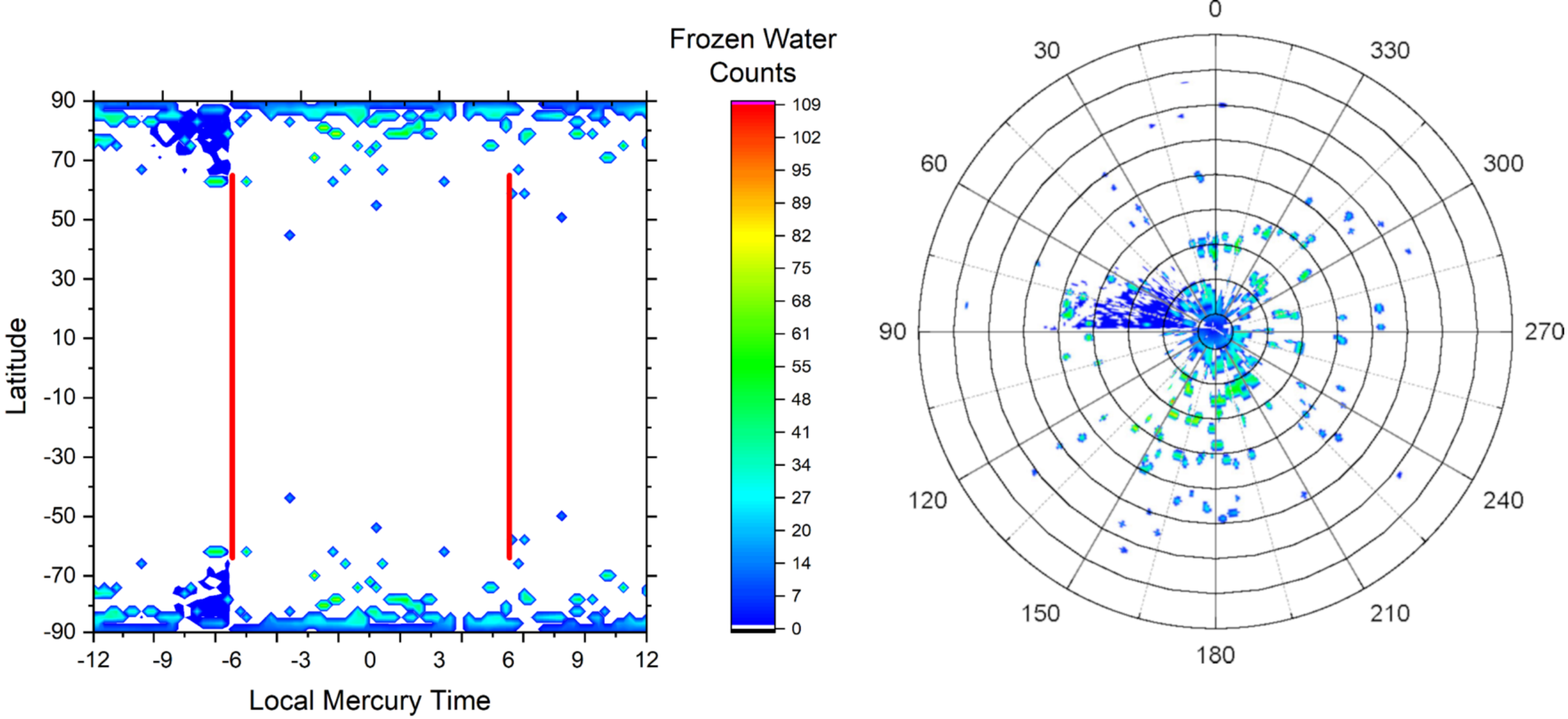
$$\frac{d[H_2O]_s}{dt} = +k_4(1-[MOH])[H_2O]_g - k_9[H_2O]_s$$



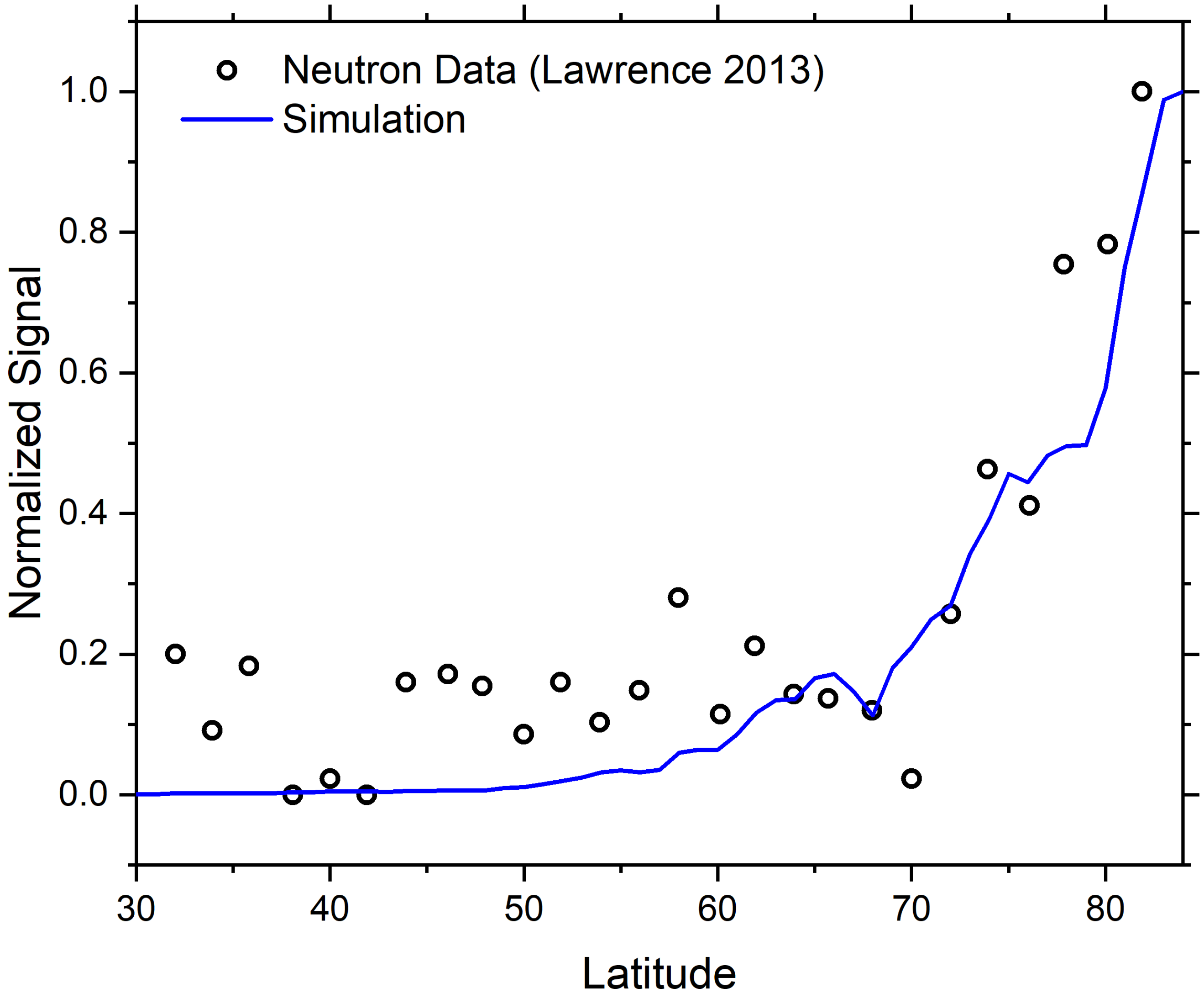
A) Total sum and spatial distribution of water molecules formed via recombinative desorption after six Mercury days or twelve orbits with red lines designating the day (-6 or 6 am) and night (+6 or 6 pm) terminators. **B)** Spherical projection of the model grid data presented in part A.



A) Location of frozen water without PSRs after one Mercury day with red lines designating the day (-6 or 6 am) and night (+6 or 6 pm) terminators. **B)** Spherical projection of data presented in part **A** rotated to show nightside location of physisorbed (frozen) water. **C)** North pole perspective of part **B** that simultaneously shows the dayside (top) and nightside (bottom).



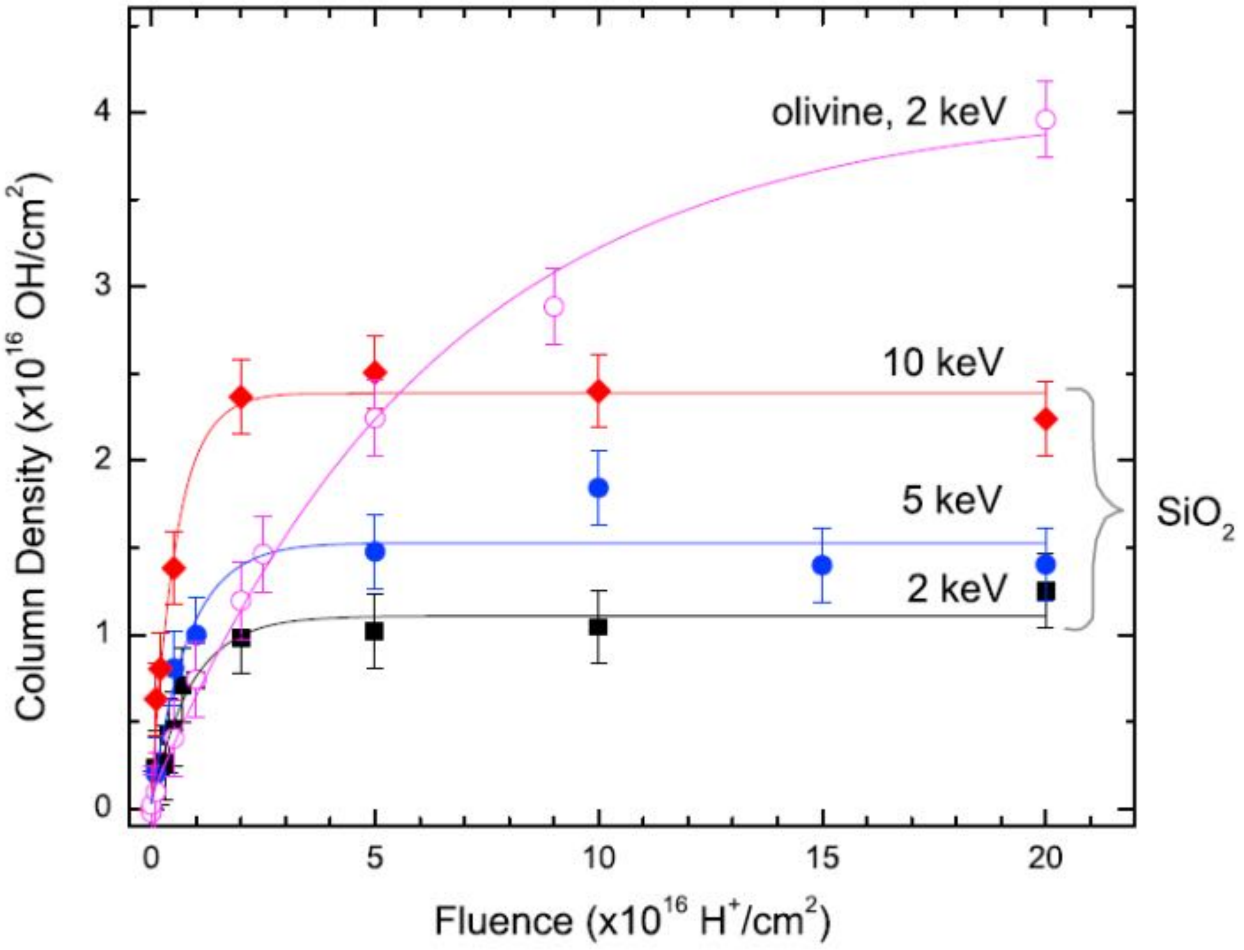
Frozen water locations after simulating water evolution (formation and migration) with permanently shadowed regions. The left displays an intensity map of the model data with red lines designating the day and night terminators. Shown on the right is a polar contour projection of the model grid data. The cold spots act as molecular water traps where water accumulation will occur over time resulting in a significant and detectable amount.



Comparison of the simulated normalized water concentration as a function of latitude with normalized neutron spectrometer data digitized from Lawrence et. al.[1] The predicted water signal overlaps with observation except for the mid latitude areas. Here, the elevated epithermal neutron counts may be the result of hydrogen rich regolith formed from solar wind proton implantation

[1]D. J. Lawrence, *Science* 339, 292-296

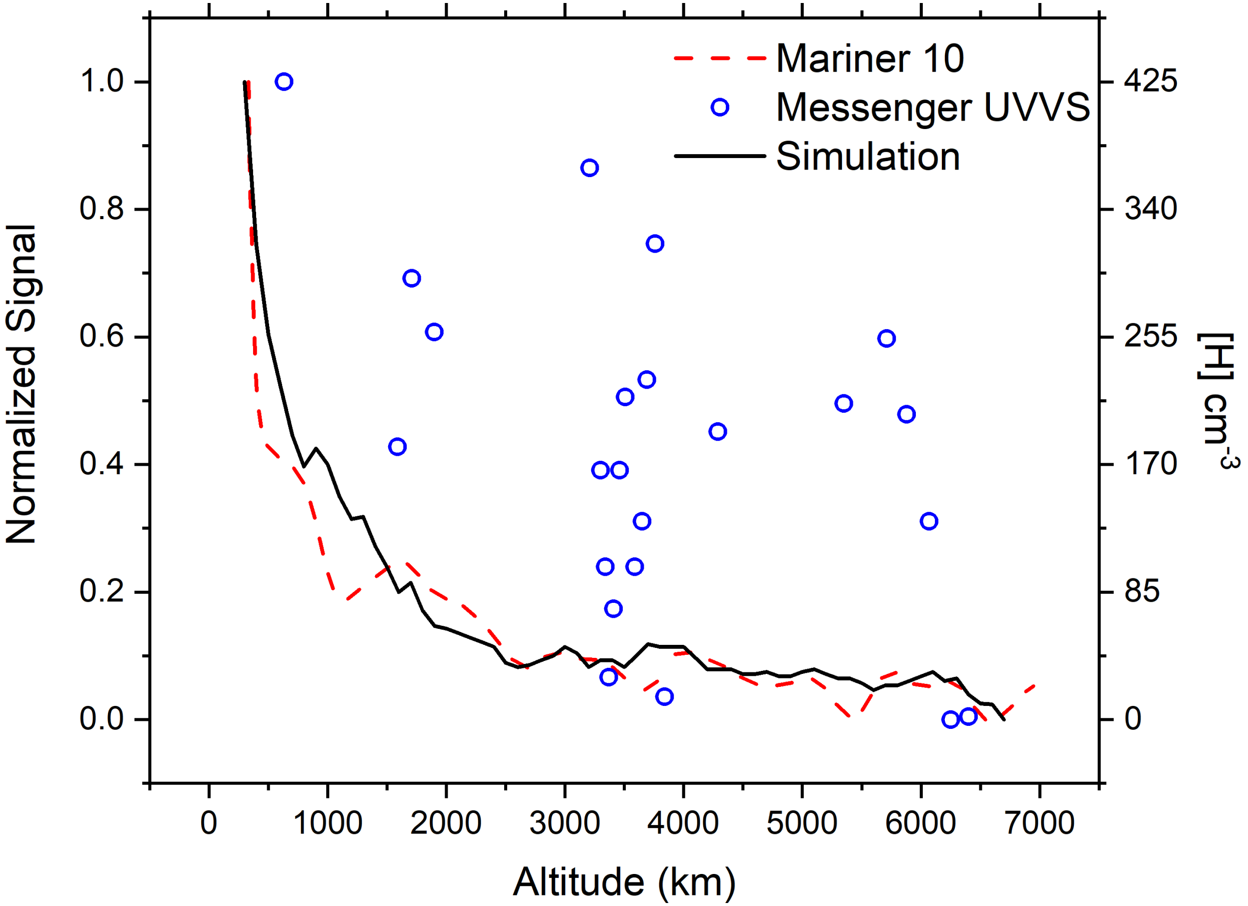
Molecular Hydrogen Formation



Here, I am simply assuming a mass balance between the OH formed and the input fluence. As time progresses, the less OH is formed and the more H_2 is formed.

Schaible M., *JGR Planets*, **2014,** 119(9)

H exosphere



Simple photodissociation model matches with Mariner 10 data:

$E_{avl} = E_{hv} - D_o - E_{L\alpha}$

$H_2 + hv \rightarrow$ H(1s) and H(2p/2s)

KER can be 0.88 eV at *hv* = 79.5 nm

Similarly, $H_2O + hv_{L\alpha} \rightarrow$ H(1s) + OH

KER is ~1.5 eV

Summary

- Water can be formed *in situ* by thermally induced reactions of solar wind implanted hydroxyls.
- Water will inevitably amass in the cold PSRs and will contribute significant amounts to the surface of Mercury over geological time periods.
- The simulation agrees well with the observed trend in the epithermal neutron spectrometer data and adds merit to the notion that the radar bright spots are due to frozen water.
- Water formed via RD can refresh the PSRs maintaining their high albedos.
- Though water delivery via cometary and meteoritic impacts has in general been accepted as the source term for water on Mercury, recent efforts estimating the total amount of water on Mercury have emphasized that delivery alone from large impactors cannot explain the observed amount and requires an additional source term.

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