Solar wind implantation into lunar regolith: Hydrogen retention in a surface with defects

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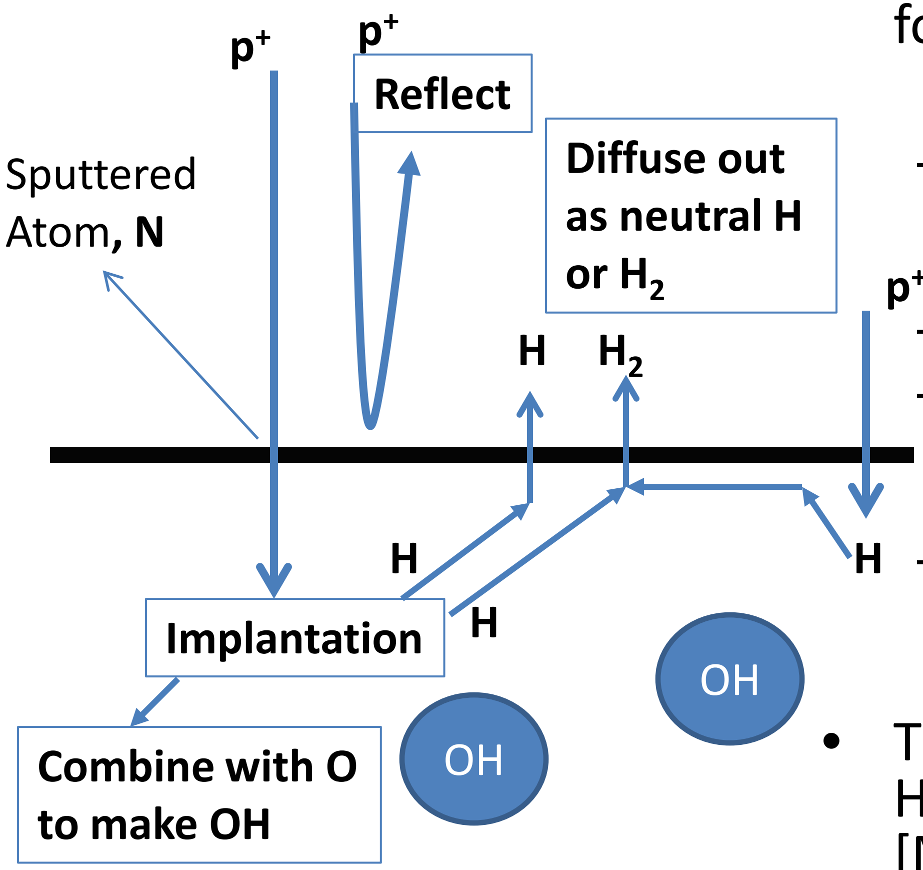
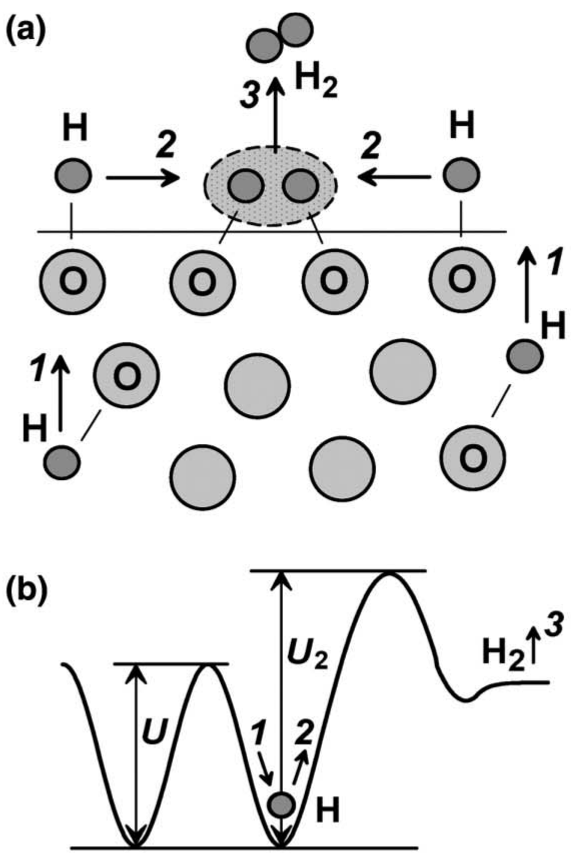
Proton/surface interaction pathways:



- The end state for proton in surface interactions can be one of the following [Starukhina, 2001, 2006] :
  - H thermally migrates & diffuse out of crystal to form neutral H exosphere emission or H_2 emission
  - H gets trapped in crystal vacancy
  - H creates a local ionization event to immediately react [Poston et al., 2012]
  - Proton reflects from surface back into solar wind [Saito et al., 2008]

- The observation of substantial neutral H emission from the lunar surface [McComas et al., 2009] and H_2 [Cook et al., 2013] suggests implantation and outward diffusion is a substantial pathway

H Implantation & Internal Reactions



Starukhina 2006

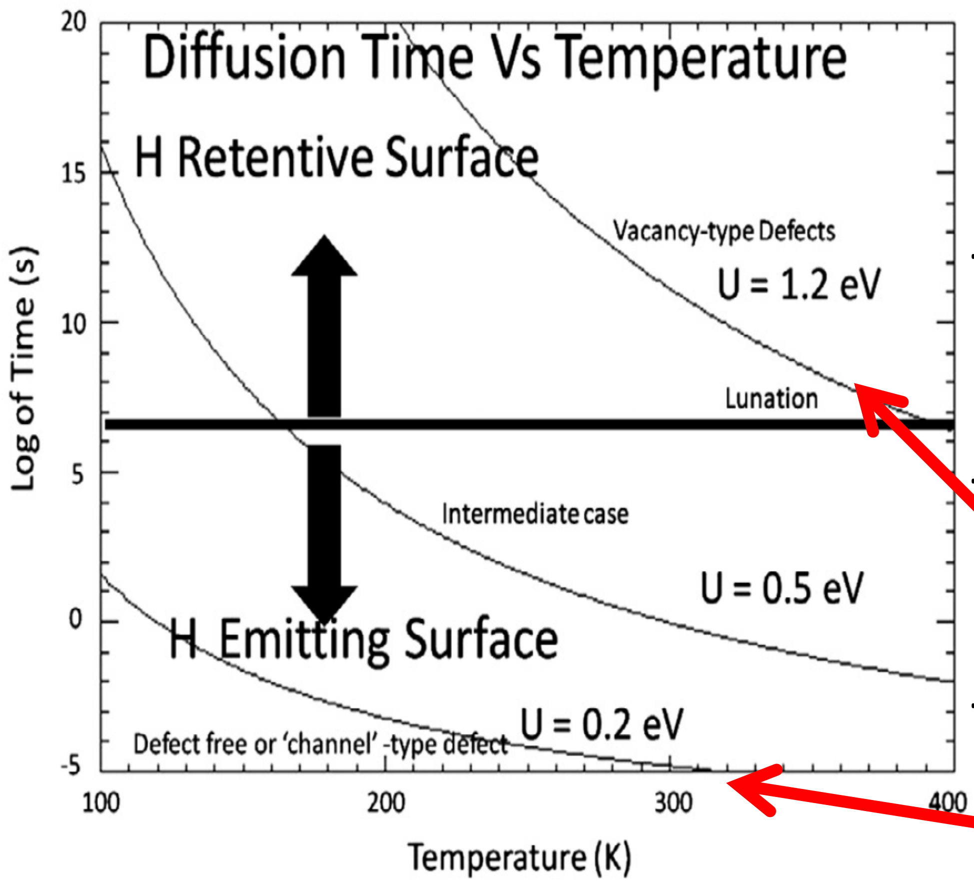
From **Starukhina [2001, 2006, 2012],** an implanted H will migrate from the surface with diffusion time

$$\boldsymbol{\tau_D = h^2 D_o^{-1} \exp(U/kT)}$$

- Depth: h ~10^{-7} m,
- Diffusion D = D_o exp (-U/kT)
- U is diffusion 'activation' energy defining both mobility and trapping of H at a position.
- With defects, U has a range of values, but U > 1 eV in regions leading to trapped or **'loitering'** H's in vacancies

H Diffusion (or Residency) time

Farrell et al., 2014

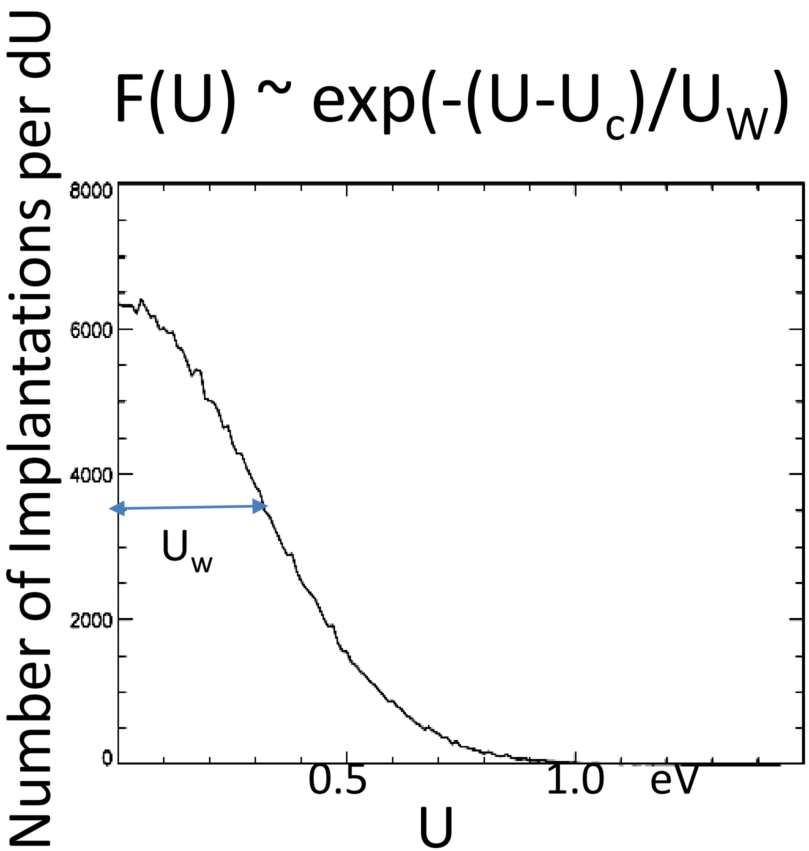


Diffusion time as a function of temperature for a family of activation energies, U.

- **Diffusion (outward) time, $\tau_D = h^2 D_o^{-1} \exp(U/kT)$** can also be considered the H residency time
- Residency time is STRONGLY controlled by temperature and activation energy, U
- **High U:** the H can **'loiter'** for 10's of days to possibly form OHs..H retentive surface
- **Low U value:** the H is emitted back out of the surface in seconds ..H emitting surface

New Statistical Approach: Distribution of Activation Energy

$$F(U) \sim \exp(-(U-U_c)/U_W)$$



U_c = distribution center,
U_w = distribution width

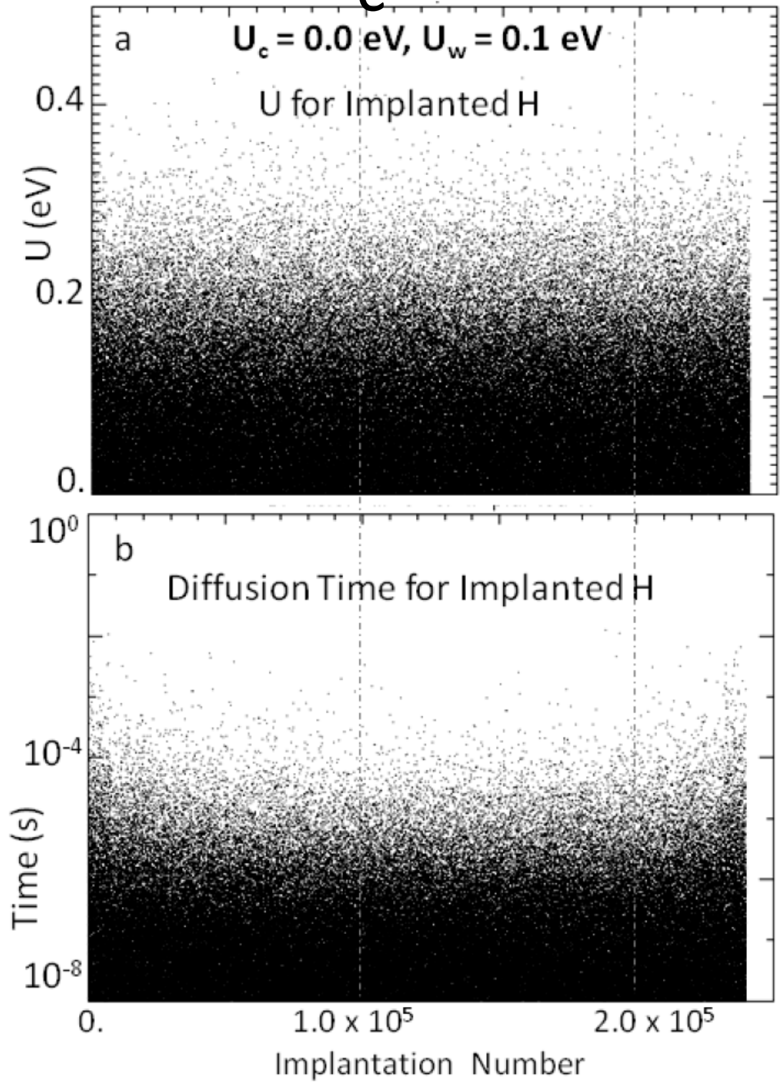
- For a given sample, the numerous implantations have a **distribution of U values** – not a single U but an **average <U>** and **δU deviation** about the average.
- Expect many of implantations into complete lattice structure (with low U), but some implantations onto lattice with defects represented by higher U
- This statistical view lends itself to a Monte Carlo approach
- We attempt to search for the distribution of U's and temperatures that provides long-lasting, **loitering Hs** ....candidates to form OH.

Methodology

- Divide the lunar equatorial frontside region into local time bins (~1 hour LT or 15^o long bins)
- Solar wind ions flux represented by N = 240000 test particles delivered to surface in a flux which varies with local time (i.e., cos of SZA)
- For each implantation, **assign an individual U value quasi-randomly but weighted by a pre-defined Gaussian.**
- We then determine diffusion (residency) time as a function of local surface temperature.
- The number of H's with residency time, $\tau_D > 10^5$ s are considered loitering Hs and **candidates to eventually form OH**. We count these in each local time bin.
  - **H Continuity Eq.:** $dn_H/dt = S - L_{diff} - L_{OH}$
  - **Cold, terminator:** Balance near-terminator solar wind flux, F, onto surface vs estimated amount of OH content from IR observations:

    $T > n_{OH}h/F > 10^5$ s (cannot be much longer than a ¼ lunation)
- We thus examine the conditions to obtain substantial amounts of these 'loitering', long-lasting Hs that are candidates to form OH.
- Example cases now shown

Case A: $U_c = 0$ eV , $U_w = 0.1$ eV



U

Nearly defect free lattice with low U values

No loitering H's!

-Most of implantations have activation energies below 0.4 eV.

-Retention time/loitering time of H's less than 1 second at all locations – all H's lost, no OH.

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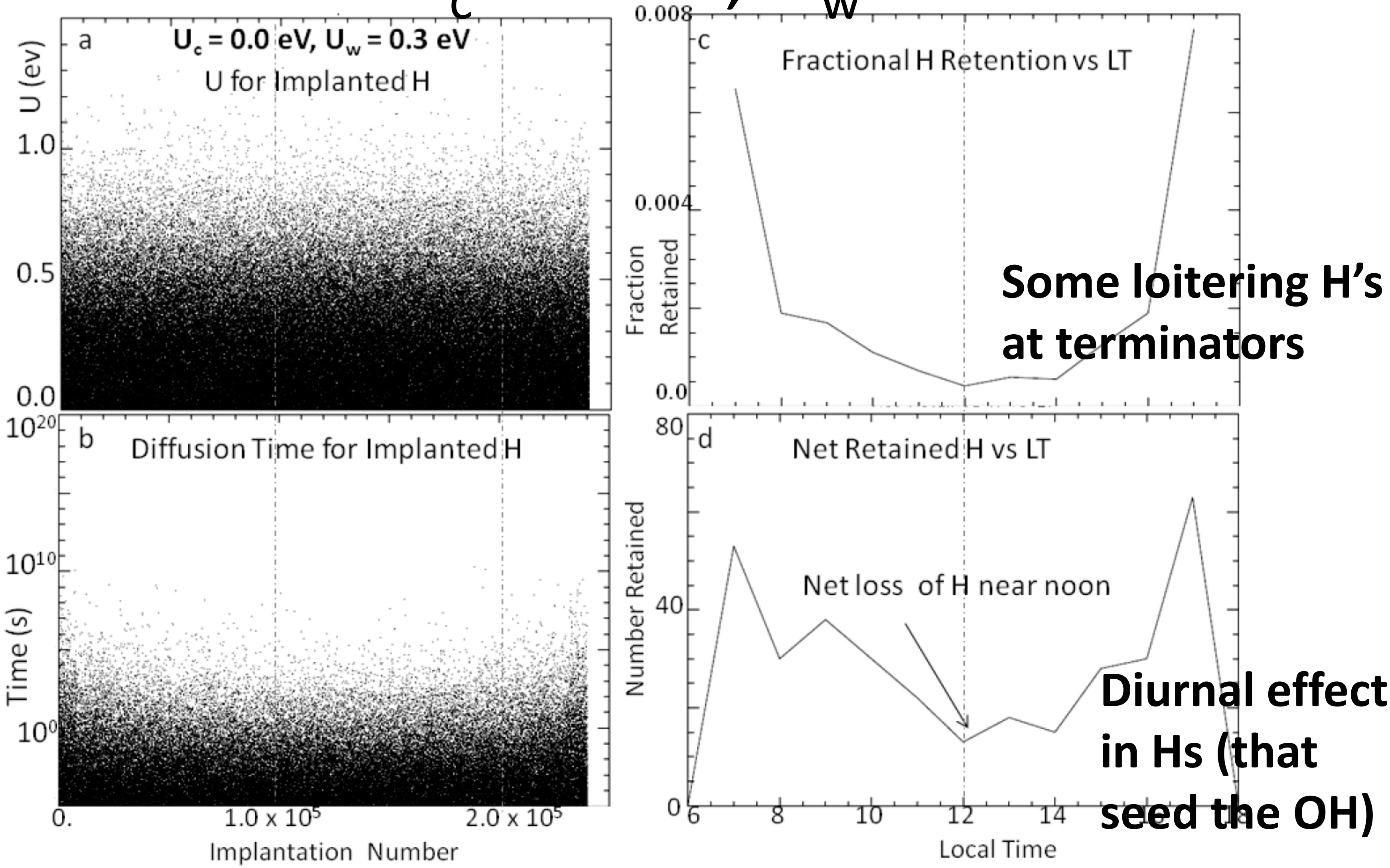
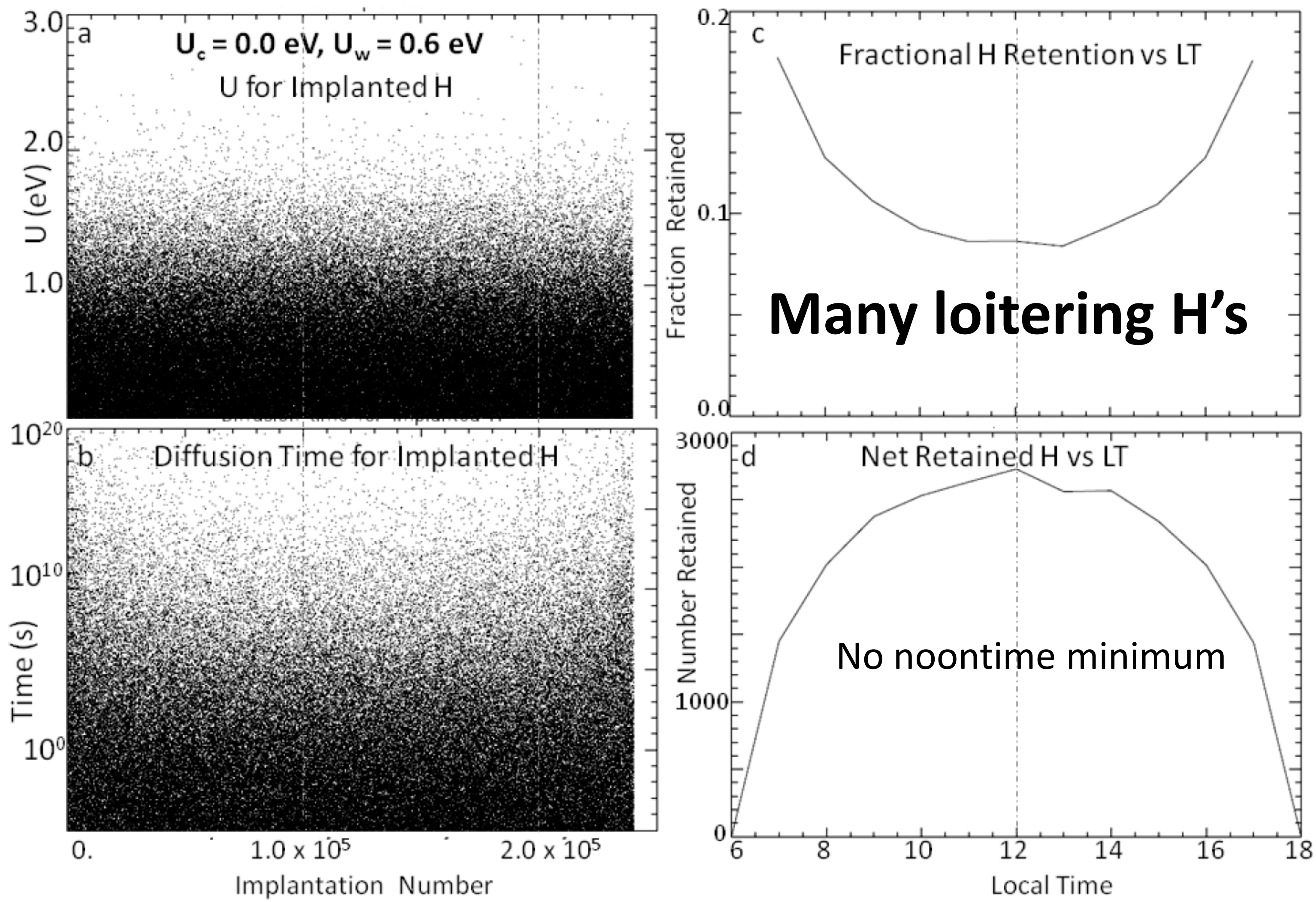
Case B: U_c = 0 eV , U_w = 0.3 eV



-Only at the terminators is there a substantial population of loitering Hs

-The warmer regolith near noon releases the Hs, possibly creating a neutral H exosphere

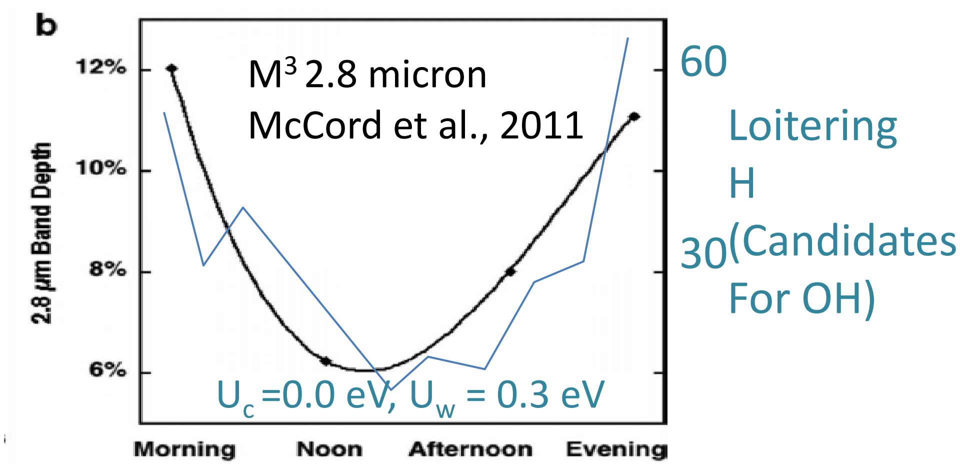
Case C: $U_c = 0$ eV , $U_w = 0.6$ eV



-Substantial population of loitering Hs even at warm noontime

-Still noontime loss via diffusion, but the loss is offset by greater retention at numerous defects sites

Comparison to the Moon



- Clark et al. 2009: Mild retention of OH (well below saturation) at 10-1000 ppm (over long term)
- Sunshine et al 2009: Reduction in OH at sub-solar point
- Consistent with H implantations having U_c < 0.3 eV, U_w < 0.2 eV

Table 1
Values of total fraction retained and the relative retention at noon LT (compared to 8 h LT) for a set of runs under varying U_c and U_w for a thermal profile like that at the lunar equator. Bold values indicate U_c/U_w values where a local noontime minimum is modeled. The shaded values are U_c/U_w values that could be similar to the Moon's mild retention (see text for further discussion).

	U_c = 0.0 eV	U_c = 0.3 eV	U_c = 0.6 eV	U_c = 0.9 eV
U_w= 0.1 eV	0.0 | 0.0	0.0 | 0.0	0.001 | **-1.0**	0.22 | **-0.60**
U_w= 0.2 eV	0.0 | 0.0	0.001 | **-0.64**	0.034 | **-0.51**	0.34 | +0.06
U_w= 0.3 eV	0.001 | **-0.56**	0.013 | **-0.29**	0.10 | **-0.004**	0.39 | +0.35
U_w= 0.4 eV	0.016 | **-0.19**	0.04 | +0.02	0.17 | +0.27	0.42 | +0.51
U_w= 0.6 eV	0.10 | +0.35	0.14 | +0.41	0.27 | + 0.53	0.45 | +0.67
Uw=0.75 eV	0.19 | +0.54	0.22 | +0.56	0.33 | +0.63	0.46 | +0.72
U_w= 0.9 eV	0.27 | +0.64	0.30 | +0.65	0.37 | +0.70	0.48 | +0.76

3 Classes of Implantations

	U (eV)	Diffusion time (s)	Loss from surface via	Observed in	Observed via
Low U	< 0.3	< 10^1	Quick diffusion	Emitted H or H_2	IBEX, LAMP
Intermediate U	0.3 to 0.9	10^2 - 10^{14}	Diurnal –scale thermal diffusion	Surface	IR (e.g., M^3)
High U	> 0.9	10^7 To over $10^{16.5}$	Impactors	Surface	IR (e.g., M^3)

- Model a continuum in U but 'classes' based on loss process

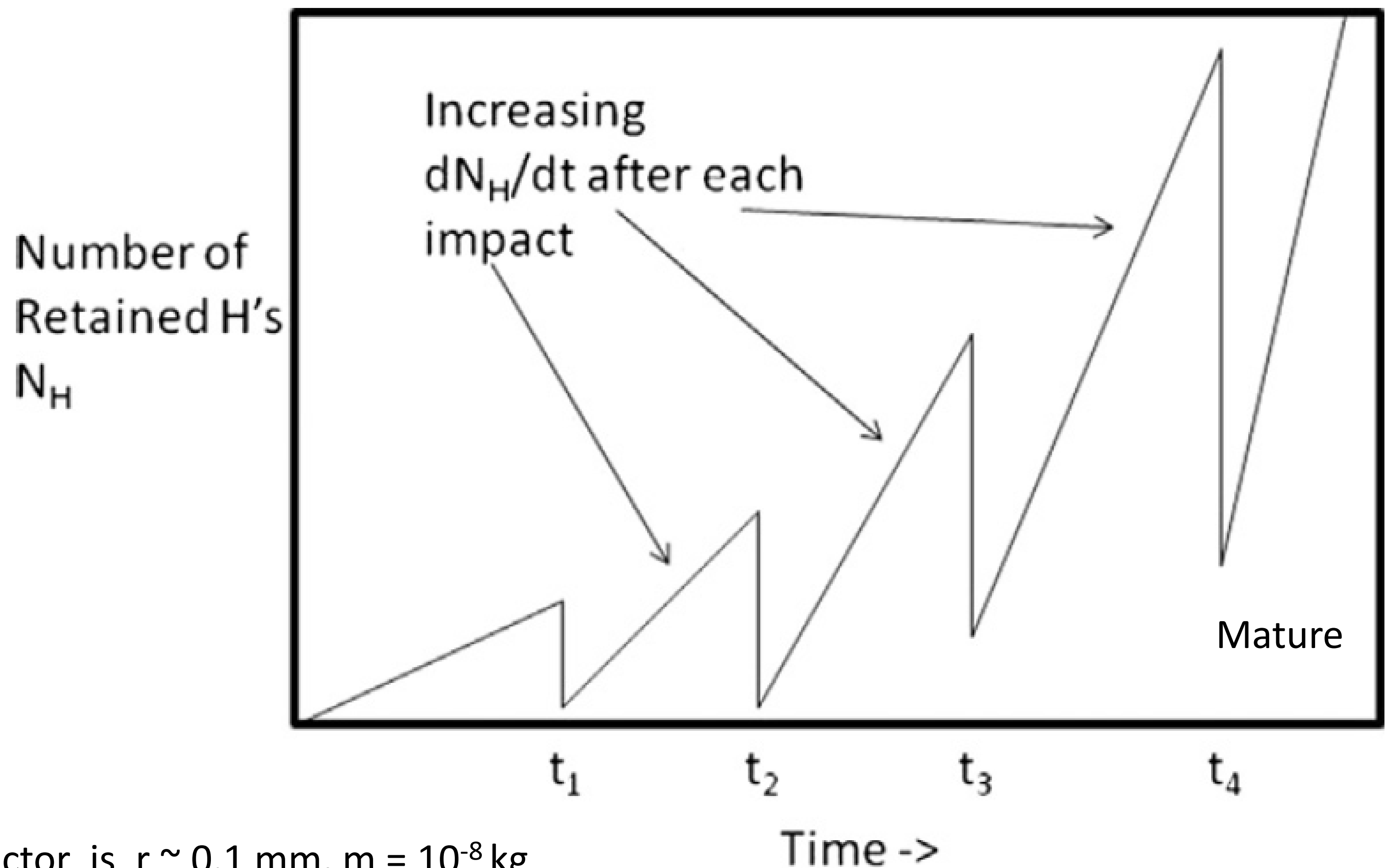
-We propose that **impactors** as a loss process regulate the amount of long-term loitering H

-**Micro-meteoroids** act to 'reset' the affected regolith by releasing H's and by adding defects to make the surface more retentive.

-Keep surface from becoming saturated by 'impact-reset' (Over long term, see only 10-1000 ppm –well below saturation)

-Look at U/T: Explains both thermal effect and increase H in mature (highland) soils

Illustration of Implantation history of a 1 mm x 1mm area



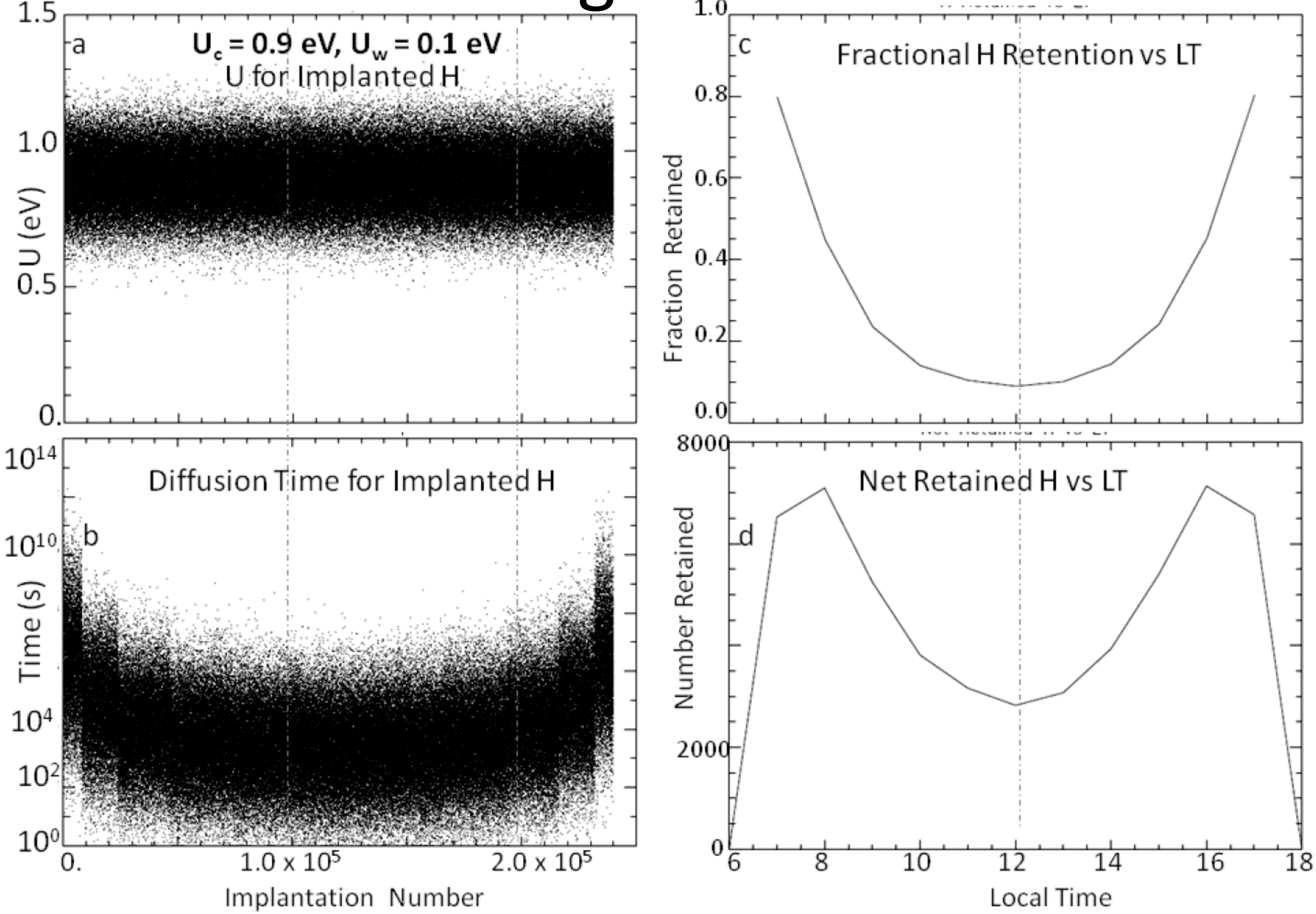
Impactor is r ~ 0.1 mm, m = 10^{-8} kg
Impacts a 1 mm x 1mm region every 10^5 years.

Conclusions

- The **defect properties of a crystal** has as much (or more) control on solar wind H retention in an exposed regolith as temperature and solar wind influx
- **U/T** is the primary variable in residency, not just T
  - T varies by a factor of 4, U varies by a factor of 100
  - T appears as a controlling variable only at intermediate U values
- The nature of the crystal may be a variable in H retention and OH formation that is **under-appreciated**.
- Focus on U/T: Can explain a diurnal cycle to H and also increased retention in mature soils (lunar highlands)
- We use Gaussian's to illustrate of effect but real crystal defect distribution (U distribution) likely more complicated (e.g., amorphized rims - Noble et al., 2005)
- Starukhina's work pioneering
- Extended discussion in recent Icarus paper!

backup

Interesting Test Case



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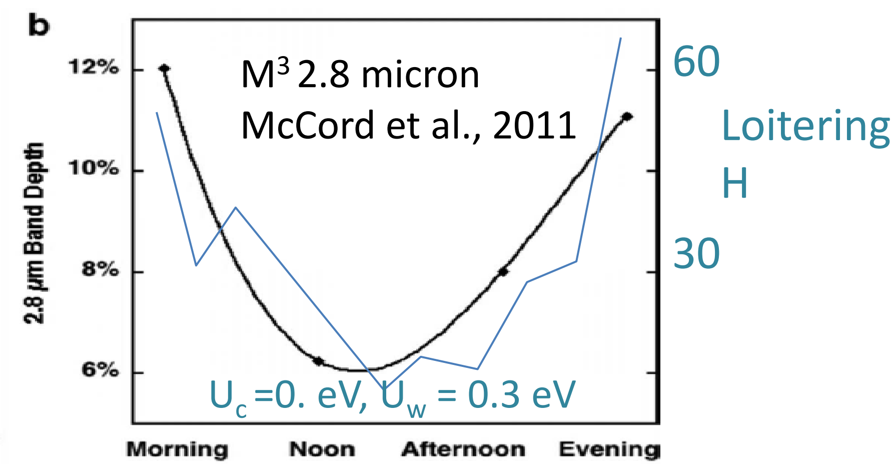

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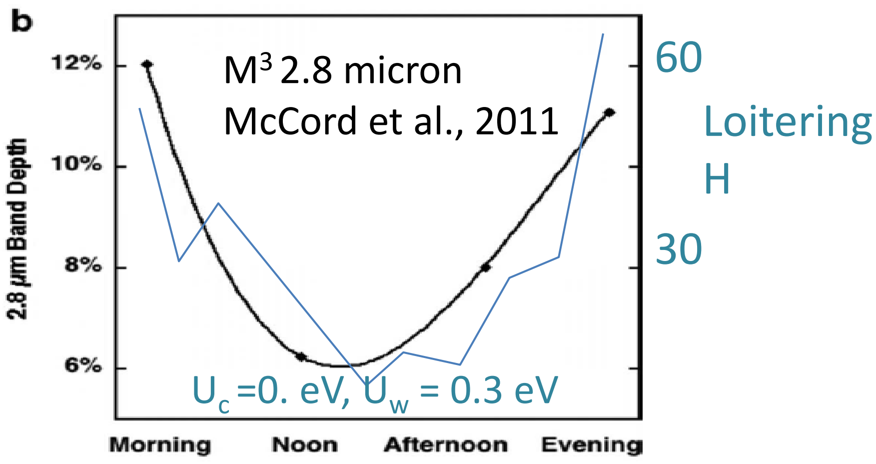
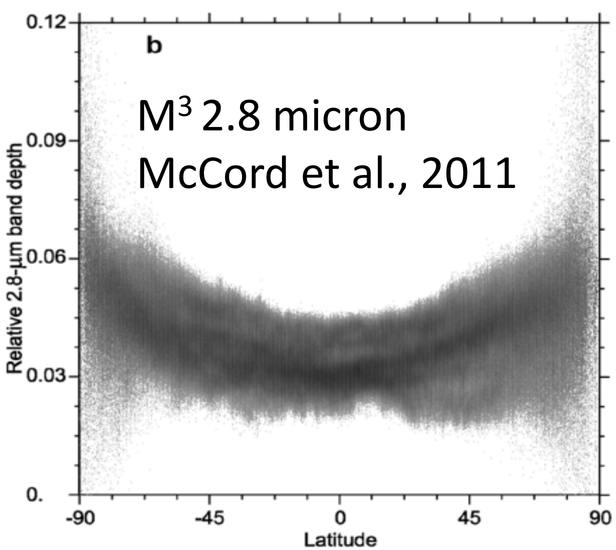
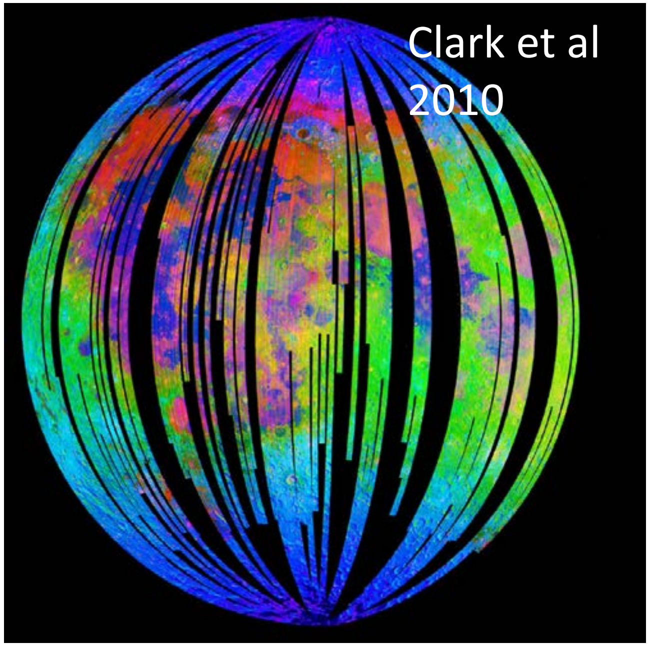


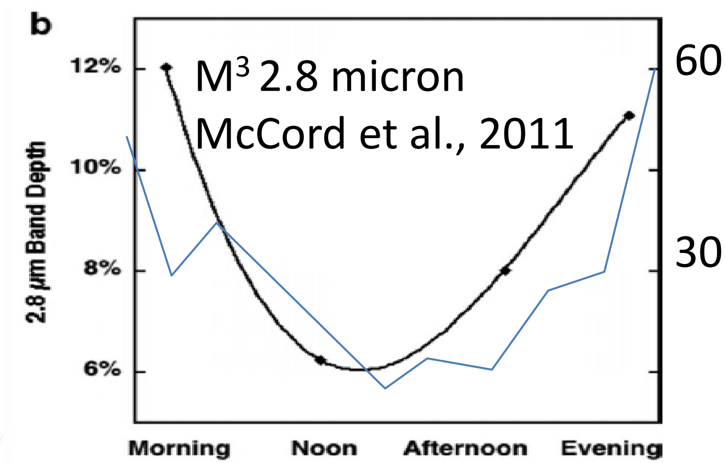


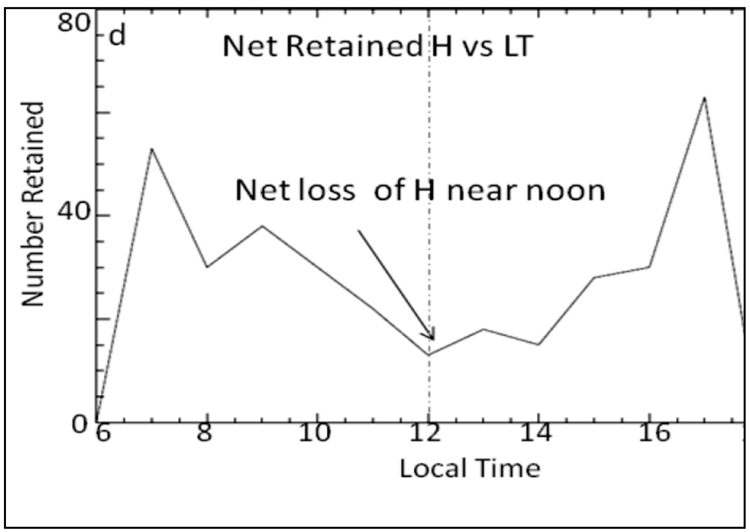
- Mild retention (well below saturation)
- Reduction in H (and hence OH) at sub-solar point
- Consistent with $U_c < 0.3$ eV, $U_w < 0.2$ eV
- Have a fraction of implantations with 0.3 eV $< U < 0.9$ eV



Comparison to Moon

H's Retained





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