

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

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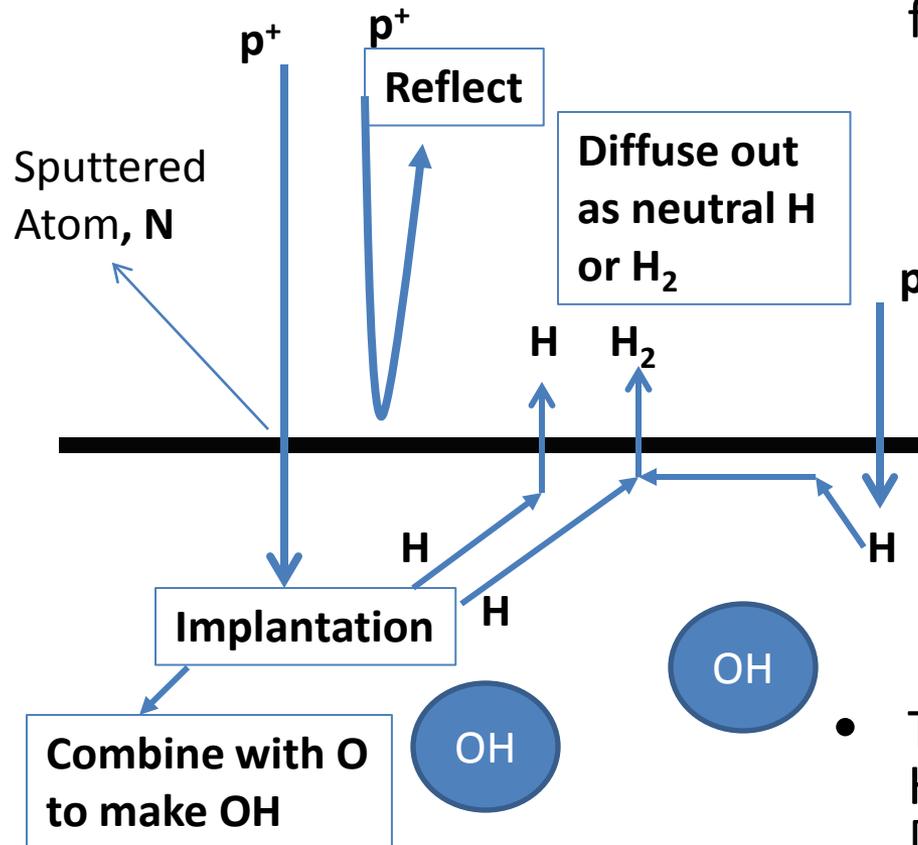
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3. NASA's Solar System Exploration Research Virtual Institute, NASA/Ames Research Center, Moffett Field, CA

Proton/surface interaction pathways:

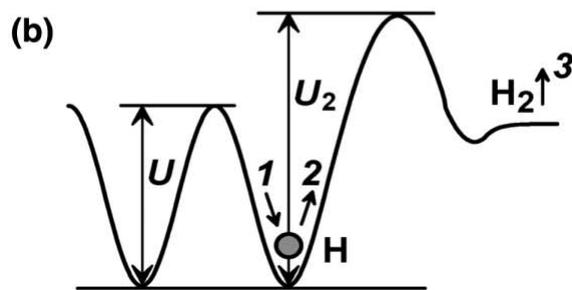
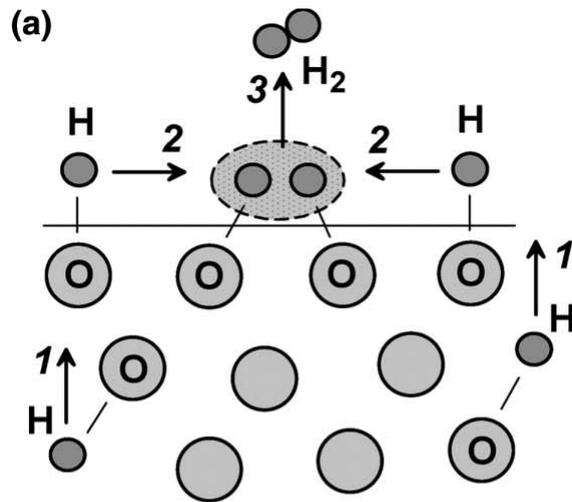
- The end state for proton in surface interactions can be one of the following [Starukhina, 2001, 2006] :



- 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

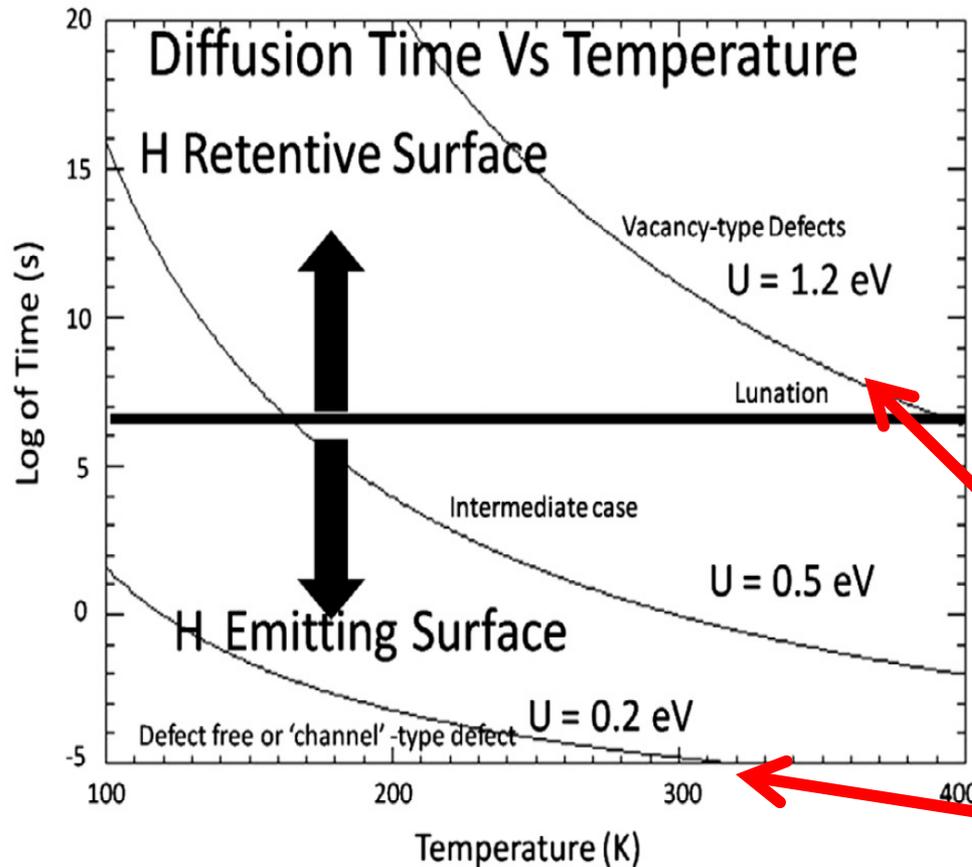
From **Starukhina [2001, 2006, 2012]**, an implanted H will migrate from the surface with diffusion time

$$\tau_D = h^2 D_0^{-1} \exp(U/kT)$$

- Depth: $h \sim 10^{-7}$ m,
- Diffusion $D = D_0 \exp(-U/kT)$
- 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

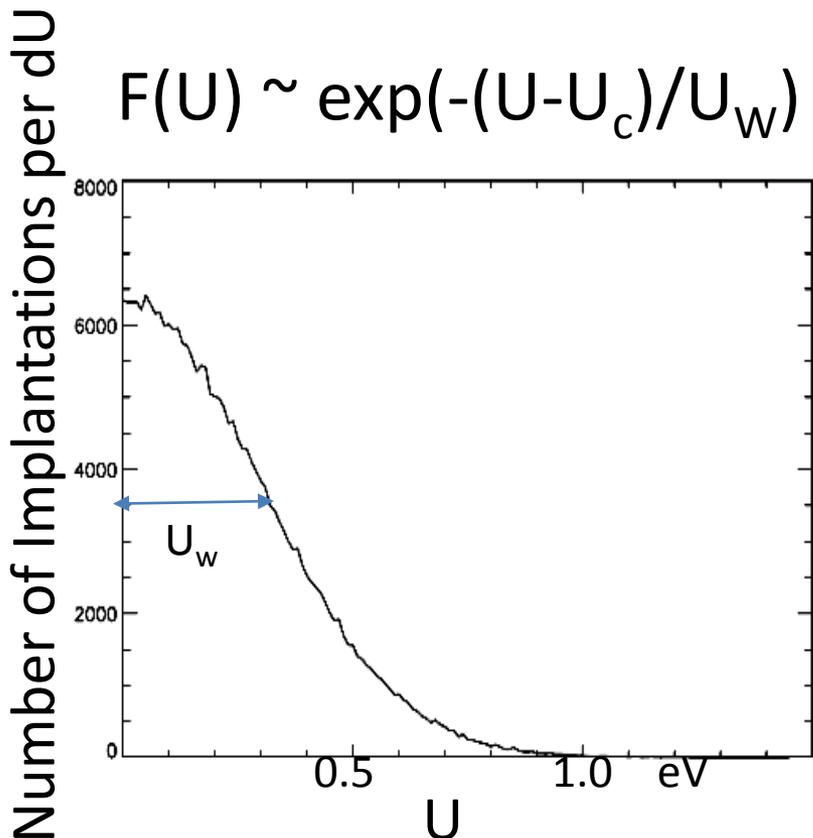
Farrell et al., 2014



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

- Diffusion (outward) time, $\tau_D = h^2 D_0^{-1} \exp(U/kT)$ 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



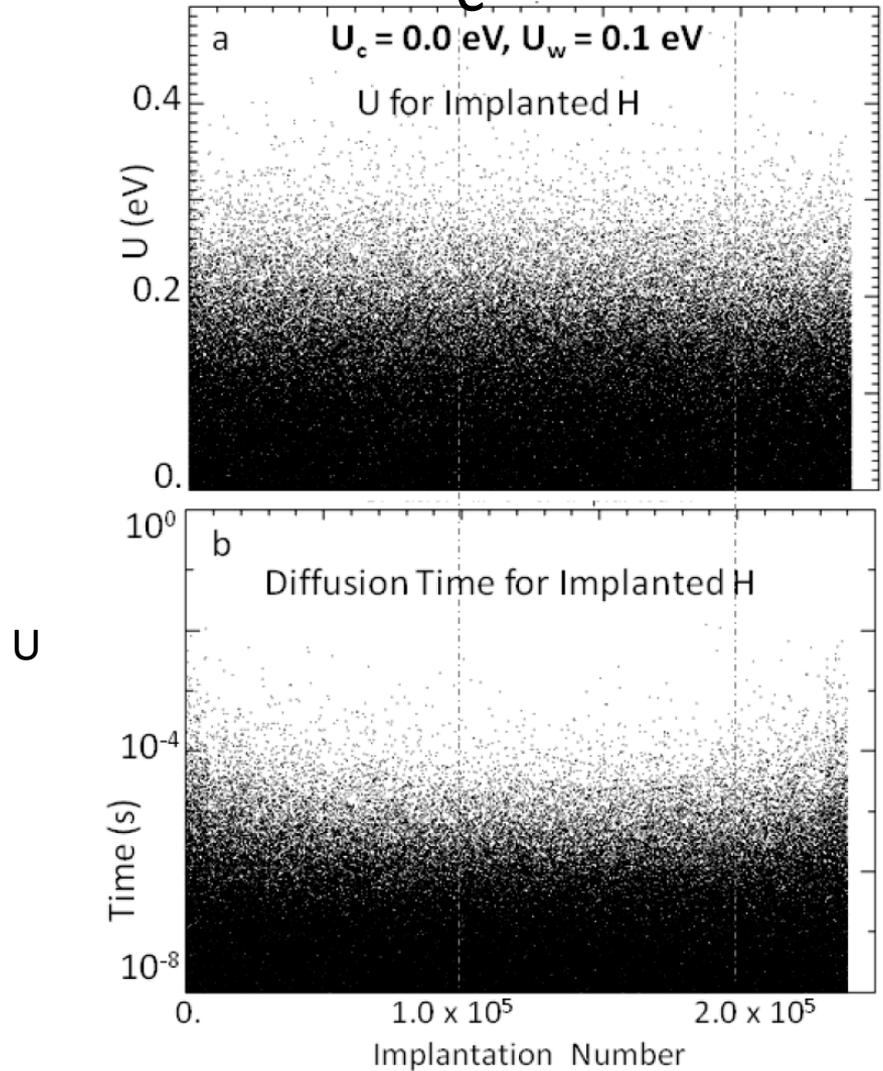
U_c = distribution center,
 U_w = distribution width

- For a given sample, the numerous implantations have a **distribution of U values** – not a single U but an **average $\langle U \rangle$** 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° 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: $U_c = 0 \text{ eV}$, $U_w = 0.1 \text{ eV}$

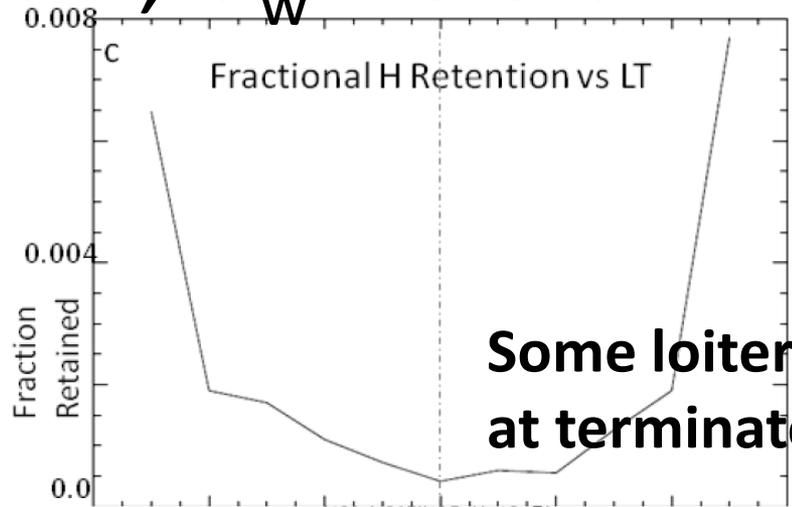
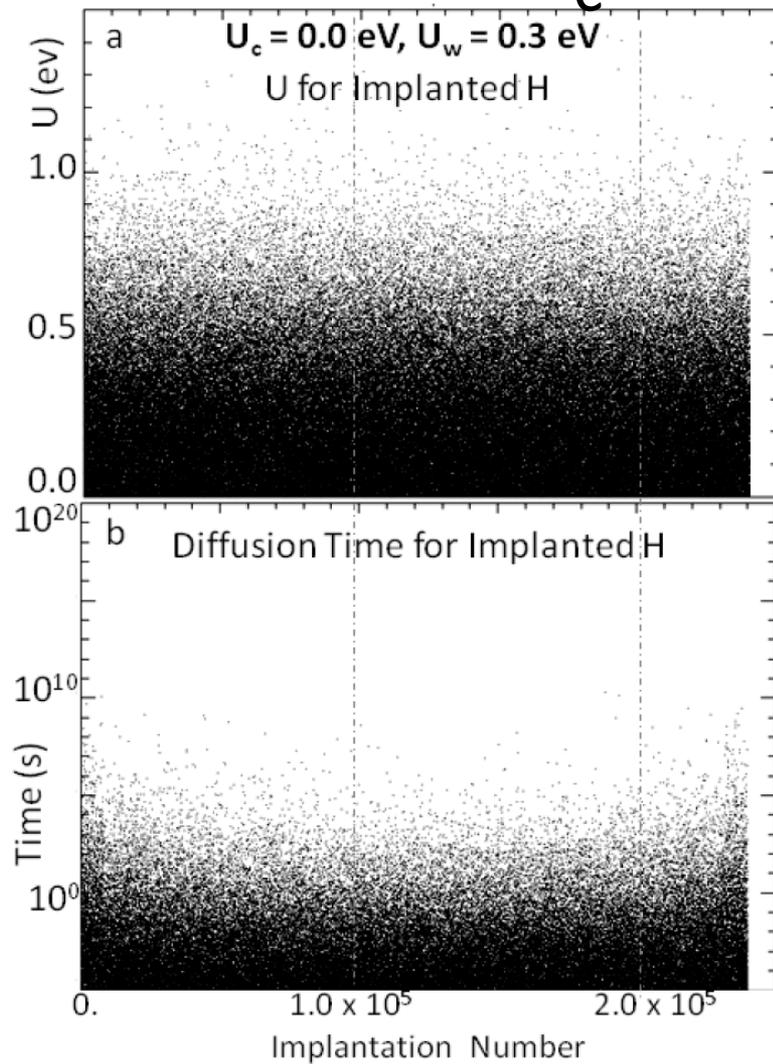


Nearly defect free lattice with low U values

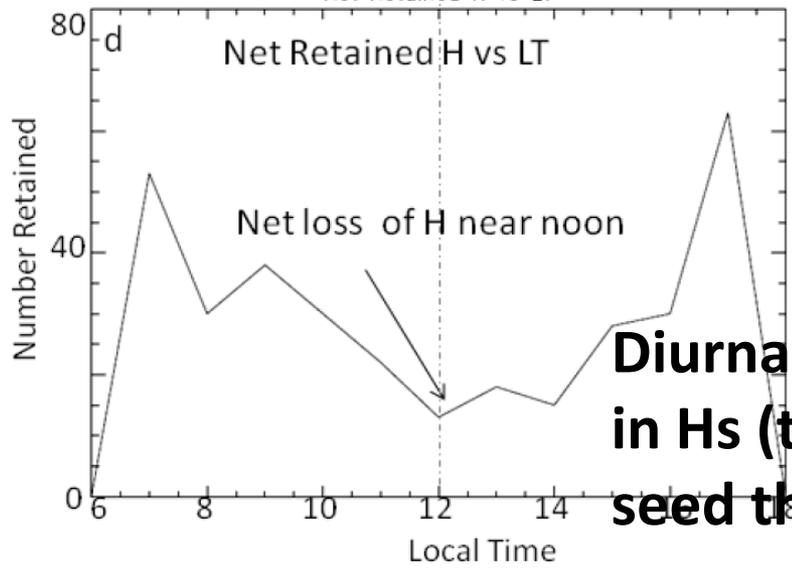
No loitering H's!

- 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.

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



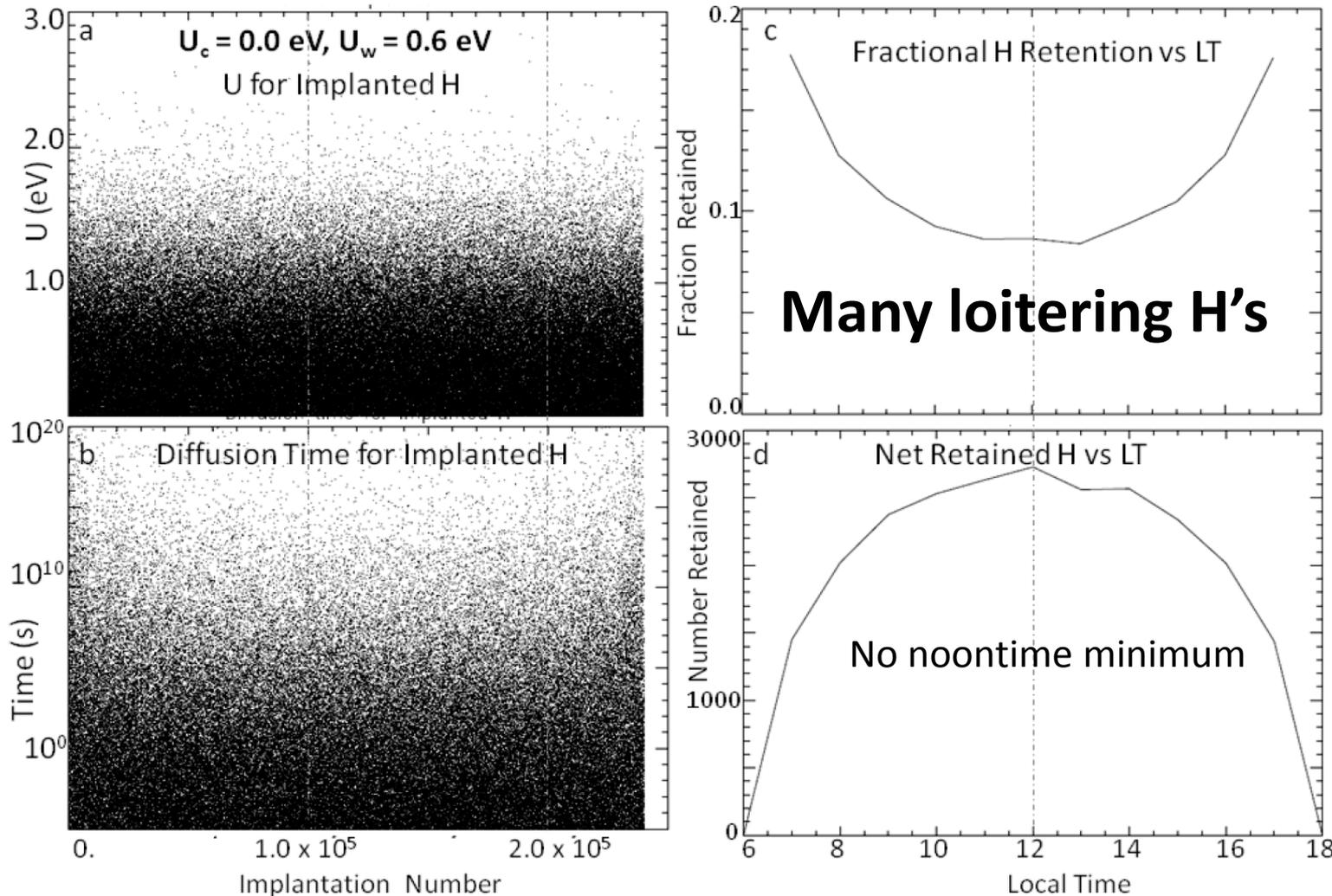
Some loitering H's at terminators



Diurnal effect in Hs (that seed the OH)

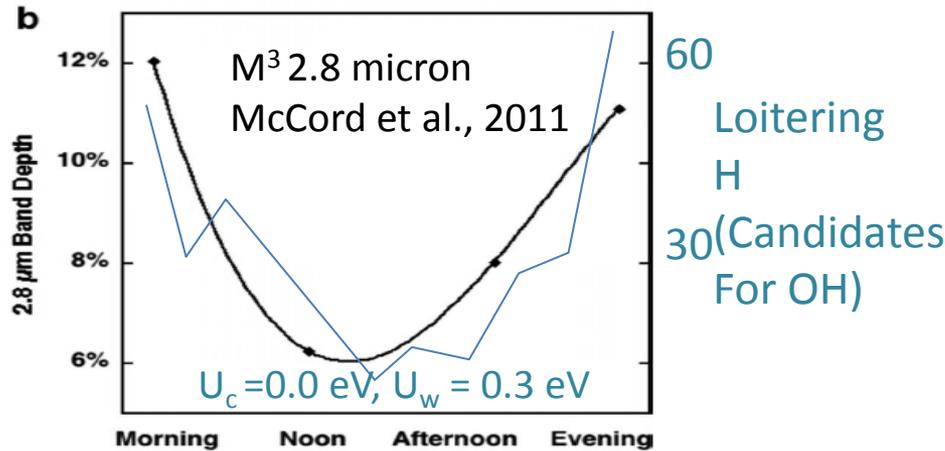
- Only at the terminators is there a substantial population of loitering Hs
- The warmer regolith near noon releases the Hs, possibly creating a neutral H exosphere

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).

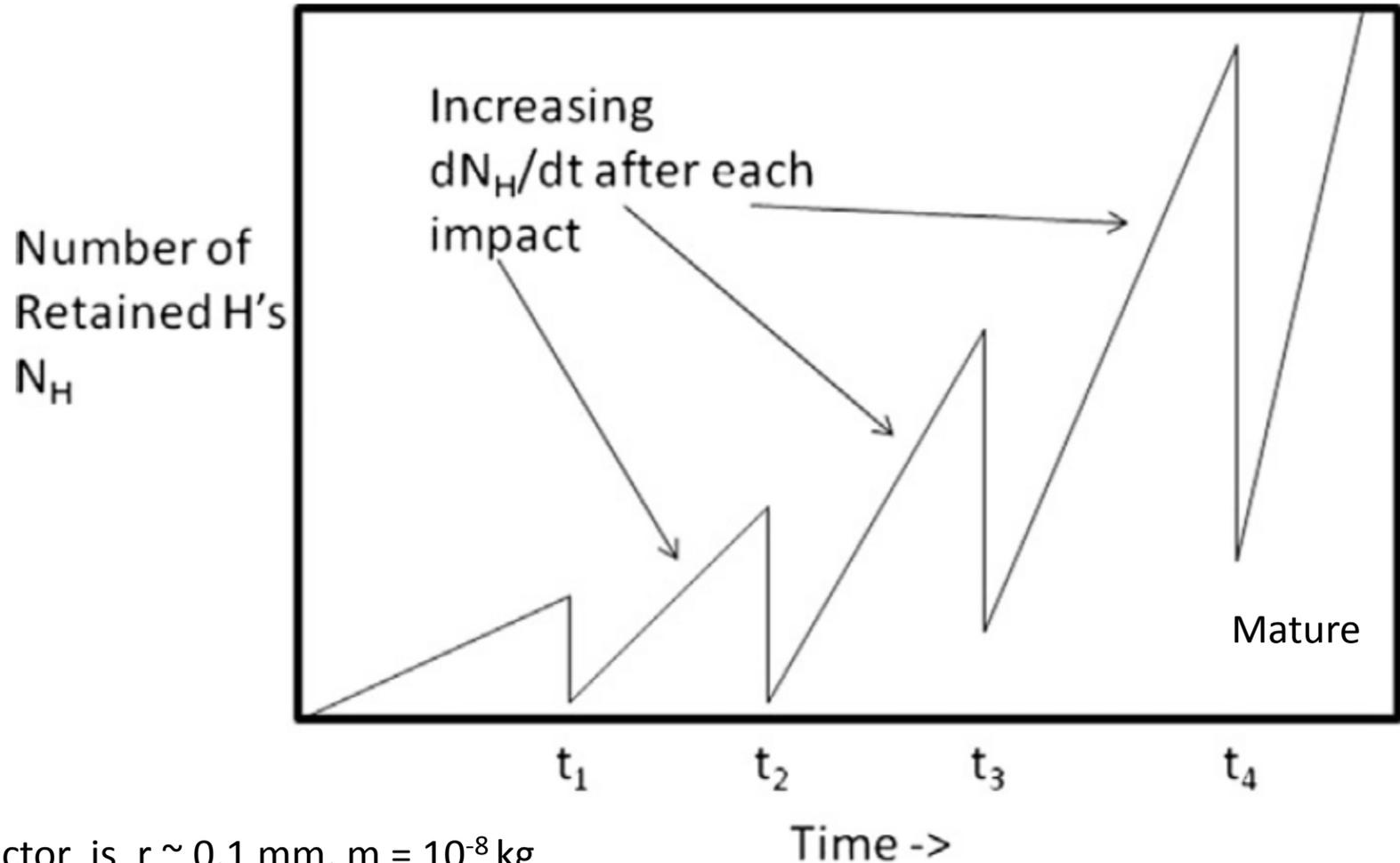
	$U_c = 0.0$ eV	$U_c = 0.3$ eV	$U_c = 0.6$ eV	$U_c = 0.9$ eV
$U_w = 0.1$ eV	0.0 0.0	0.0 0.0	0.001 -1.0	0.22 -0.60
$U_w = 0.2$ eV	0.0 0.0	0.001 -0.64	0.034 -0.51	0.34 +0.06
$U_w = 0.3$ eV	0.001 -0.56	0.013 -0.29	0.10 -0.004	0.39 +0.35
$U_w = 0.4$ eV	0.016 -0.19	0.04 +0.02	0.17 +0.27	0.42 +0.51
$U_w = 0.6$ eV	0.10 +0.35	0.14 +0.41	0.27 +0.53	0.45 +0.67
$U_w = 0.75$ 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



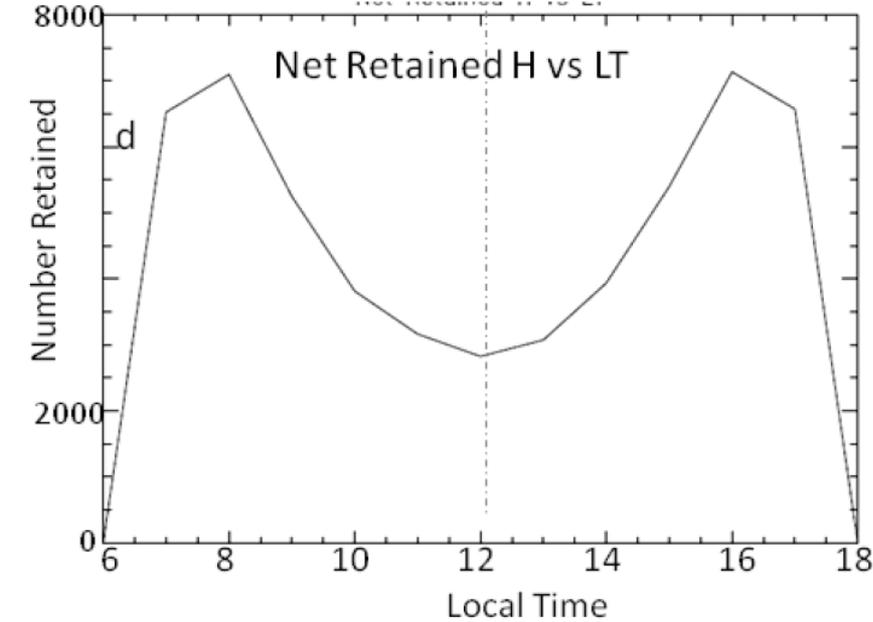
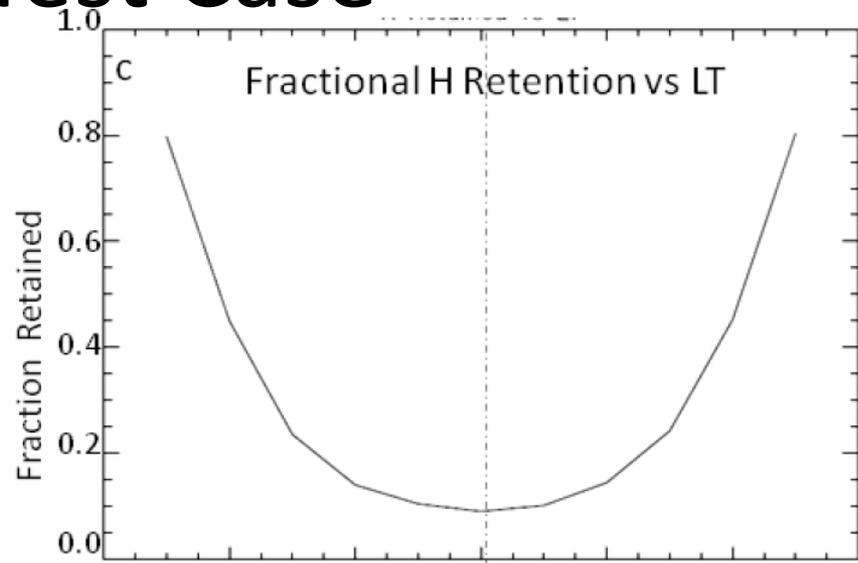
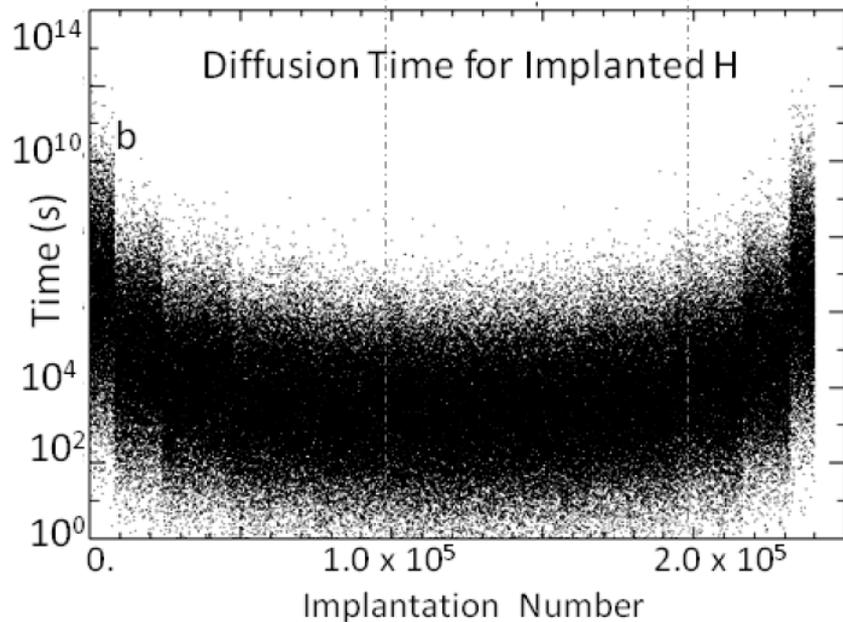
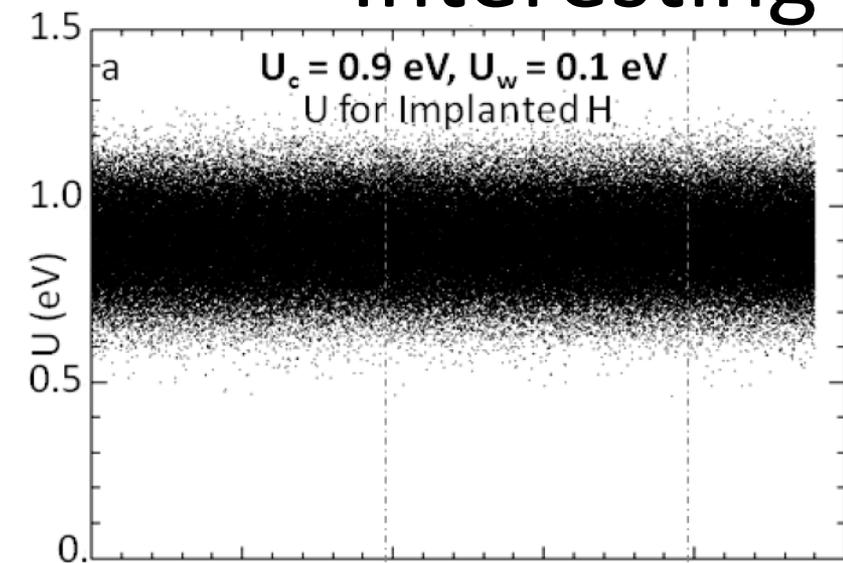
Impactor is $r \sim 0.1$ mm, $m = 10^{-8}$ kg
Impacts a 1 mm x 1mm region every 10^5 years.

Conclusions

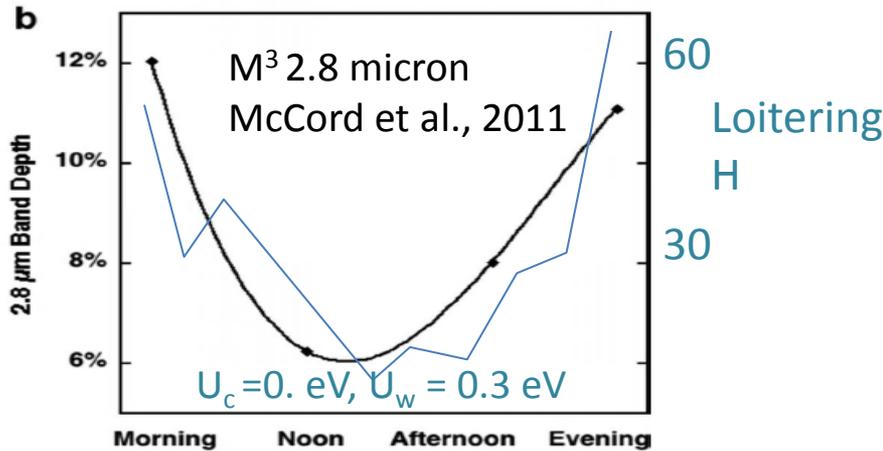
- The **defect properties of a crystal** has as much (or more) control on solar wind H retention in an exposed regolith as temperature and solar wind influx
- **U/T** is the primary variable in residency, not just T
 - T varies by a factor of 4, U varies by a factor of 100
 - T appears as a controlling 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!

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Interesting Test Case



Comparison to the Moon



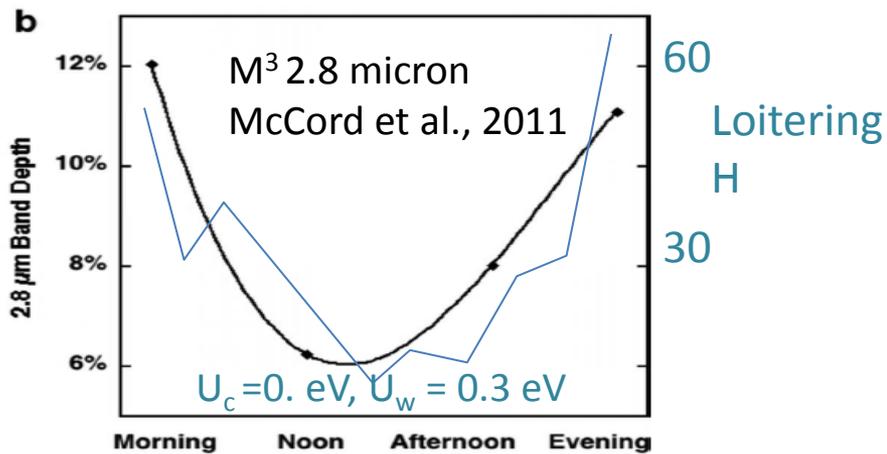
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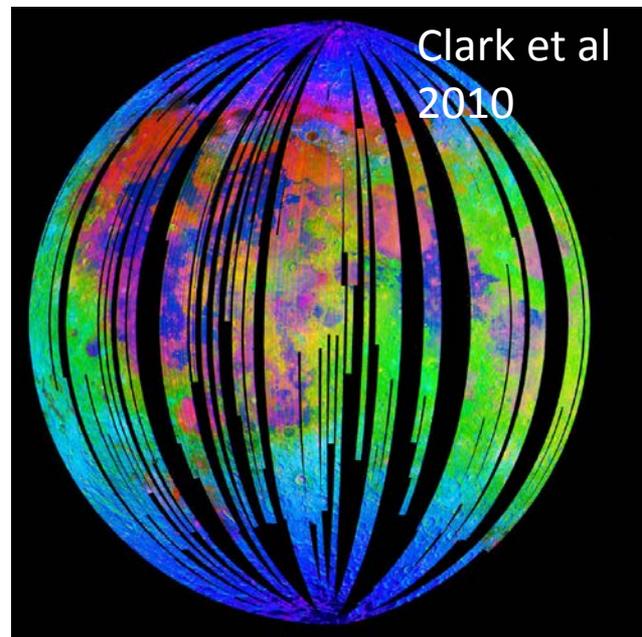
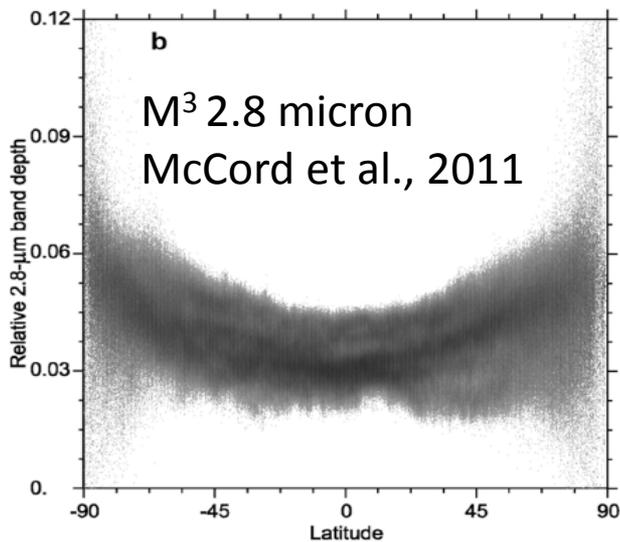
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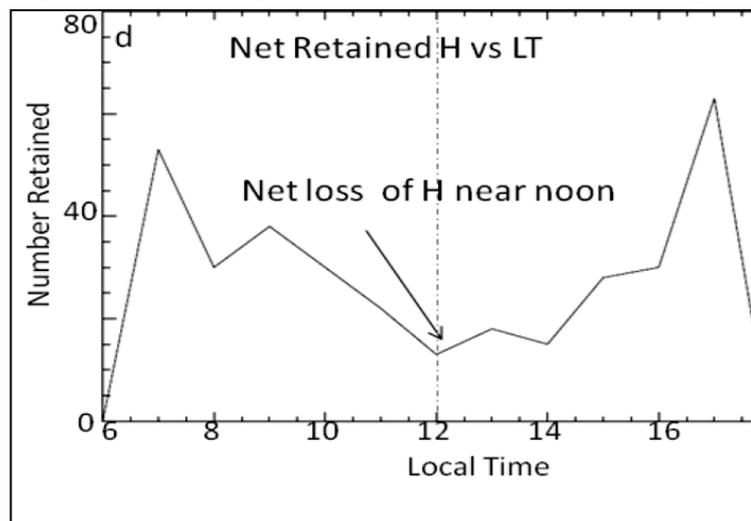
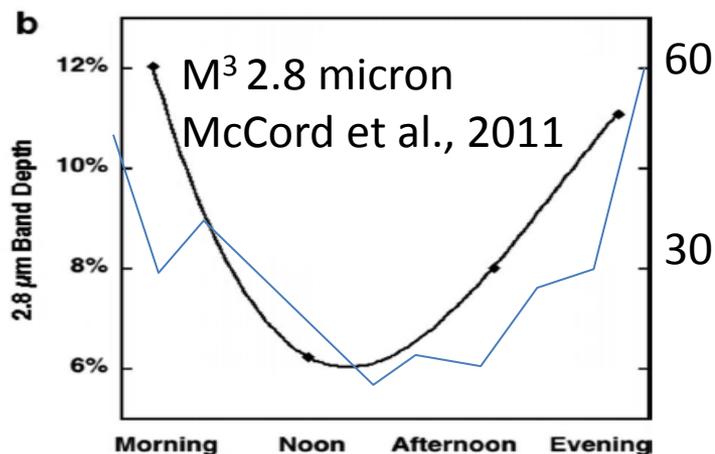
- Mild retention (well below saturation)
- Reduction in H (and hence OH) at sub-solar point
- Consistent with $U_c < 0.3$ eV, $U_w < 0.2$ eV
- Have a fraction of implantations with 0.3 eV $< U < 0.9$ eV



Comparison to Moon

H's
Retained

- Mild retention
- 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



$U_c = 0.0$ eV, $U_w = 0.3$ eV

