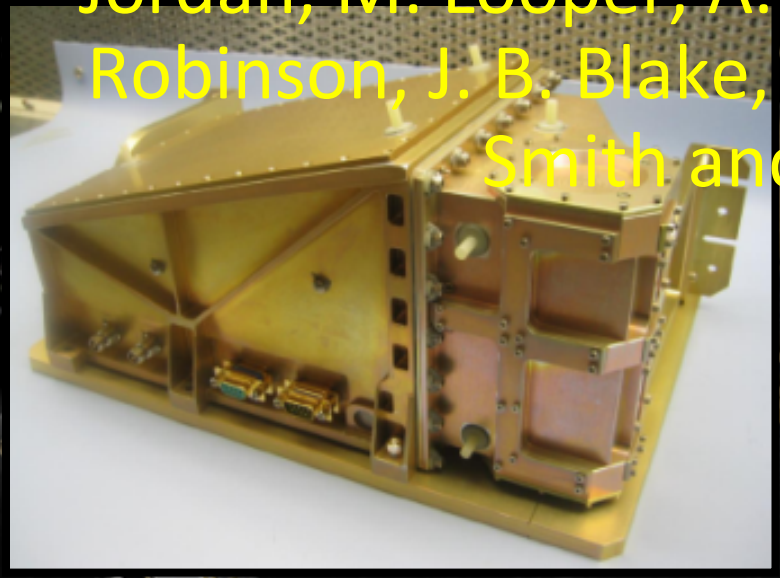
LRO/CRaTER's Discoveries of the Lunar Radiation Environment and Lunar Regolith Alteration by Radiation

N. A. Schwadron, H. E. Spence, J. K. Wilson, A. Jordan, M. Looper, A. W. Case, N. E. Petro, M. S. Robinson, J. B. Blake, J. Kasper, J. E. Mazur, S. S. Smith and L. Townsend



UNH - BU - MIT - AEROSPACE - SAO - UTK

DREAM2

Dynamic Response of the Environments at Asteroids, the Moon, and moons of Mars

SERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE

Formerly the NASA LUNAR SCIENCE INSTITUTE

Select Recent Publications

>50 Refereed Publications from the CRaTER team

CRaTER Special Issue of *Space Weather* - 10 Articles on CRaTER Measurements and Implications

- Schwadron, N. A., S. Smith and H. E. Spence, The CRaTER Special Issue of Space Weather: Building the observational foundation to deduce biological effects of space radiation, *Space Weather, 11,* 47, doi:10.1002/20026, 2013
- Case, A.W., The Deep-space Galactic Cosmic Ray Lineal Energy Spectrum, 2013, Space Weather, doi:10.1002/swe.20051
- Looper, M.D. et al., The Radiation Environment Near the Lunar Surface: CRaTER Observations and Geant4 Simulations. Space Weather, Vol. 11, 142-152, doi: 10.1002/swe.20034, 2013
- Joyce, C.J., et al., Validation of PREDICCS Using CRaTER/LRO Observations During Three Major Solar Events in 2012 using CRaTER and the EMMREM Model. Space Weather, Vol. 11, pp. 1-11, doi:10.1002/swe.20059, 2013
- Spence, H. E., et al., Relative contributions of galactic cosmic rays and lunar proton "albedo" to dose and dose rates near the Moon, Space Weather, 11, 643, 2013
- Porter, J. A., et al., Radiation environment at the Moon: Comparisons of transport code modeling and measurements from the CRaTER instrument, Space Weather, 12, 329, 2014
- Joyce, C. J., et al., Radiation modeling in the Earth and Mars atmospheres using LRO/CRaTER with the EMMREM Module, Space Weather, 12, 112, 2014
- Zeitlin, C.;et al. Measurements of Galactic Cosmic Ray Shielding with the CRaTER Instrument. Space Weather, Vol. 11, pp. 284-296, doi:10.1002/swe.20043, 2013
- Schwadron, N., Bancroft, C., Bloser, P., Legere, J., Ryan, J., Smith, S., Spence, H., Mazur, J., and Zeitlin, C., Dose spectra from energetic particles and neutrons, Space Weather, 11, 547, 2013
- Schwadron et al., Does the Worsening Galactic Cosmic Radiation Environment Preclude Future Manned Deep Space Exploration, *Space Weather,* 2014

Articles on Charging of Regolith and Changing Space Environment

- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A Schwadron, H. E. Spence and C. J. Joyce, **Deep dielectric charging of regolith withn the Moon's permanently shadowed regions**, JGR Planets, *119*, doi:10.1002/2014JE004648.
- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A. Schwadron, and H. E. Spence (2015), Dielectric breakdown weathering of the Moon's polar regolith, *J. Geophys. Res. Planets,* in press, doi: 10.1002/2014JE004710.
- Smith, C. W., McCracken, K. G., Schwadron, N. A., and Goelzer, M. L., The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum, Space Weather, 12, 499, 2014
- Jordan et al.,The rate of dielectric breakdown weathering of lunar regolith in permanently shadowed regions, LRO Special Issue of Icarus, 2015

Articles on Proton Albedo and Implications

- Wilson, J, et al., **Localized Features in the Albedo Proton Map of the Moon,** LRO Special Issue of Icarus, 2015
- Schwadron et al., Possible Albedo Proton Signature of Hydrated Lunar Surface Layer, LRO Special Issue of Icarus, 2015

Recent Results

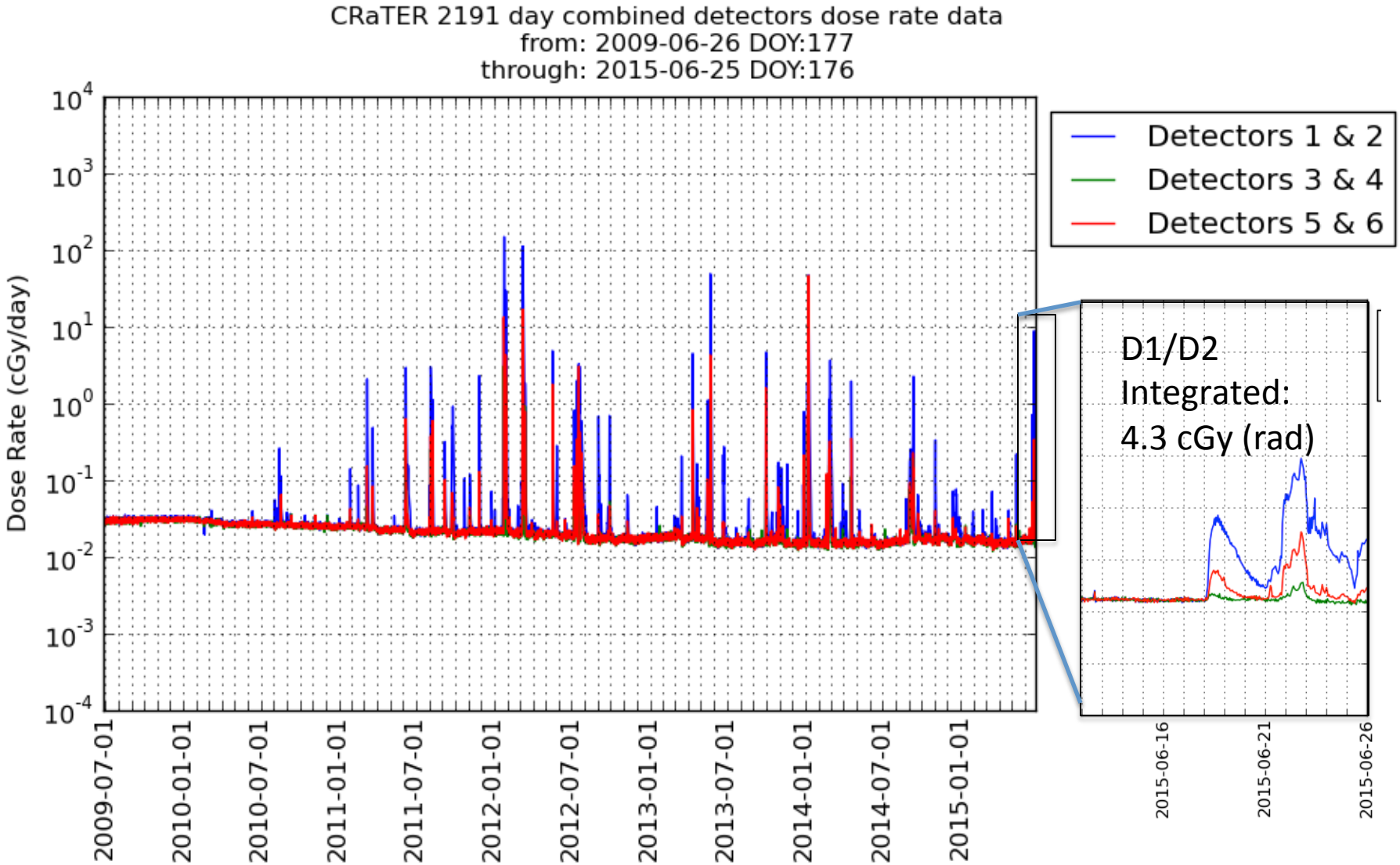
- Radically New Radiation Environment, Implications for Human Exploration
- Lunar Subsurface Charging and Dielectric Breakdown – Implications for Regolith
- New Insights on Energetic Particle Albedo Protons – Hotspots and *possible Implications for Surface Hydrated Layer*

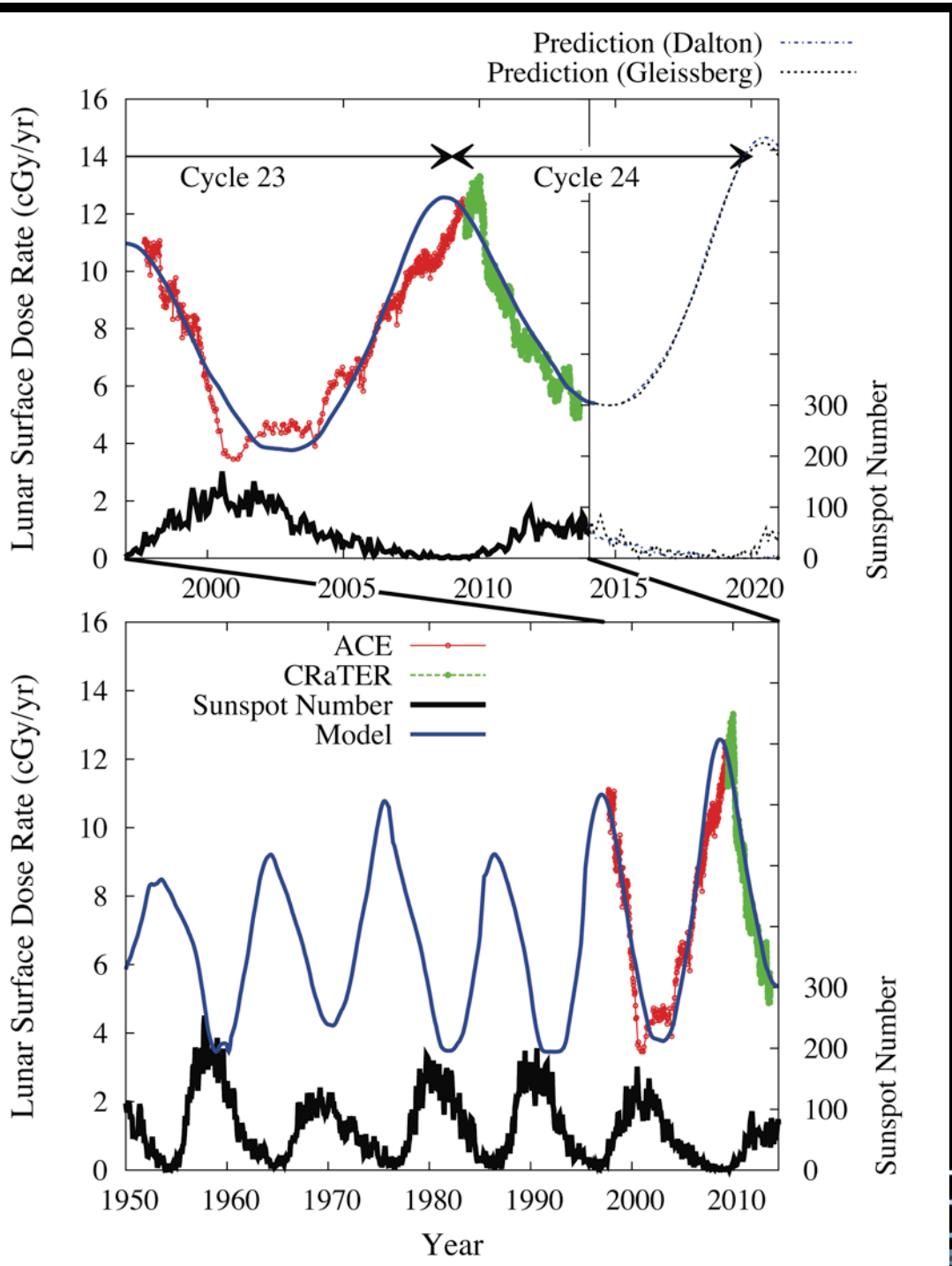
SSERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE
Formerly the NASA LUNAR SCIENCE INSTITUTE

CRaTER Cosmic Ray Telescope for the Effects of Radiation

Experiment on NASA's Lunar Reconnaissance Orbiter

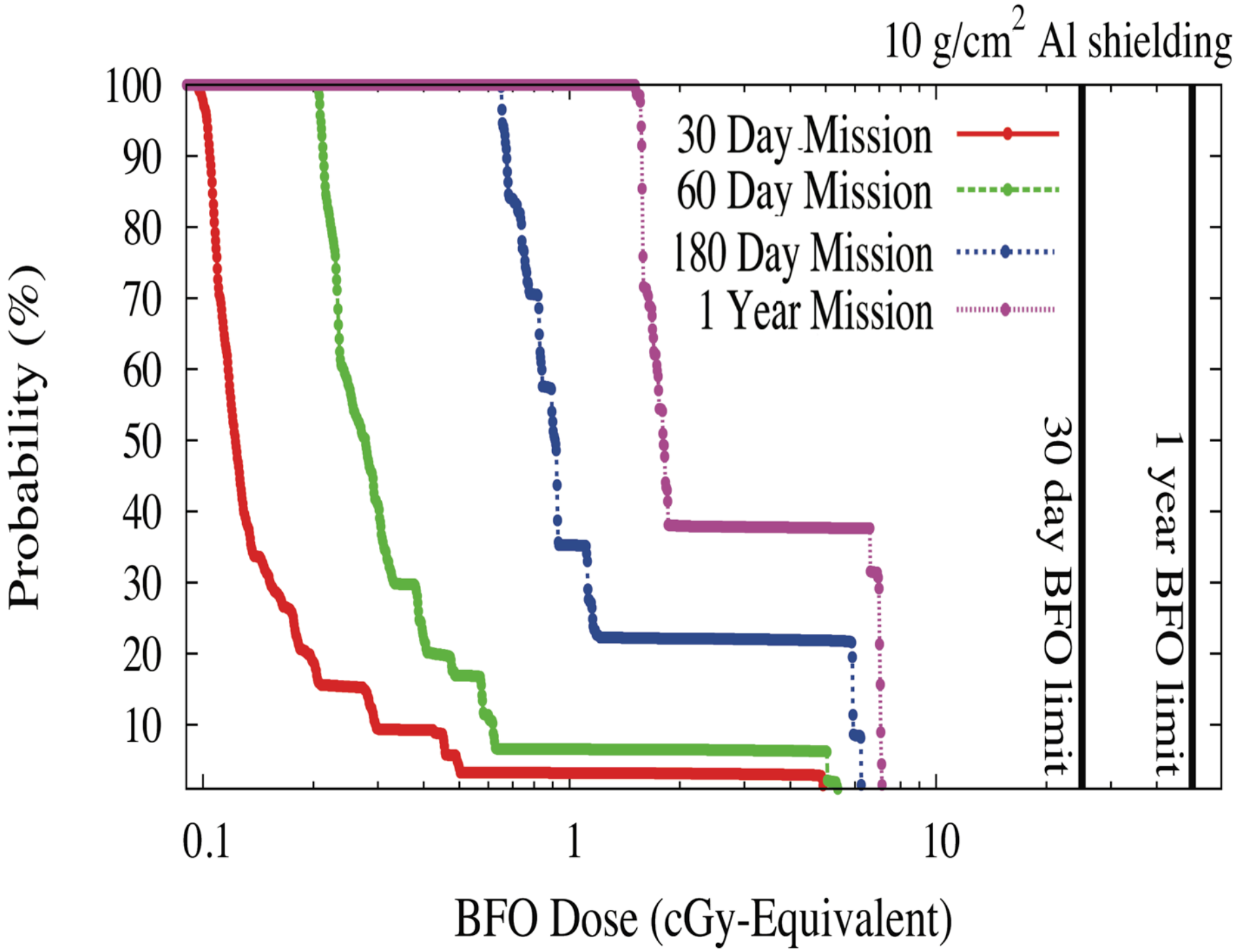
http://crater-web.sr.unh.edu



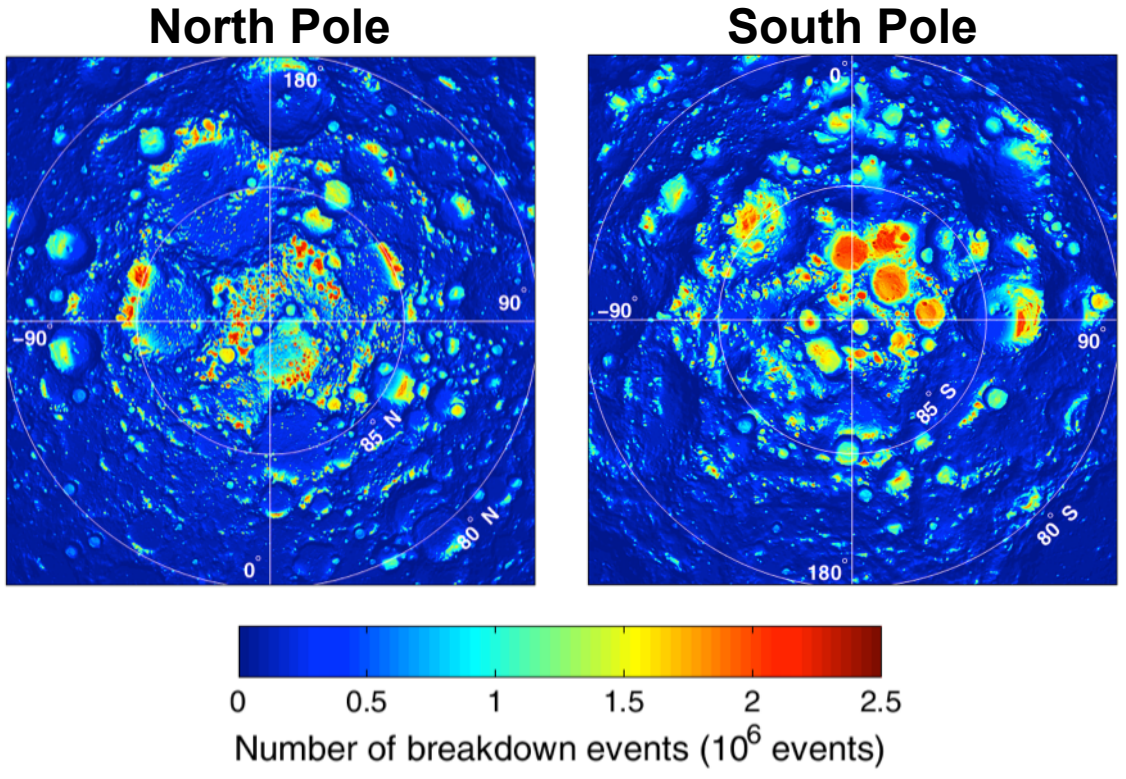


Dynamic Response of the Environments at Asteroids, the Moon, and moons of Mars

SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE


10 g/cm2 Al shielding
100
90
80
70
60
50
40
30
20
10
Probability (%)
30 Day Mission
60 Day Mission
180 Day Mission
1 Year Mission
30 day BFO limit
1 year BFO limit
0.1
1
10
BFO Dose (cGy-Equivalent)

Breakdown weathering may be comparable to meteoritic weathering

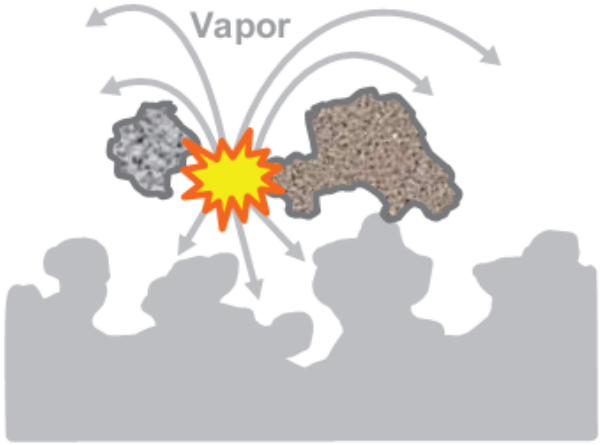


(Jordan et al., 2015)

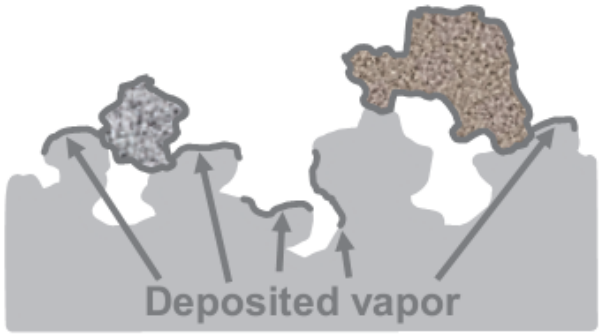
Weathering process	Energy flux (J m^{-2} yr^{-1})	Vapor + melt production (kg m^{-2} yr^{-1})	% Gardened soil melted or vaporized
Meteorites	12	1.8×10^{-7}	~10%
Breakdown	0.88	$1.8 – 3.4 \times 10^{-7}$	~10-25%

Jordan et al. (submitted)

1) Grain at regolith's surface



2) Breakdown vaporizes some of grain's material and splits grain



3) Grain fragments move, changing regolith's porosity; some of vaporized material is deposited on surrounding regolith

We're in the process of discovering how this might affect the albedo in PSRs.

Investigations of chemical alteration of regolith by energetic particles and cosmic rays

(Schwadron et al., 2012)

[43] In summary, CRaTER provides direct observations of dose rates near the lunar surface. These CRaTER dose rates are likely underestimates of the average dose rates over long periods of time, implying dose deposition of more than 88 eV/molecule over 4 billion years. As a result, GCRs cause significant space weathering on the Moon. This is particularly the case in permanently shaded regions, which are bombarded by GCRs while being protected from visible light, UV, and solar wind. The exposure of material within these shaded regions should reduce reflectance, cause elevated carbon to hydrogen ratios, and lead to the build-up of significant chemical alteration within the outer regolith. The large GCR dose rates observed by CRaTER suggest that GCR bombardment plays an important role in the balance that determines the amounts of water ice within regolith of permanently shaded craters.

Observed amount of H_2 wrt H_2O molecules in LCROSS impact: 8% (+10%/-4%)

After 1 billion years, GCR and SEP radiolysis likely accounts for 10-100% of observed H_2

(Jordan et al., 2013)

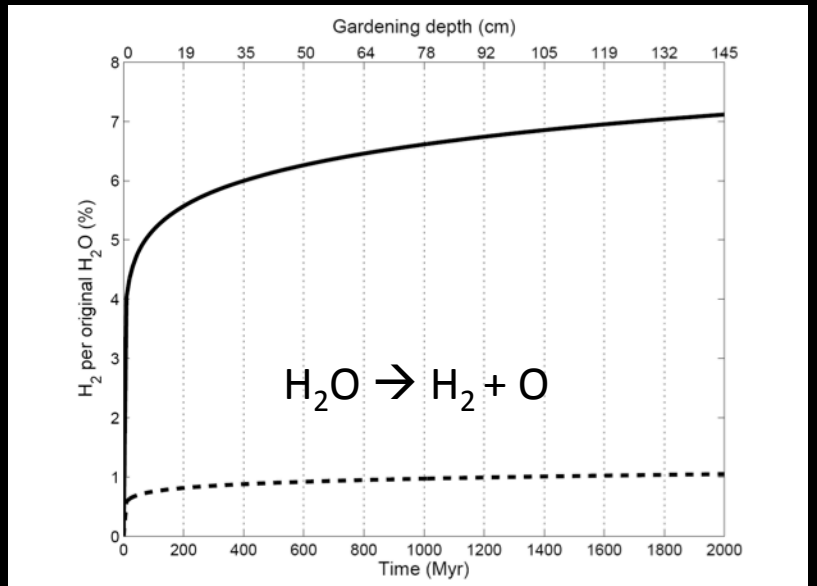


Figure 6. The number (as a percentage) of H_2 molecules created by GCRs and SEPs with respect to the original number of water molecules as a function of gardening time (lower axis) and depth (upper axis). We have assumed that the GCR dose is applicable to 36 cm and the SEP dose to 0.18 cm. The dashed line shows the percentage if G = 0.1, and the solid line if G = 0.7.

- **Schwadron, N. A., et al., Lunar radiation environment and space weathering from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER), *J. Geophys. Res. – Planets, 117,* DOI: 10.1029/2011JE003978, 2012.**
- **Jordan, A. P, et al., The formation of molecular hydrogen from water ice in the lunar regolith by energetic charged particles, *J. Geophys. Res. – Planets, DOI:10.1002/jgre.20095*, 2013.**

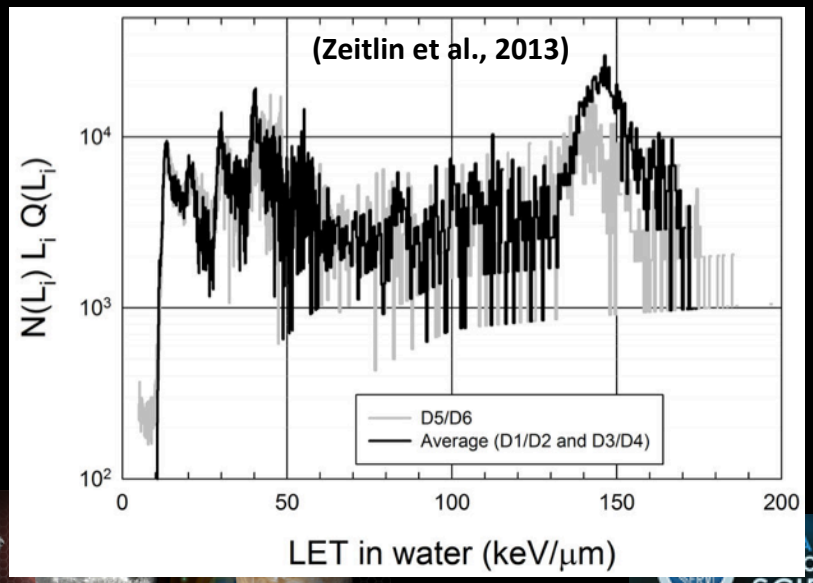
Work motivated by comment from **Mike Wargo**!!

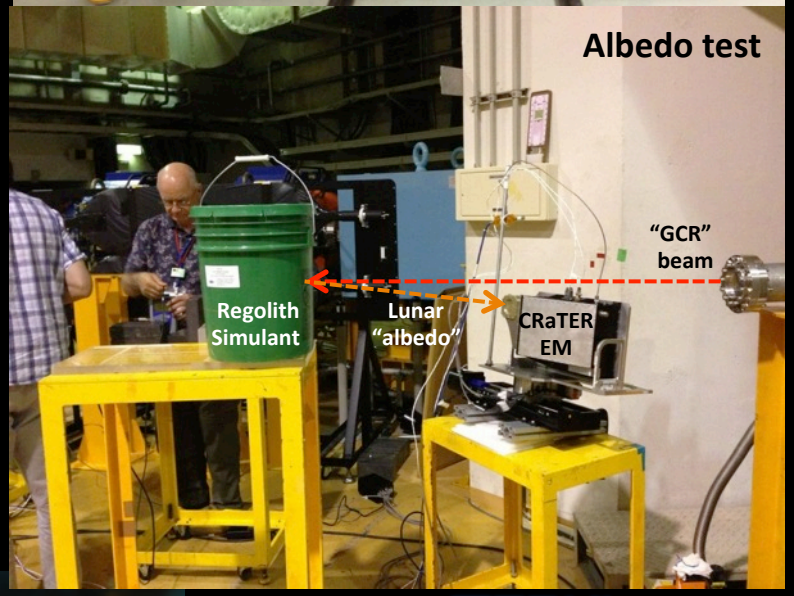
DREAM2 Dynamic Response of the Environments at Asteroids, the Moon, and moons of Mars

NASA EXPLORATION SCIENCE FORUM JULY 21-23, 2015 NASA AMES RESEARCH CENTER MOFFETT FIELD, CALIFORNIA

SSERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE Formerly the NASA LUNAR SCIENCE INSTITUTE

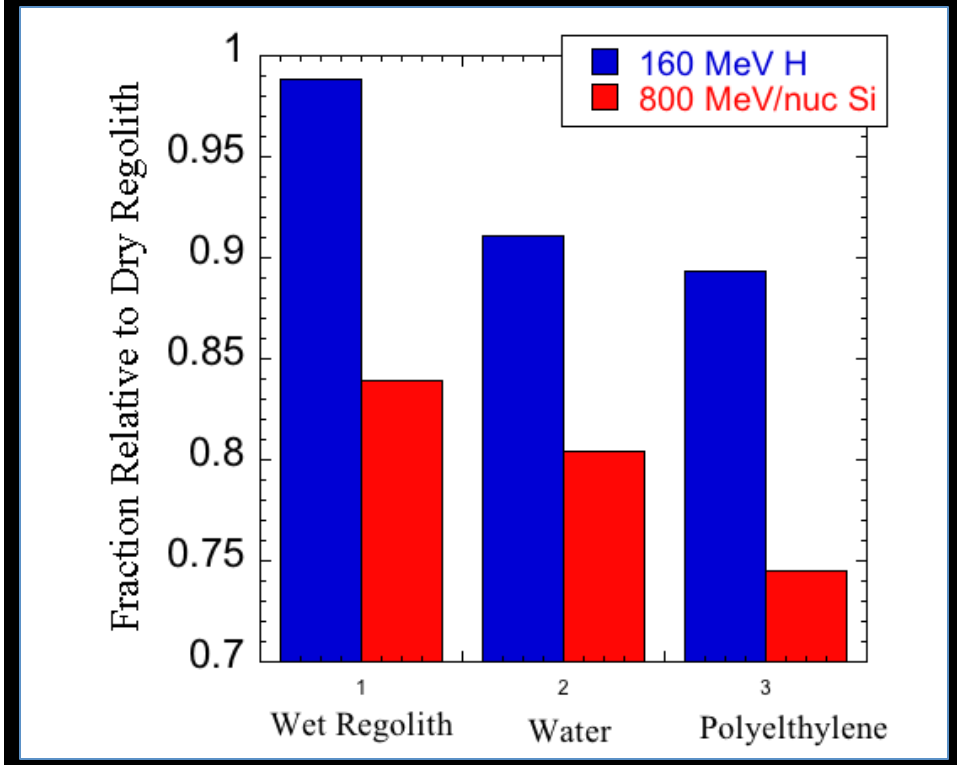
Beam runs (HIMAC & MGH) with CRaTER EM confirm nuclear evaporation concept



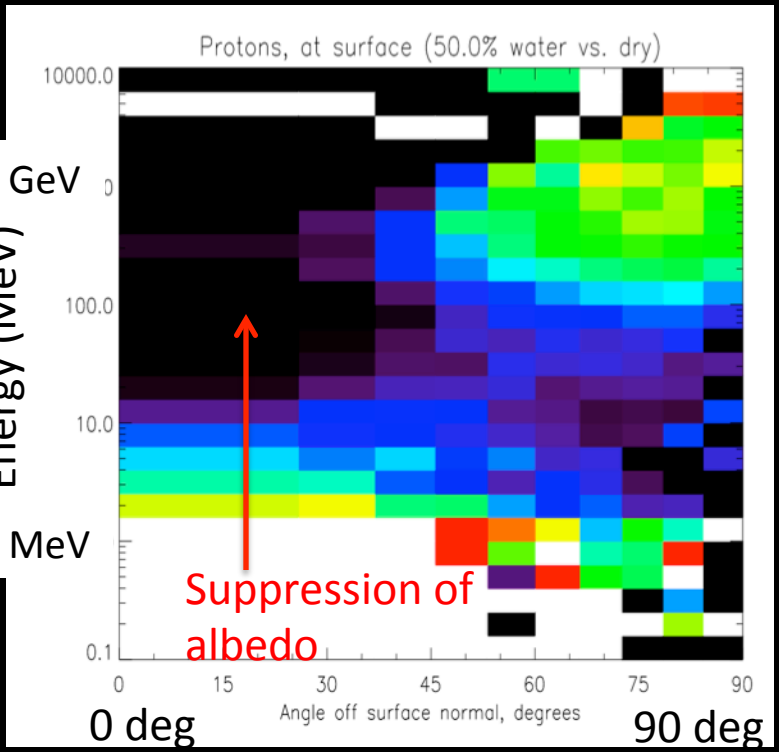


Zeitlin, C., et al., Measurements of Galactic Cosmic Ray Shielding with the CRaTER Instrument, *Space Weather, DOI: 10.1002/swe.20043*, 2013.

Beam runs with CRaTER and Simulations confirm nuclear evaporation concept



Suppression of Radiation Albedo from H-rich material



Geant Simulations by Mark Looper

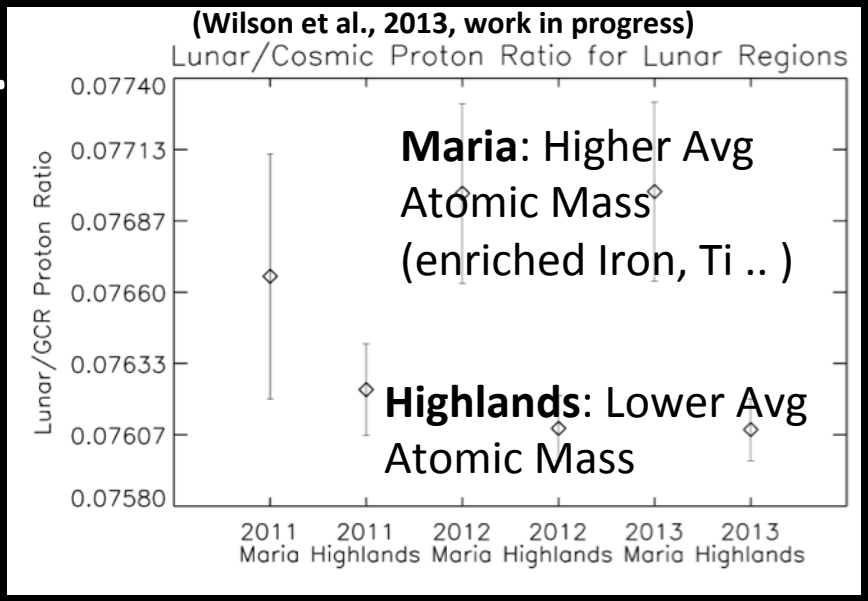
Predictions for nuclear evaporation/forward scattering

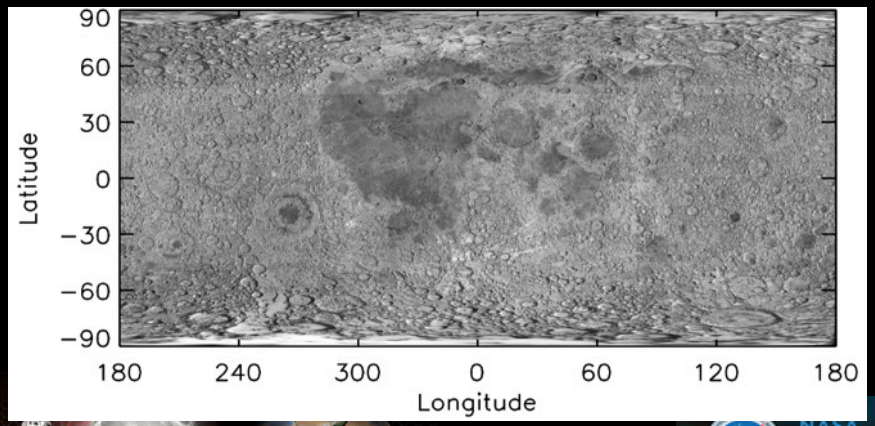
- Higher Average Nucleon Mass (density) leads to **increased** proton albedo
- Presence of H in regolith should **decrease** proton albedo!

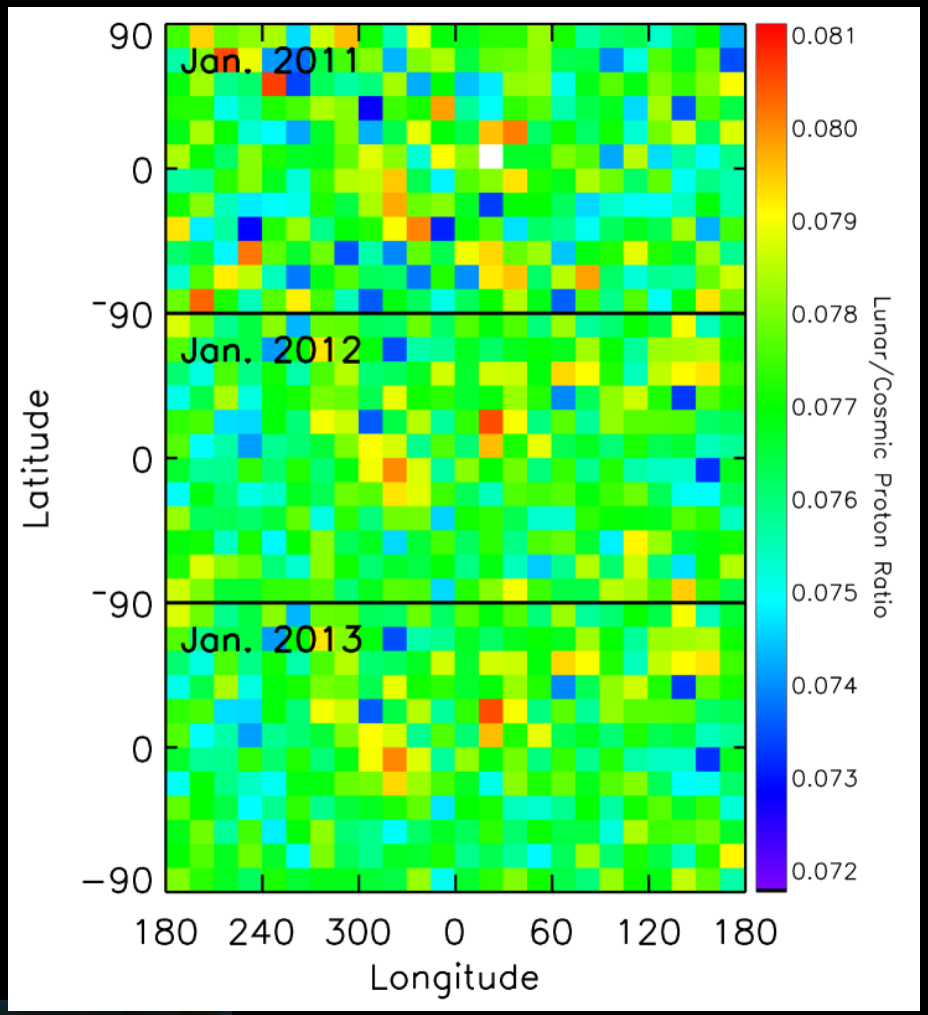
Possible composition dependence of albedo sources

See Wilson et al., Poster #

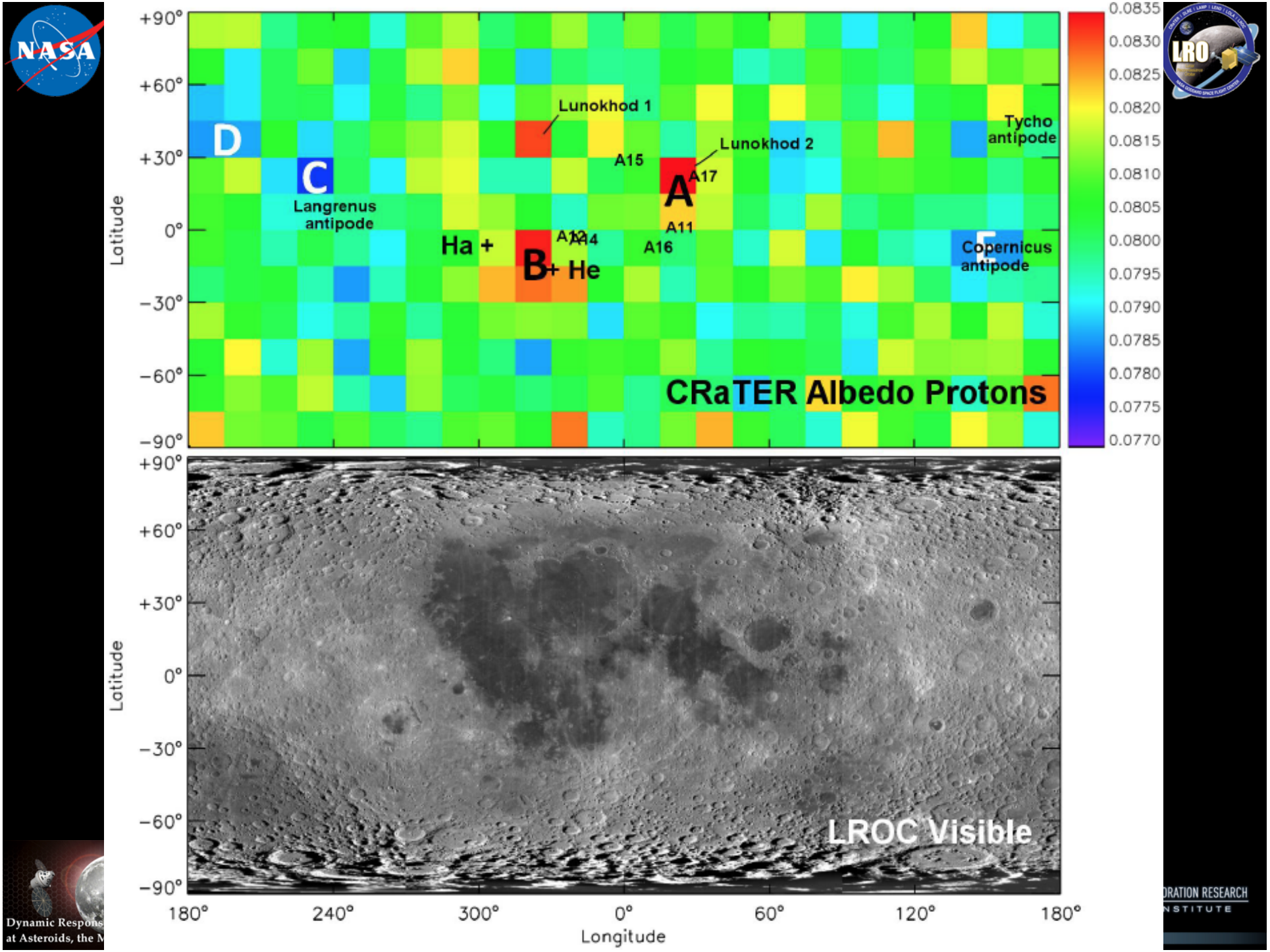
- (Wilson et al., 2013, work in progress)



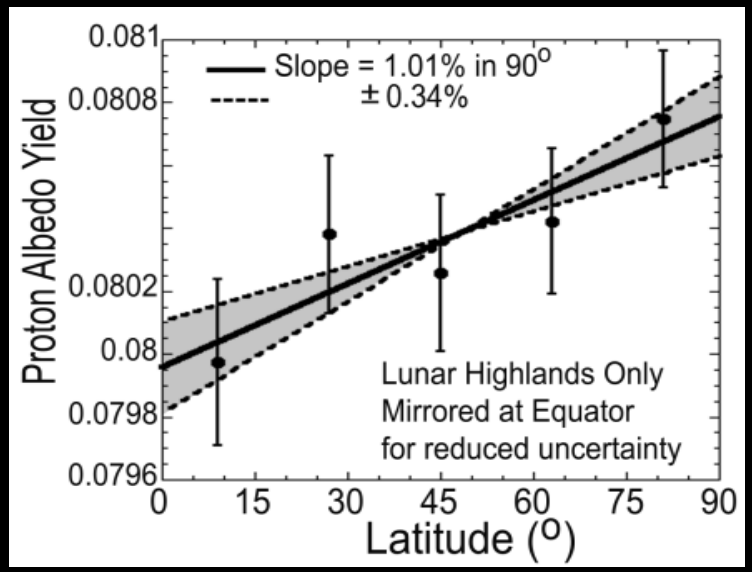




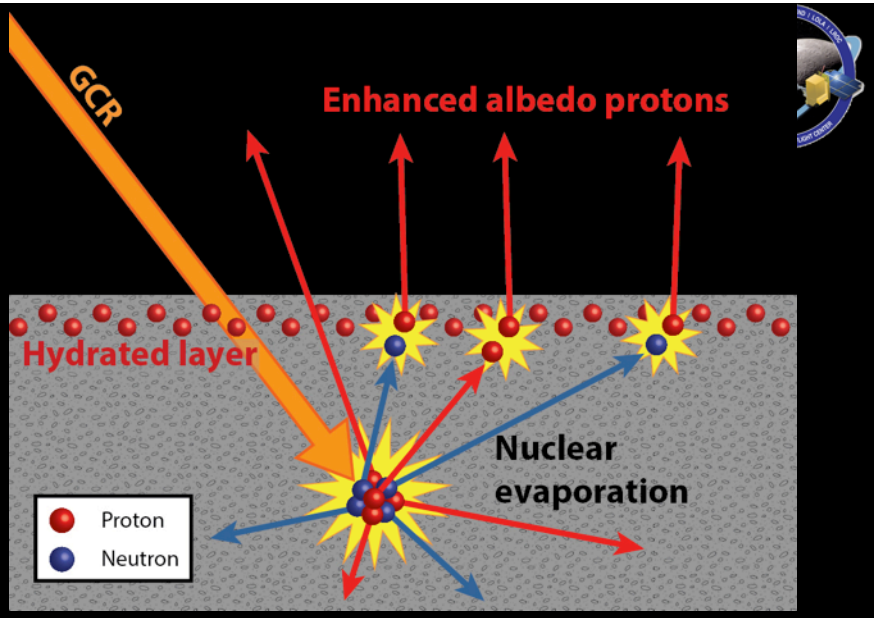
Wilson, J. K., et al. , Localized Features in the Albedo Proton Map of the Moon, LRO Special Issue of Icarus 2015


+90°
+60°
+30°
0°
−30°
−60°
−90°
Latitude
D
C
Langrenus antipode
Lunokhod 1
Lunokhod 2
A15
A17
A
A11
A16
A12
A14
Ha +
B
+ He
Tycho antipode
Copernicus antipode
F
CRaTER Albedo Protons
0.0835
0.0830
0.0825
0.0820
0.0815
0.0810
0.0805
0.0800
0.0795
0.0790
0.0785
0.0780
0.0775
0.0770
LROC Visible
180°
240°
300°
0°
60°
120°
180°
Longitude

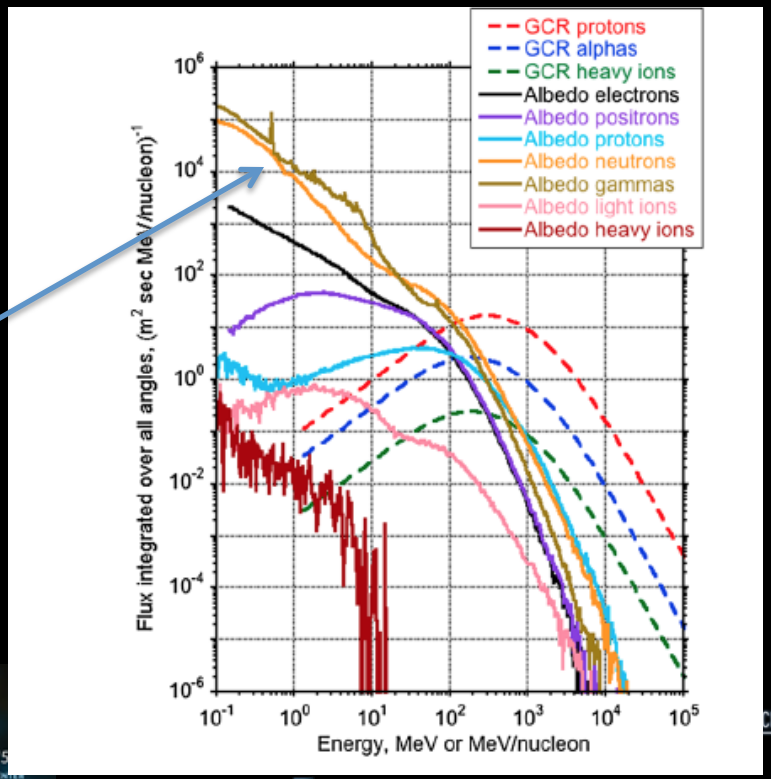
Possible Albedo Proton Signature of Hydrated Lunar Surface Layer



The latitude trend in the proton albedo suggests a 1-10 cm layer of hydrated regolith that is more prevalent near the poles [*Schwadron et al.*, submitted]



Note: Large Flux of Albedo neutrons



Hydrated Surface Layer - Properties

$$F'_p = F_p + F_n(dn_H\sigma_{np})$$

F_p' Proton Flux from Top regolith

F_p Proton Flux from depth

F_n Neutron Flux from depth

$$\Delta \approx (dn_H\sigma_{np})F_n/F_p$$

Fractional Excess

$$dn_H \approx \Delta F_p/(F_n\sigma_{np})$$

Column density in upper layer

$$\Delta = 1.01 \pm 0.34\%$$

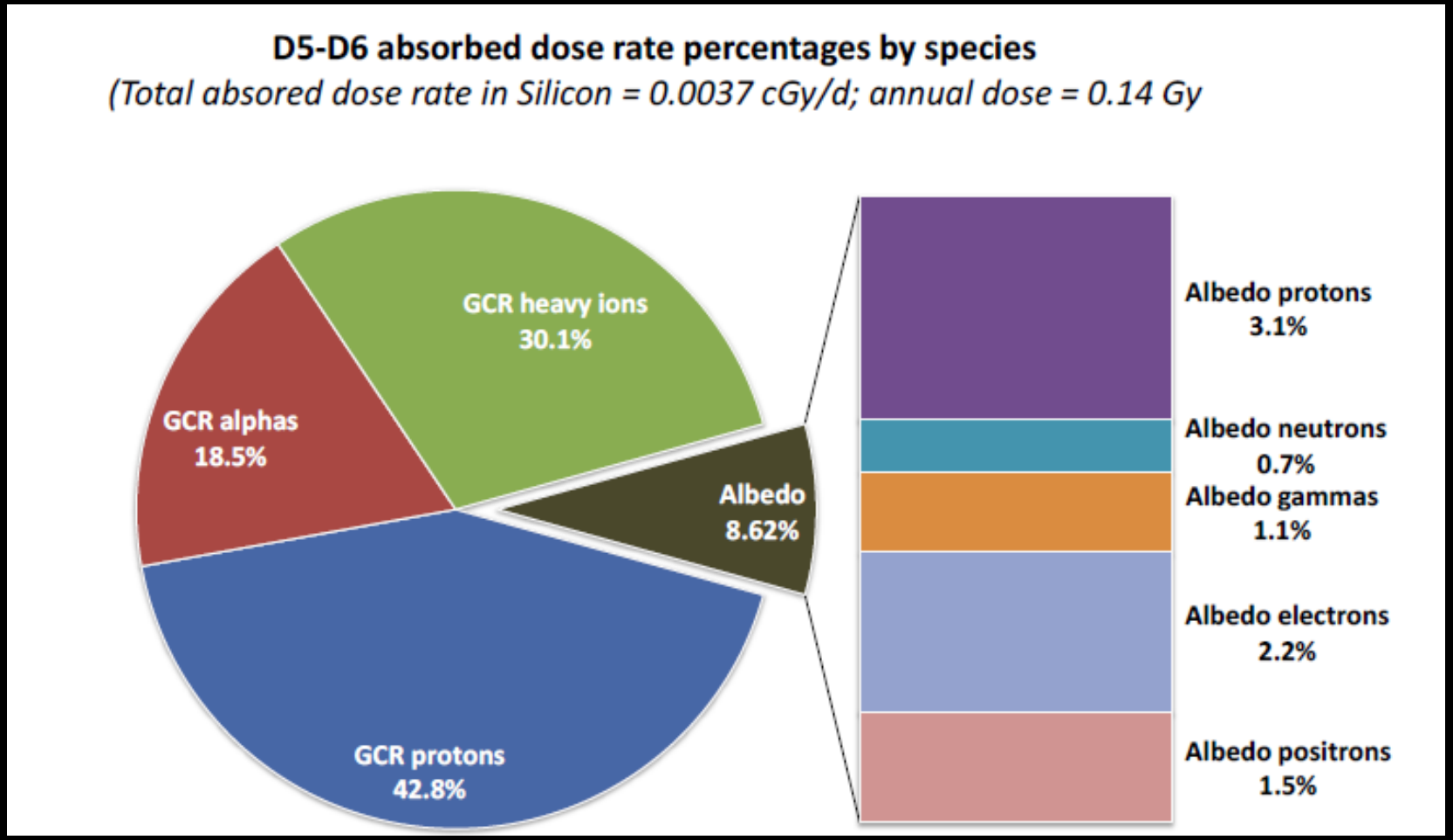
d ~ 20 cm → H 200 ppm by weight

d ~ 2 cm → H 2000 ppm by weight

Modeled H in cold traps 200-4000 ppm, Teodoro et al., GRL, 37, L12201, 2010

Dose and Dose Rate Estimates

After Spence et al., 2013



- **Use validated GEANT4 model of CRaTER response to primary GCR and lunar secondaries to assess contributions by species**
- **Secondary albedo particles account for ~10% of absorbed dose rate**

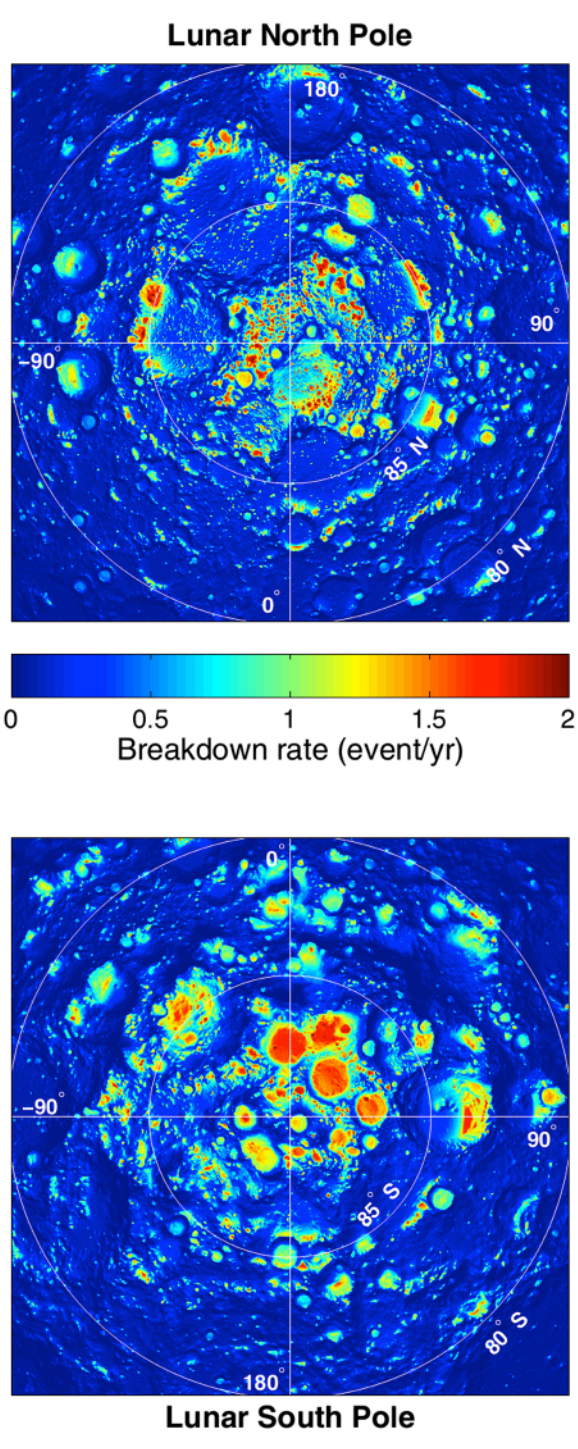
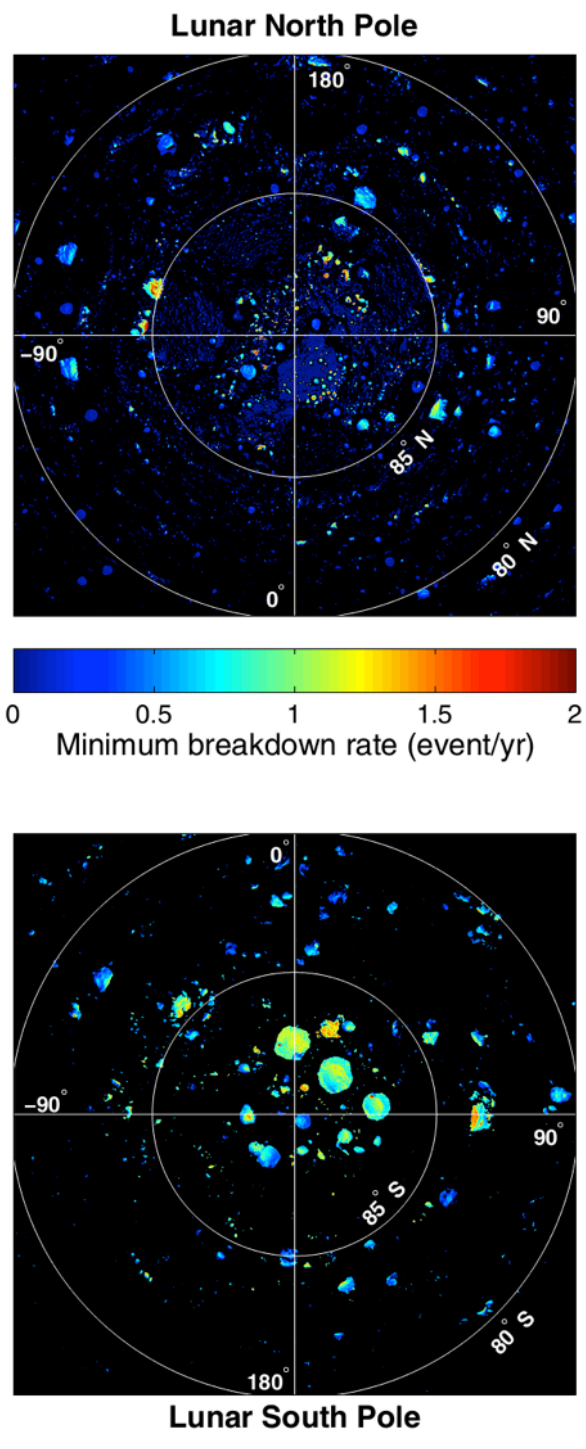
LRO/CRaTER Summary

- Deepest Solar Minimum and Weakest Maximum more than 80 years
  - Increased GCR radiation intensity in solar minima
  - Lower probability of SEP events → *Enabler* for launching missions near solar maxima
- Radiation Effects on the Moon
  - Chemical modification of Lunar Regolith
  - Deep dielectric charging → grain fragmentation in PSRs and changes in regolith porosity
- Proton (Radiation) Albedo
  - Evidence of nuclear evaporation (Maria vs. Highlands)
  - Possible evidence of Hydrated surface layer

Hear More!!

- Jordan et al., Possible Dielectric Breakdown Weathering Effects o the Comminution of Lunar Regolith, Session #8, 2:30 PM
- Spence et al., Particle Radiation Environment and Their Effects at Exploration Destinations, Session #7, 2:45 PM
- Wilson et al., Lunar Proton Albedo Anomalies: Soil, Surveyors, and Statistics, [Poster #38]
- Smith et al., The MERLIN Phobos Ionizing Radiation Experiment (MPIRE) [Poster #34]

SSERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE
Formerly the NASA LUNAR SCIENCE INSTITUTE

Understanding of Radiation Driving New Data Products

Rate of SEP events that may cause regolith breakdown