Lunar Radiation Environment Implications for the Moon

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Recent Publications

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,* In Press, 2014

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.

AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE

10.1002/2014SW001084

Key Points:

- GCR radiation is increasingly hazardous
- Limited duration for missions in deep space near
- Timing during solar cycle of missions remains a critical factor

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Does the worsening galactic cosmic radiation environment observed by CRaTER precludes future manned deep space exploration?

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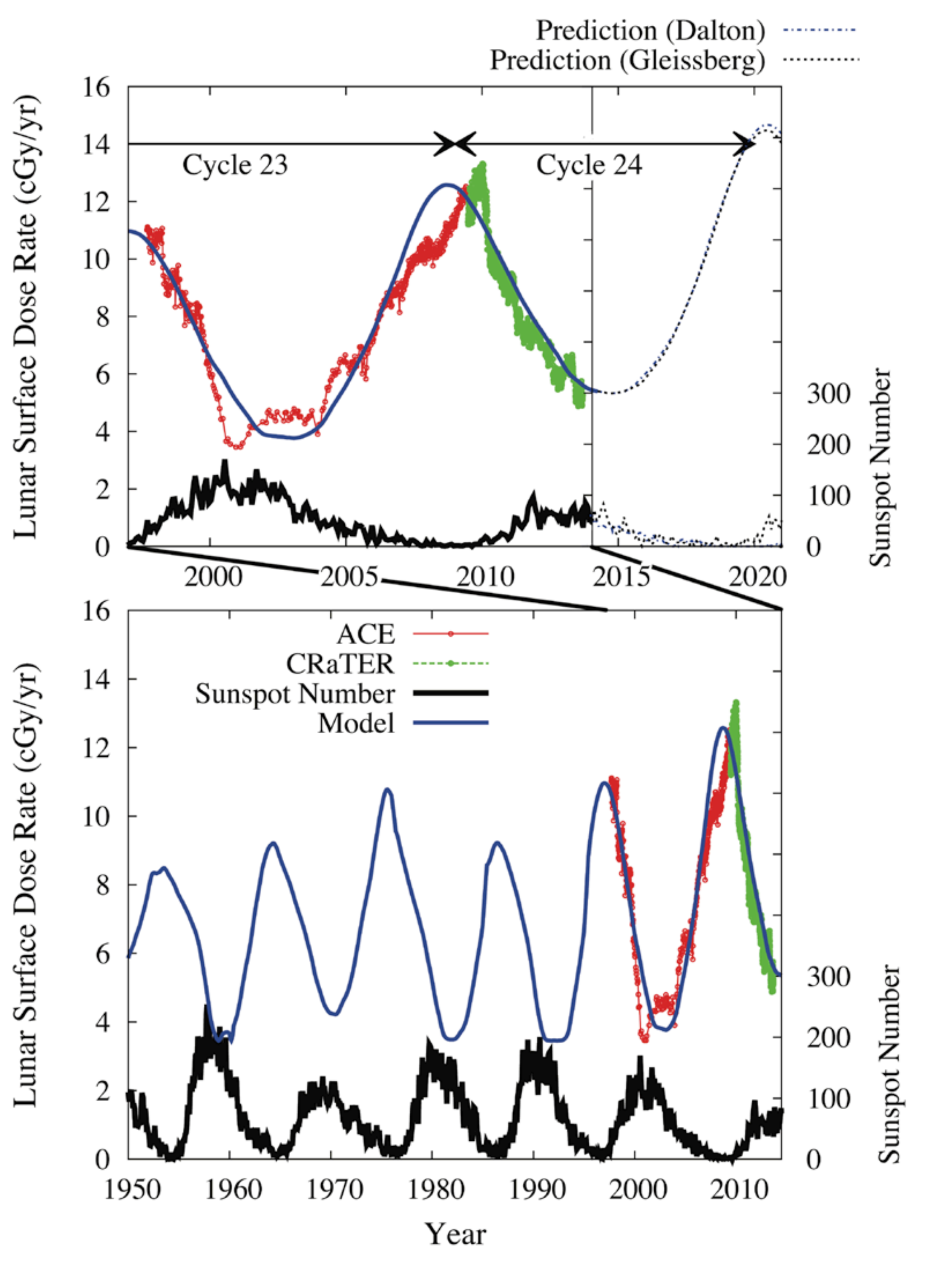
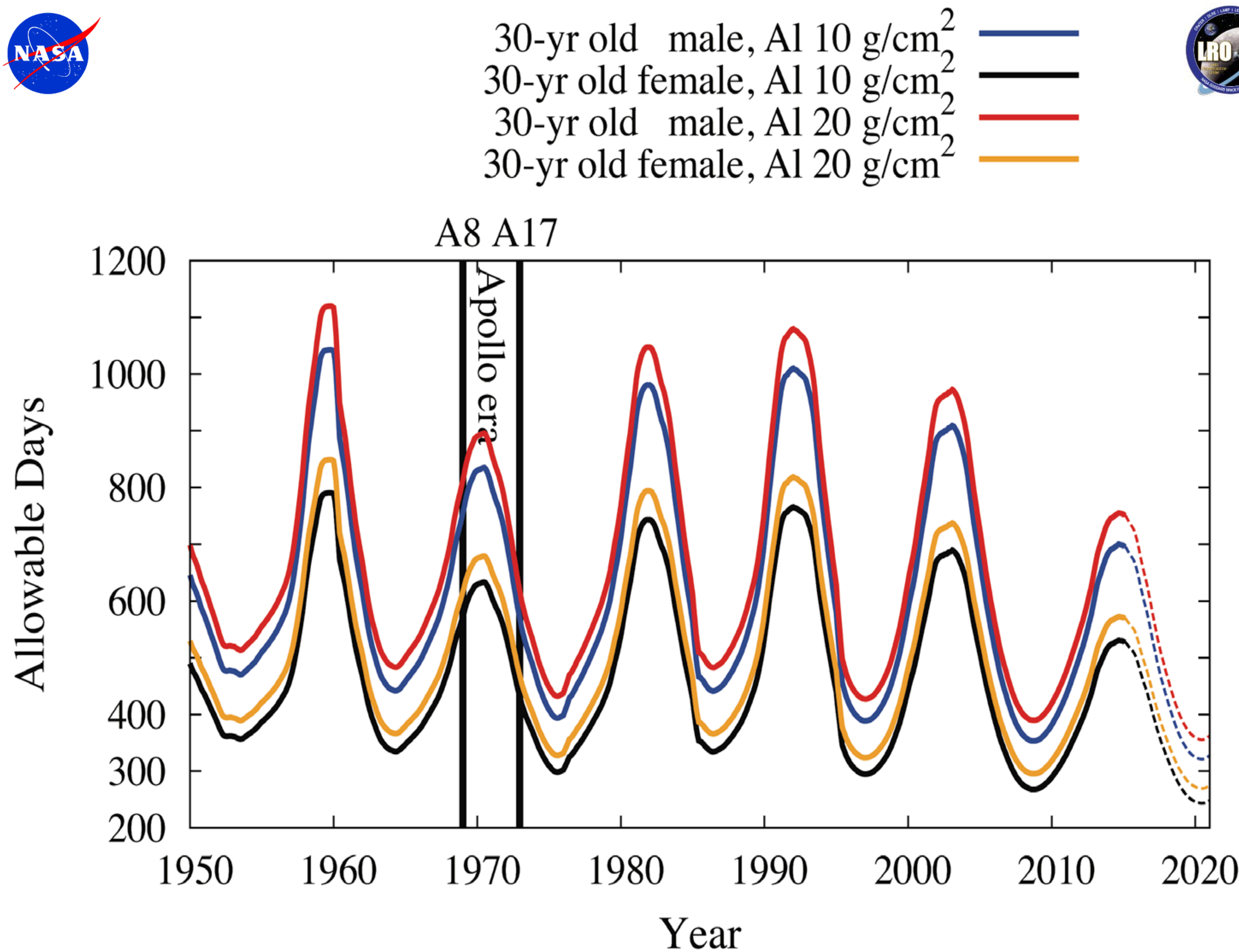
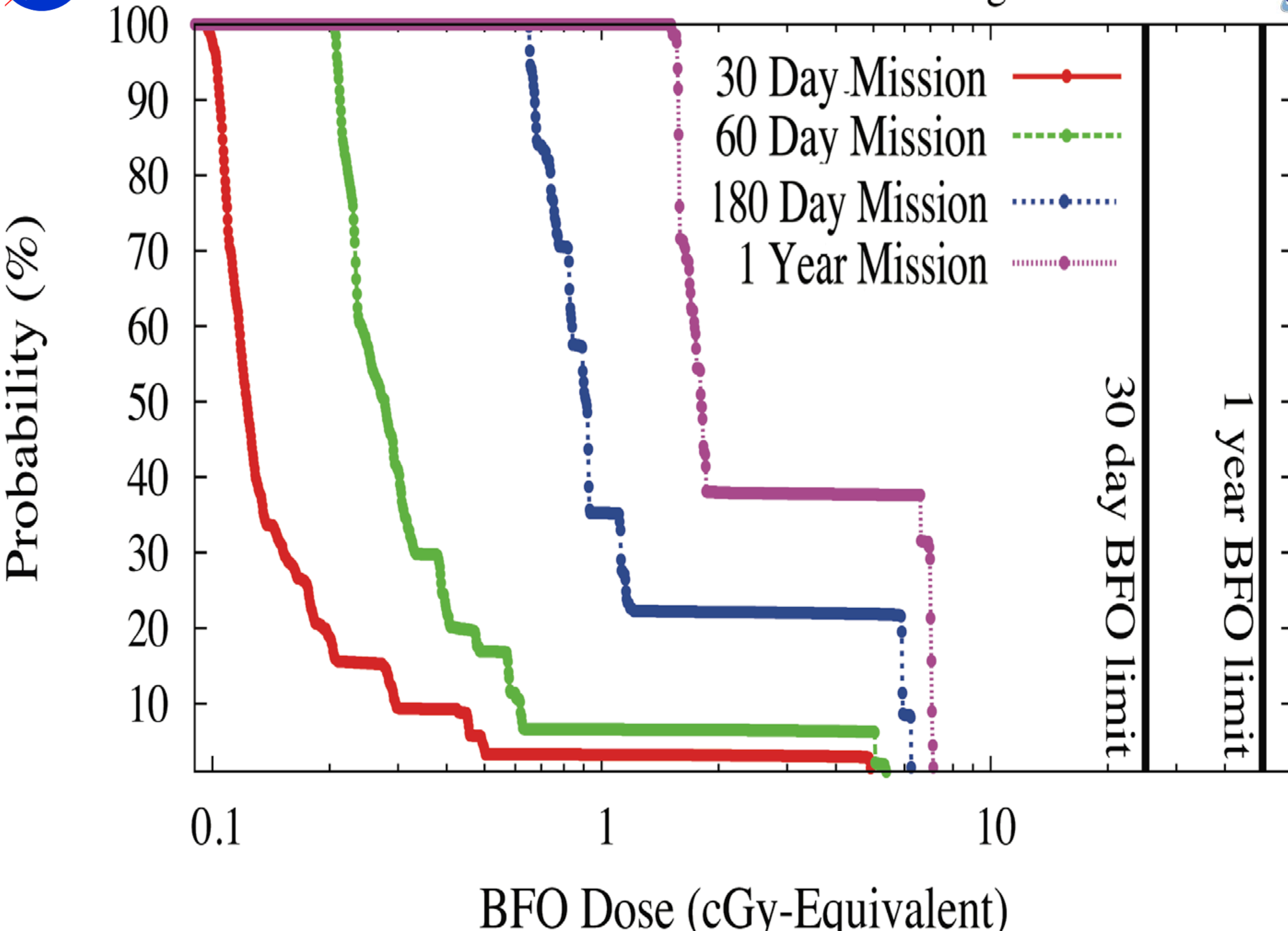
Abstract The Sun and its solar wind are currently exhibiting extremely low densities and magnetic field strengths, representing states that have never been observed during the space age. The highly abnormal solar activity between cycles 23 and 24 has caused the longest solar minimum in over 80 years and continues into the unusually small solar maximum of cycle 24. As a result of the remarkably weak solar activity, we have also observed the highest fluxes of galactic cosmic rays in the space age and relatively small solar energetic particle events. We use observations from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter to examine the implications of these highly unusual solar conditions for human space exploration. We show that while these conditions are not a show stopper for long-duration missions (e.g., to the Moon, an asteroid, or Mars), galactic cosmic ray radiation remains a significant and worsening factor that limits mission durations. While solar energetic particle events in cycle 24 present some hazard, the accumulated doses for astronauts behind 10 g/cm^2 shielding are well below current dose limits. Galactic cosmic radiation presents a more significant challenge: the time to 3% risk of exposure-induced death (REID) in interplanetary space was less than 400 days for a 30 year old



Prediction (Dalton)
Prediction (Gleissberg)
Cycle 23
Cycle 24
Lunar Surface Dose Rate (cGy/yr)
Sunspot Number
ACE
CRaTER
Sunspot Number
Model
Lunar Surface Dose Rate (cGy/yr)
Sunspot Number
Year



30-yr old male, Al 10 g/cm2
30-yr old female, Al 10 g/cm2
30-yr old male, Al 20 g/cm2
30-yr old female, Al 20 g/cm2
A8
A17
Apollo era
Allowable Days
1200
1000
800
600
400
300
200
1950
1960
1970
1980
1990
2000
2010
2020
Year



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

First energetic particle albedo maps of Moon

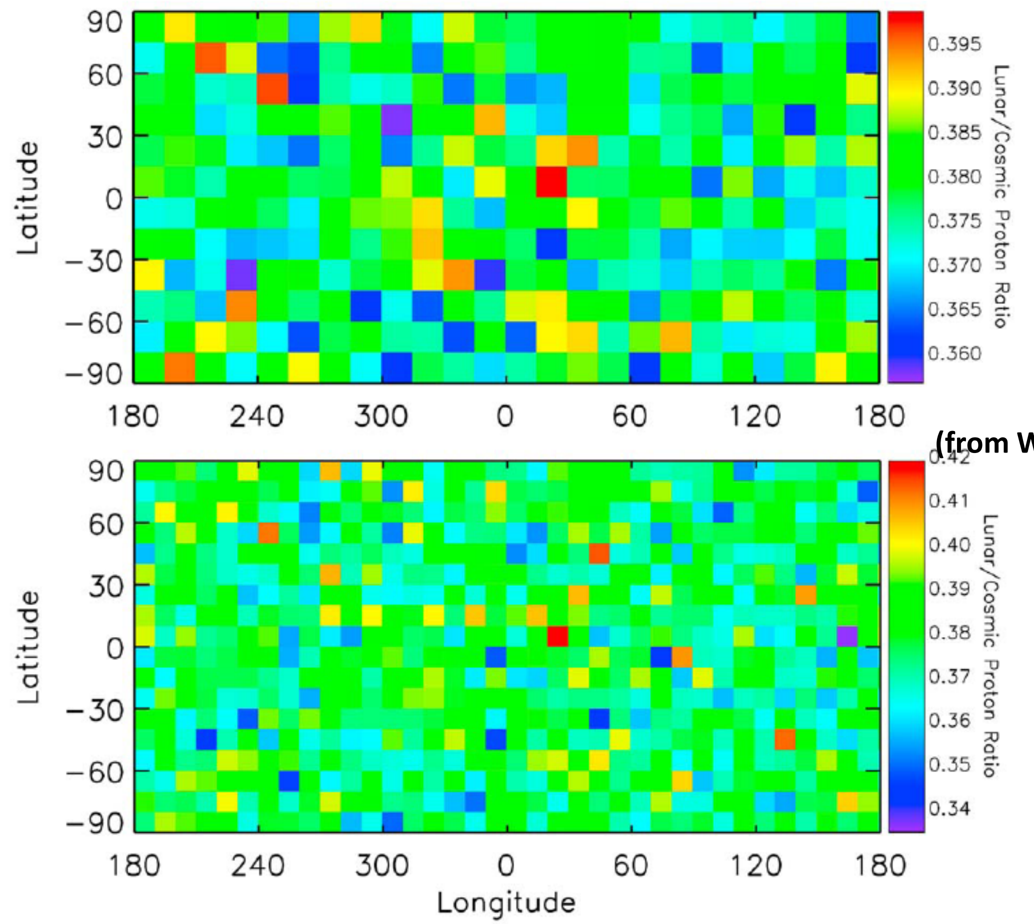
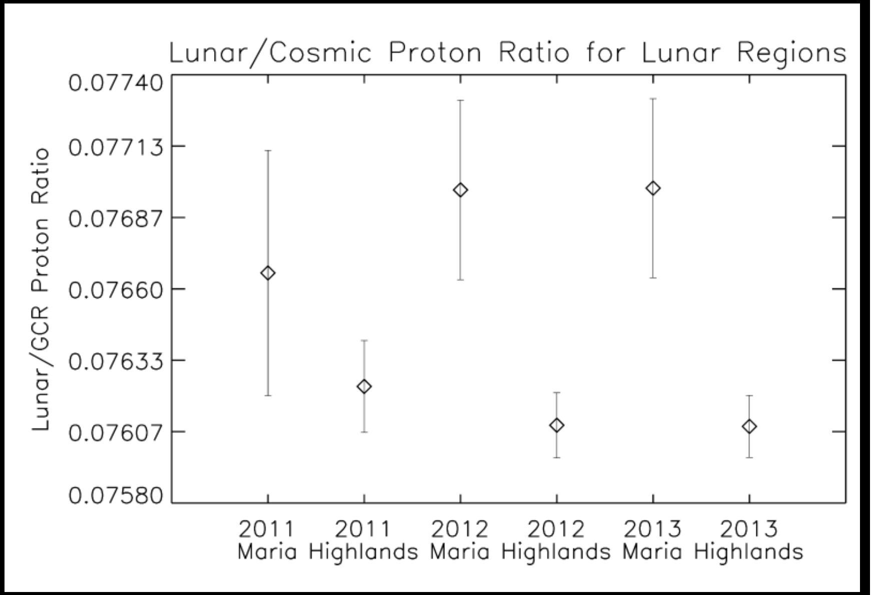
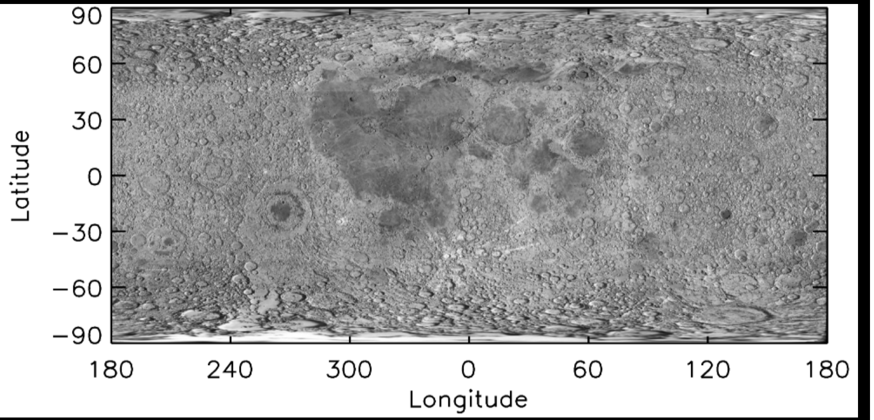


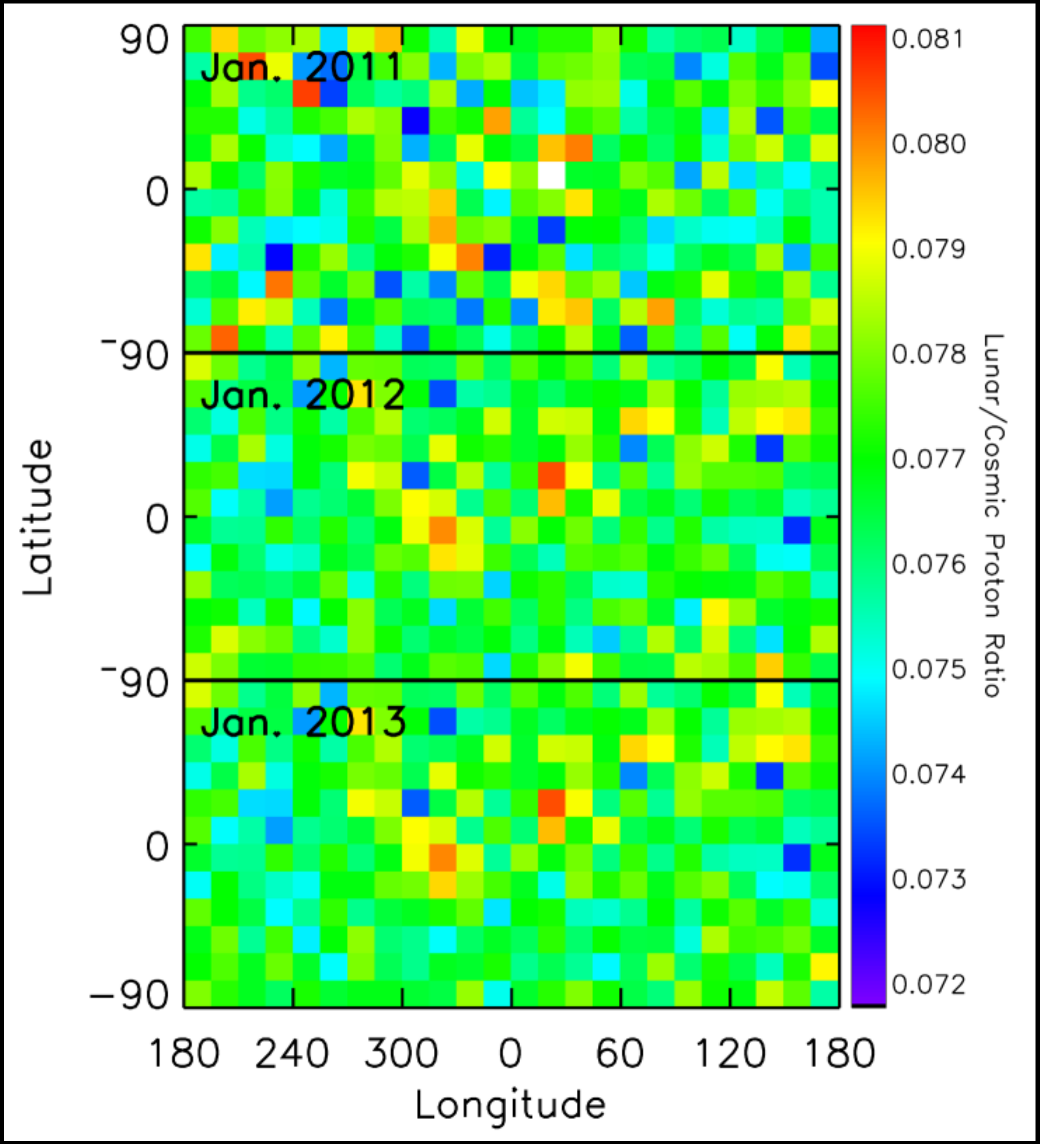
Figure 4. Cylindrical projection albedo proton maps of the Moon at two spatial resolutions: (top) 15 degrees and (bottom) 10 degrees. Colors represent the ratio of lunar protons to GCR protons, from red (high) to blue/purple (low).

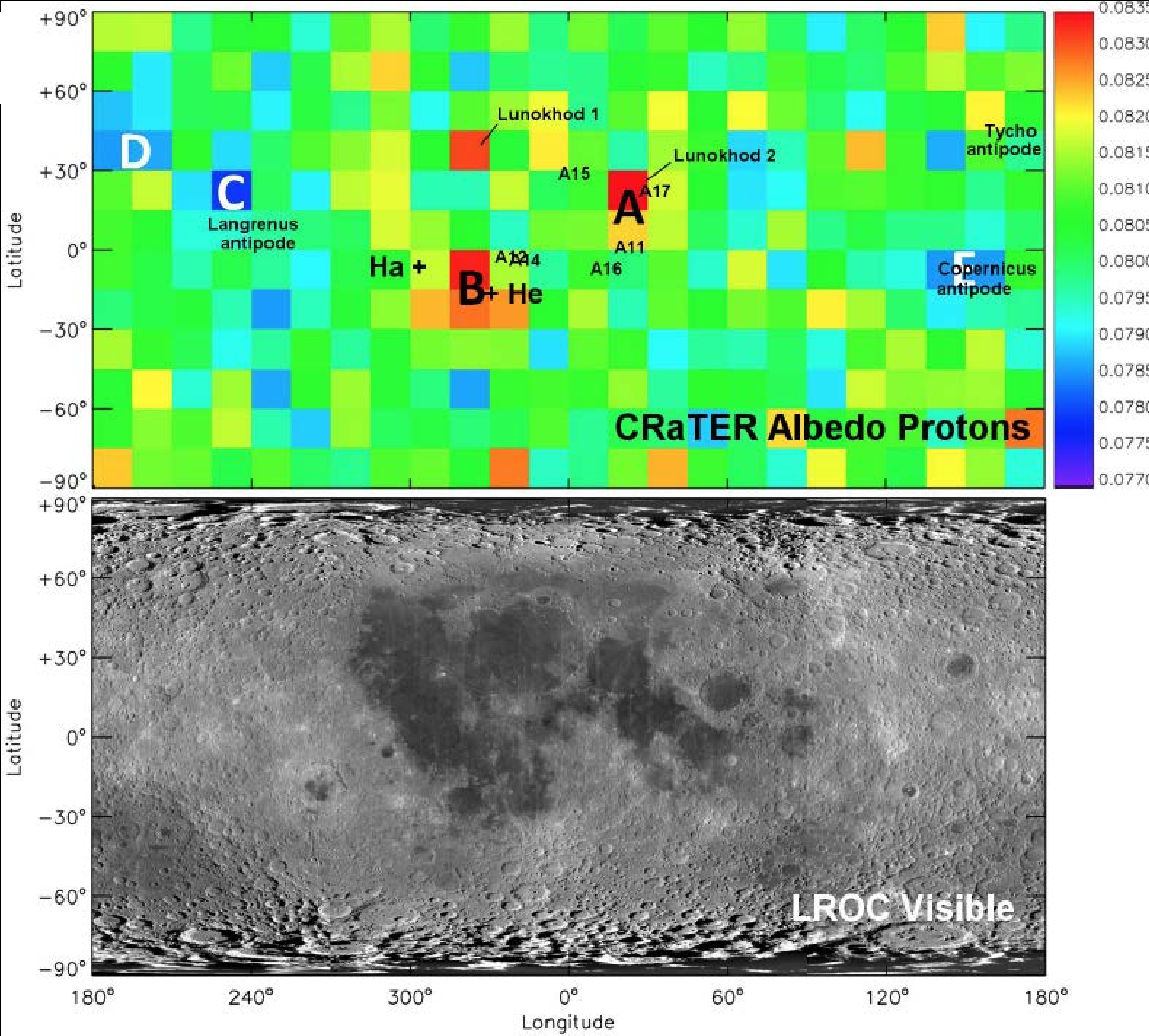
- Wilson, J. K., H. E. Spence, J. Kasper, M. Golightly, J. B. Blake, J. E. Mazur, L. W. Townsend, A. W. Case, M. D. Looper, C. Zeitlin, and N. A. Schwadron, The first cosmic ray albedo proton map of the Moon, *J. Geophys. Res. – Planets, 117*, DOI: 10.1029/2011JE003921, 2012.

Possible composition dependence of albedo sources



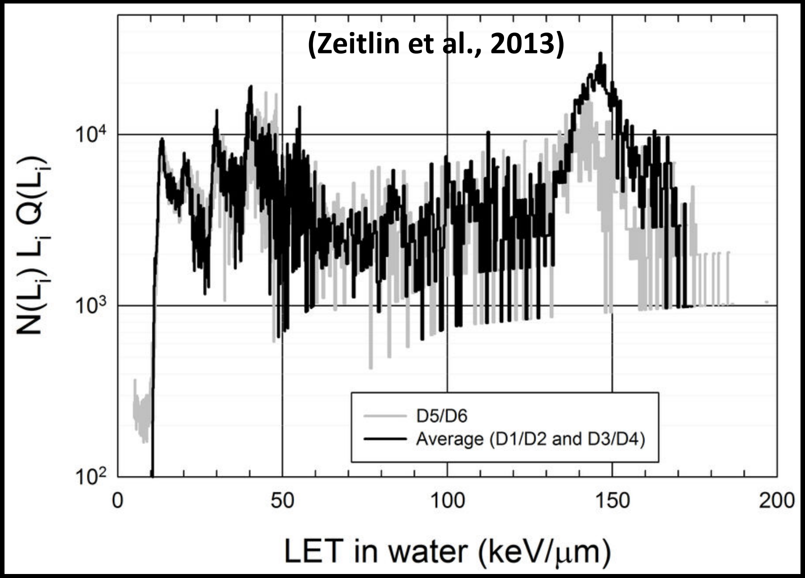


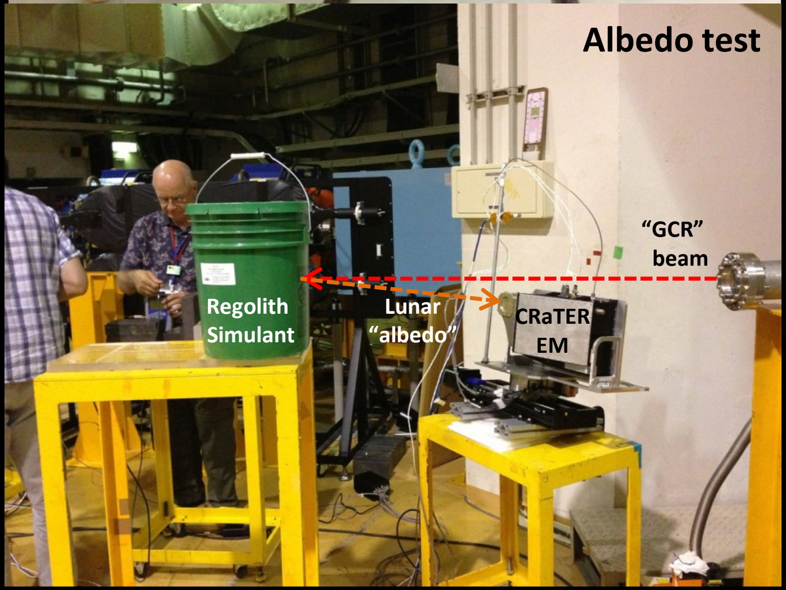




CRaTER Albedo Protons
LROC Visible
Lunokhod 1
Lunokhod 2
A15
A17
A11
A12
A14
A16
A
B
C
D
Langrenus antipode
Tycho antipode
Copernicus antipode
Ha +
+ He
Latitude
Longitude
+90°
+60°
+30°
0°
−30°
−60°
−90°
180°
240°
300°
0°
60°
120°
180°
0.0835
0.0830
0.0825
0.0820
0.0815
0.0810
0.0805
0.0800
0.0795
0.0790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

Beam runs with CRaTER EM confirm nuclear evaporation concept





- Zeitlin, C., A. W. Case, H. E. Spence, N. A. Schwadron, M. J. Golightly, J. K. Wilson, J. C. Kasper, J. B. Blake, M. D. Looper, J. E. Mazur, L. W. Townsend, and Y. Iwata, Measurements of Galactic Cosmic Ray Shielding with the CRaTER Instrument, *Space Weather, DOI: 10.1002/swe.20043*, 2013.

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

[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.

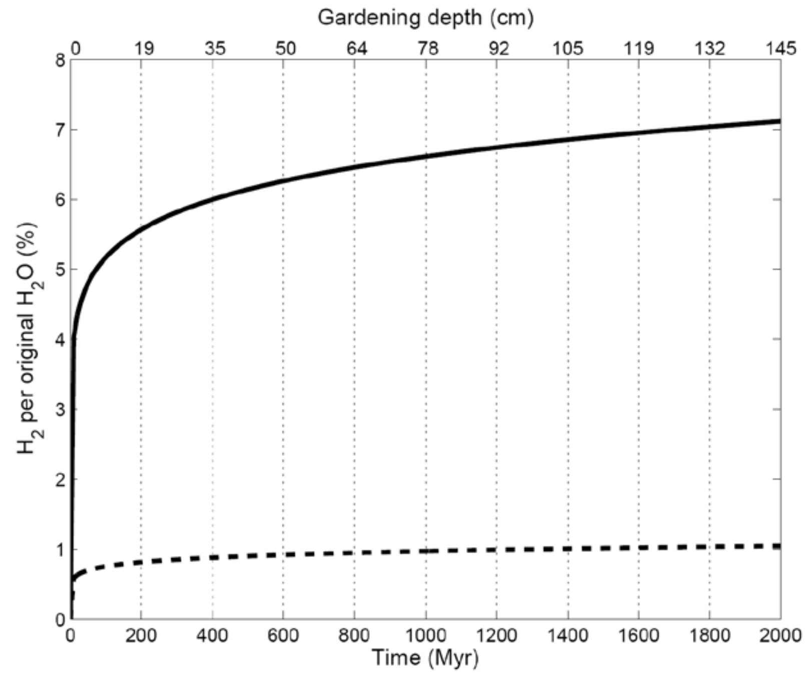


Figure 6. The number (as a percentage) of H_2 molecules created by GCRs and SEPs with respect to the original number of water molecules as a function of gardening time (lower axis) and depth (upper axis). We have assumed that the GCR dose is applicable to 36 cm and the SEP dose to 0.18 cm. The dashed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

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Published investigation on deep dielectric charging by energetic particles and cosmic rays

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Planets

RESEARCH ARTICLE

10.1002/2014JE004648

Key Points:

- Energetic charged particles deep dielectrically charge the lunar regolith
- We model the resulting subsurface electric fields
- The electric fields may be great enough to induce dielectric breakdown

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Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A. Schwadron, H. E. Spence, and C. J. Joyce (2014), Deep dielectric charging of regolith within the Moon's permanently shadowed regions, *J. Geophys. Res. Planets*, *119*, 1806–1821,

Deep dielectric charging of regolith within the Moon's permanently shadowed regions

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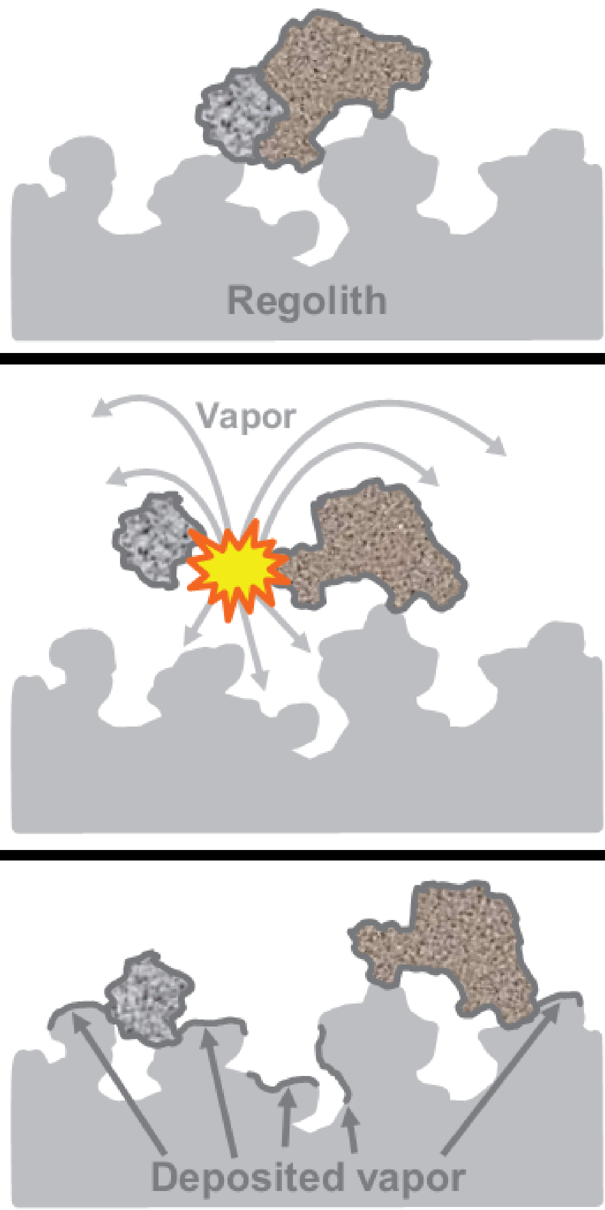
Abstract Energetic charged particles, such as galactic cosmic rays (GCRs) and solar energetic particles (SEPs), can penetrate deep within the lunar surface, resulting in deep dielectric charging. This charging process depends on the GCR and SEP currents, as well as on the regolith's electrical conductivity and permittivity. In permanently shadowed regions (PSRs) near the lunar poles, the discharging timescales are on the order of a lunation (~20 days). We present the first predictions for deep dielectric charging of lunar regolith. To estimate the resulting subsurface electric fields, we develop a data-driven, one-dimensional, time-dependent model. For model inputs, we use GCR data from the Cosmic Ray Telescope for the Effects of Radiation on board the Lunar Reconnaissance Orbiter and SEP data from the Electron, Proton, and Alpha Monitor on the Advanced Composition Explorer. We find that during the recent solar minimum, GCRs create persistent electric fields up to ~700 V/m. We also find that large SEP events create transient but strong electric fields ($\geq 10^6$ V/m) that may induce dielectric breakdown. Such breakdown would likely result in significant modifications to the physical and chemical properties of the lunar regolith within PSRs.



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 expect regolith in lunar PSRs to have lower albedo in colder regions.

The New York Times | http://nyti.ms/1q4elL3

SPACE & COSMOS | NYT NOW

The Moon Comes Around Again

SEPT. 7, 2014

Basics

By NATALIE ANGIER

As the moon wheels around Earth every 28 days and shows us a progressively greater and then stingier slice of its sun-lightened face, the distance between moon and Earth changes, too. At the nearest point along its egg-shaped orbit, its

Sparks of Discovery

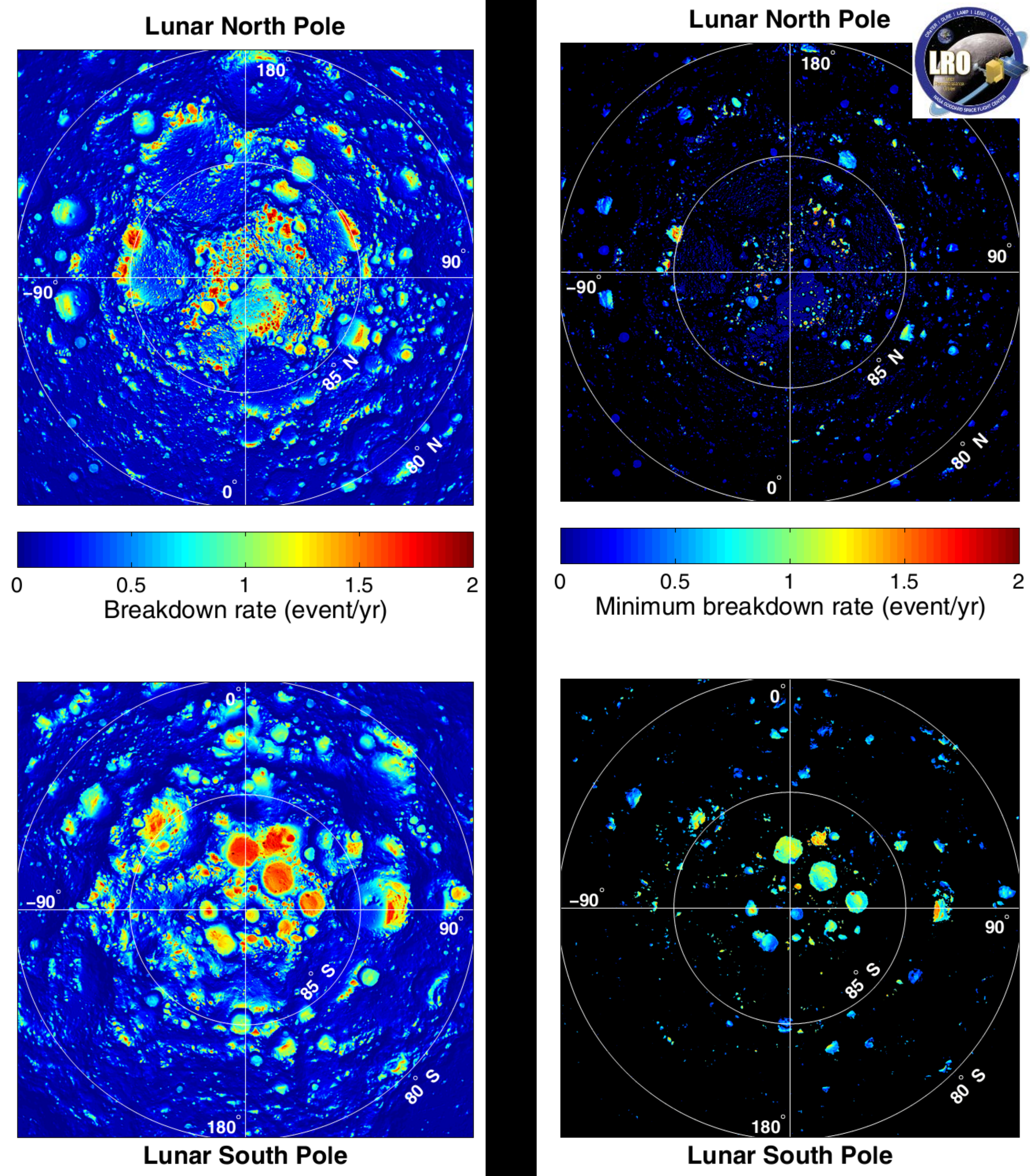
Scientists say that while the public may think of the moon as a problem solved and a bit retro — the place astronauts visited a half-dozen times way back before Watergate and then abandoned with a giant “meh” from mankind — in fact, lunar studies is a vibrant enterprise that is yielding a wealth of insights and surprises.

Sparking events, the researchers said, could explain the foamy appearance of soil recently detected by NASA’s orbiter. The lunar surface “may be far more active than we thought,” Dr. Jordan said. “It’s amazing to have this kind of natural laboratory almost in our spatial backyard.”

The moon’s “sparkiness”!

Understanding of Radiation Driving New Data Products

Rate of SEP events that may cause regolith breakdown



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
- Development of new LRO derived mapping products