Particle Radiation Environments and Their Effects at Planetary Surfaces: Lessons Learned at the Moon by LRO/CRaTER and Extension to Other Planetary Objects

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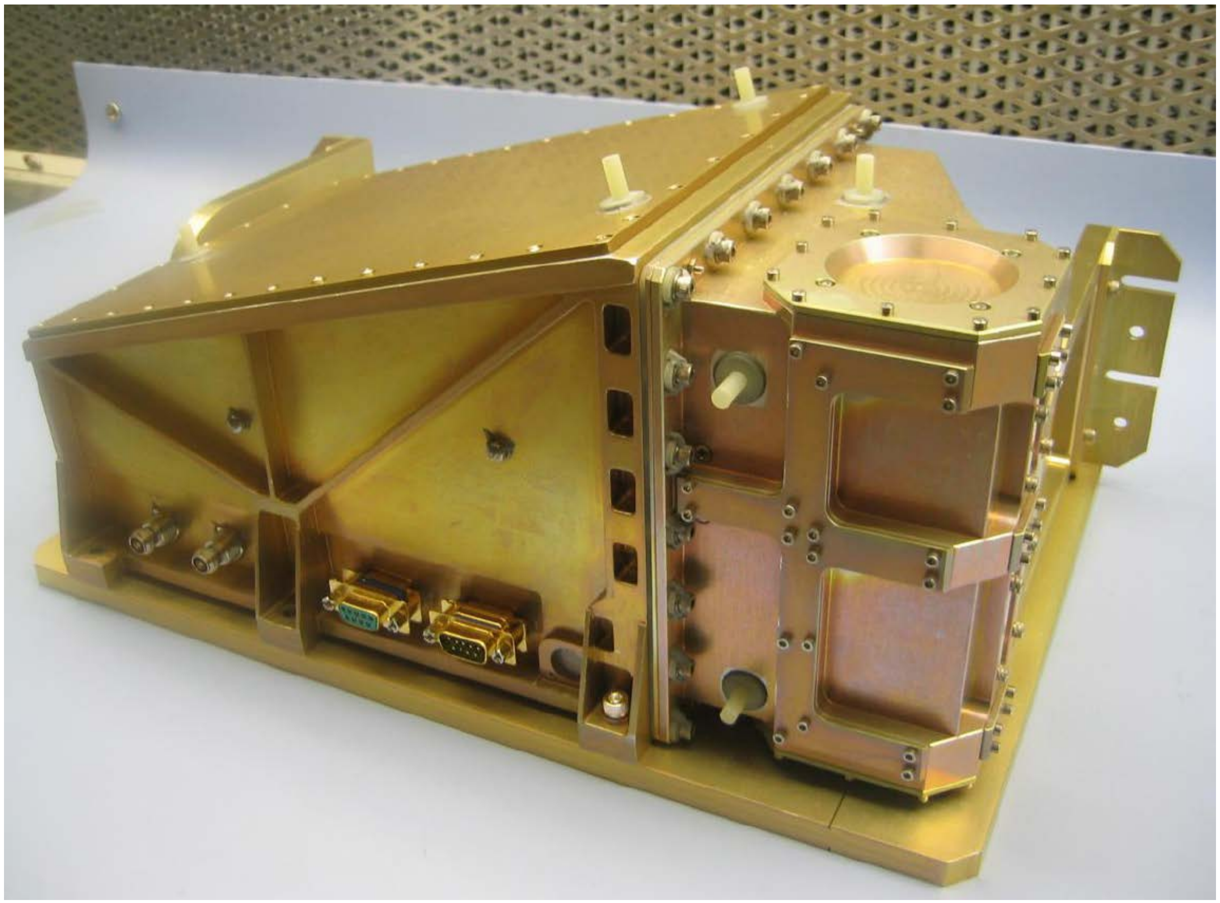
Lunar Exploration Analysis Group (2015)
22 October 2015

Overview

- We focus primarily on the 2nd **GOAL** of the meeting, namely: "…results of recent and ongoing missions (LRO) to examine the dynamic nature (and effects) of the Moon('s radiation environment) and how this could influence future science and exploration missions (back to the Moon and other bodies)."
- We address primarily the 2nd **THEME** of the meeting, namely: "Dynamic Moon"
- Presentation structure
  - Brief summary of what have we learned at the Moon from CRaTER – environment and effects
  - Scaling the lunar particle radiation environment (GCR and SEP) to other exploration destinations
  - Comparing other key parameters (temperature) of airless planetary bodies that control the effects of radiation
  - Estimating relative importance of effects – still a work in progress, but ultimate goal of study (and paper for Icarus nearing completion….)

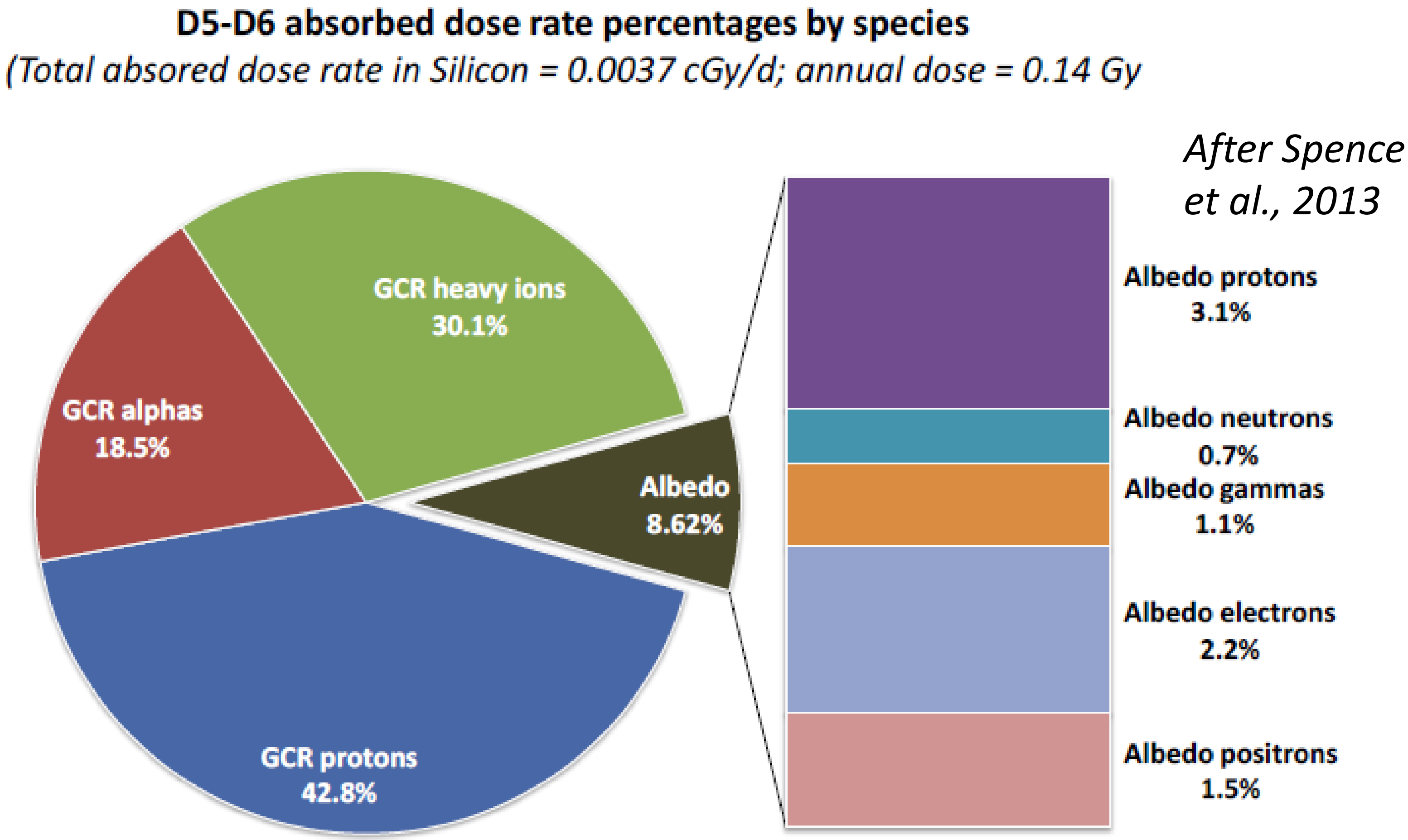
Cosmic Ray Telescope for the Effects of Radiation (CRaTER) Investigation

(Spence et al., Space Sci. Rev., 2010)



- **Launched in June 2009**
- **Nadir/Zenith viewing along “telescope” axis**
- **Designed to estimate Linear Energy Transfer of galactic cosmic rays and solar protons near the Moon and to characterize the ionizing radiation environment and its effects**

GCR Important for Human Exploration, Albedo Production, and Chemical Weathering

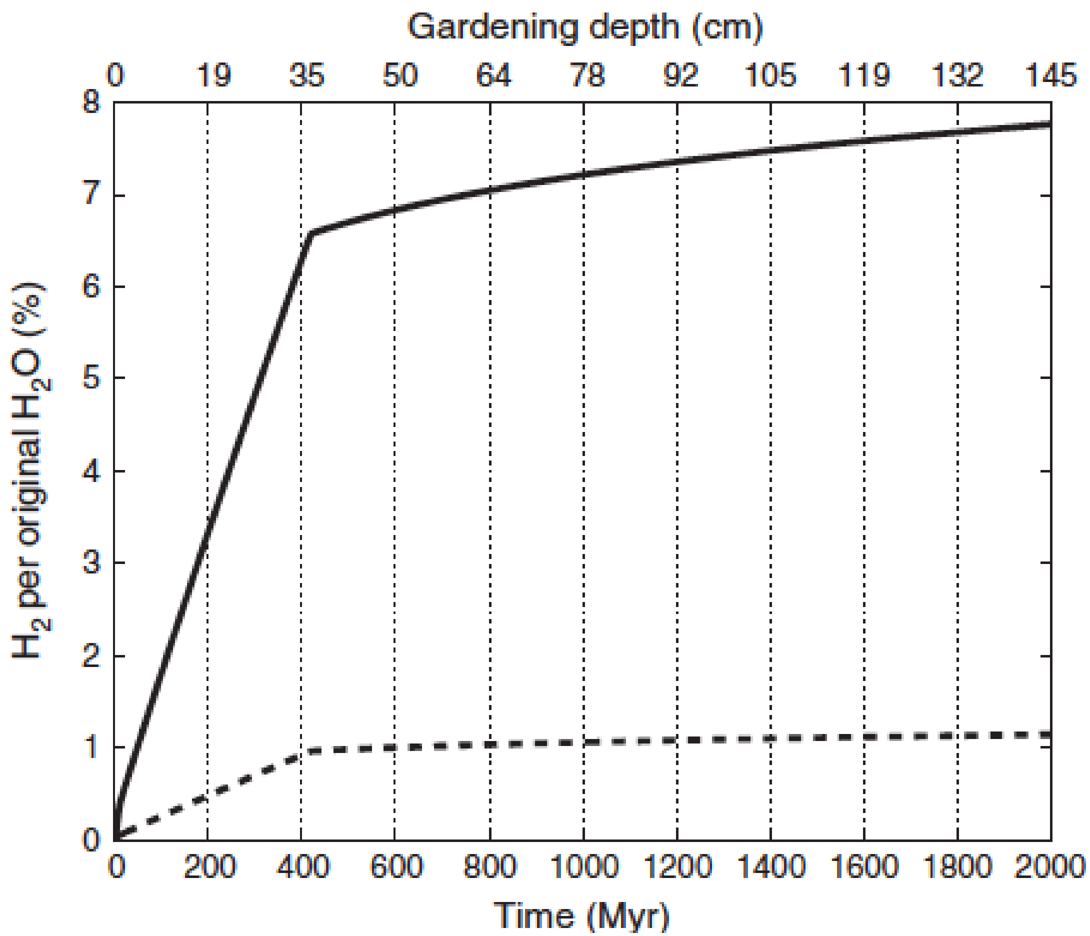


- Use validated GEANT4 model of CRaTER response to primary GCR and lunar secondaries to assess contributions by species
- Secondary albedo particles account for ~10% of absorbed dose rate

Chemical Weathering by Energetic Particles

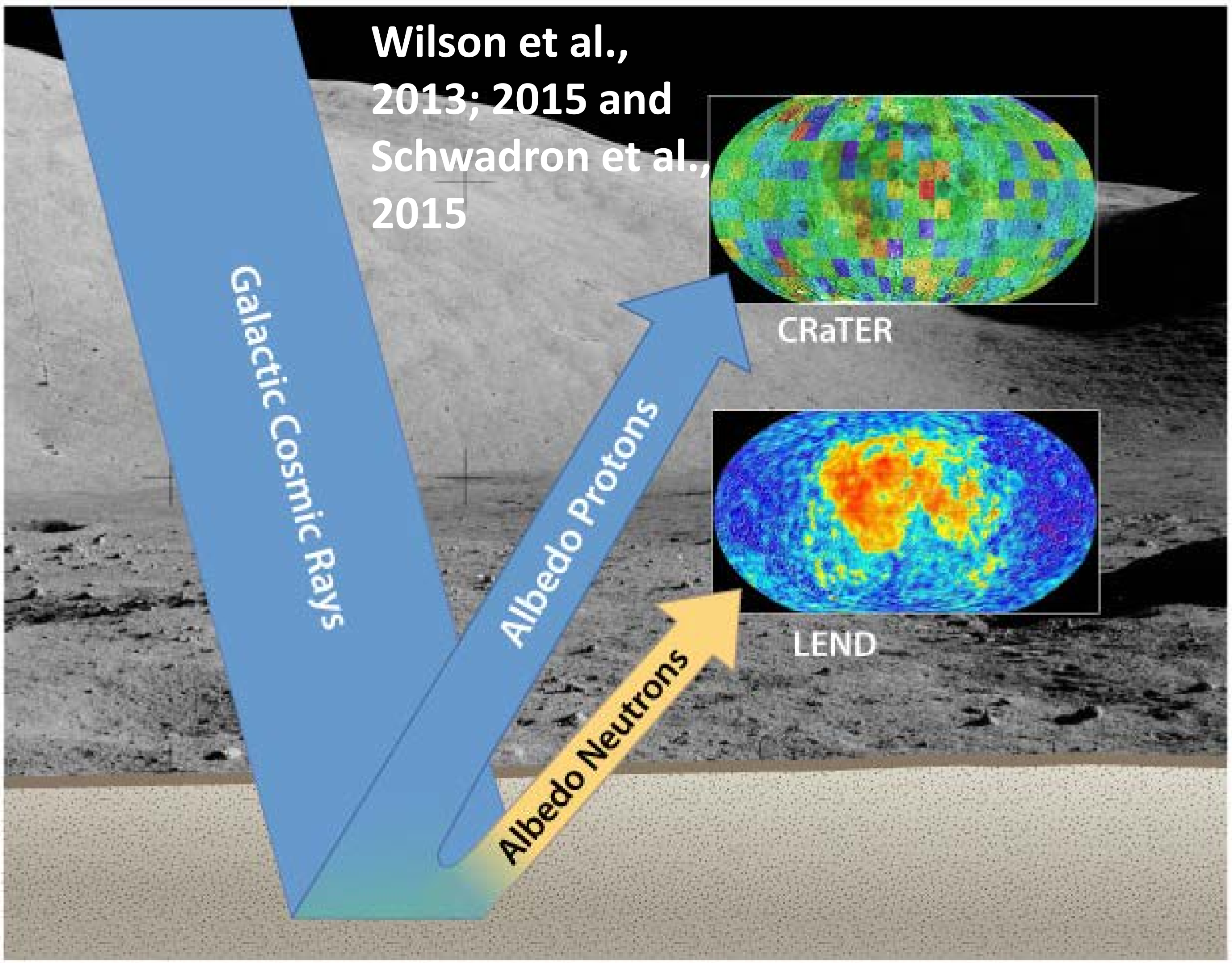
After Jordan et al., 2013

- GCRs and SEPs can penetrate the regolith in permanently shadowed regions and dissociate molecules in water ice and form H_2.
- We discover that GCRs and SEPs can convert 1-8% of the original water molecules into H_2 as observed by LCROSS and LRO's Lyman Alpha Mapping Project (LAMP) during the impact

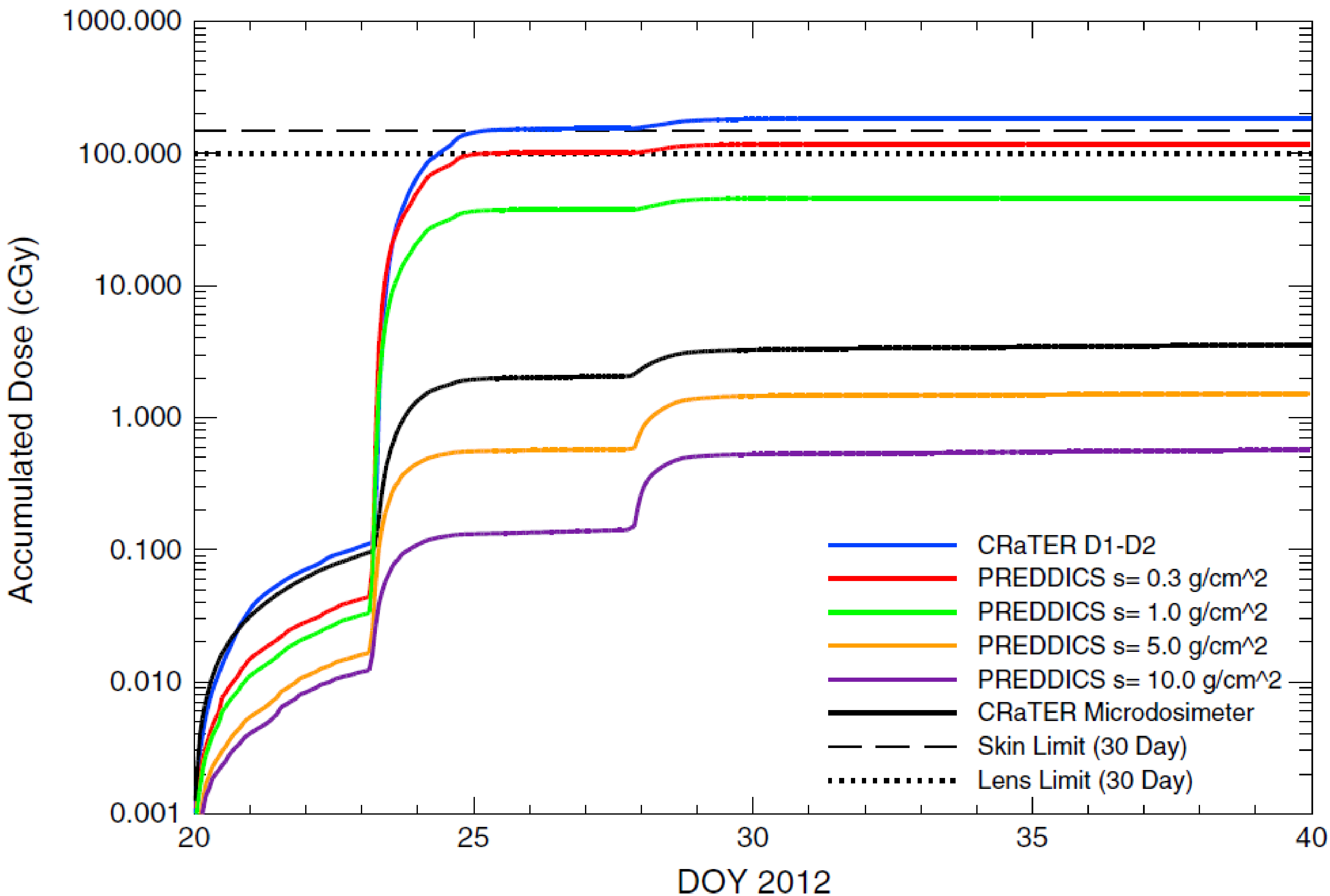


The percentage of H_2 molecules created by GCRs and SEPs with respect to the original number of water molecules as a function of gardening time (lower axis) and depth (upper axis). We assume that the GCR dose is applicable to 36 cm and the SEP dose to 0.18 cm.

Remote Sensing of Regolith Properties from Energetic Particle Albedo

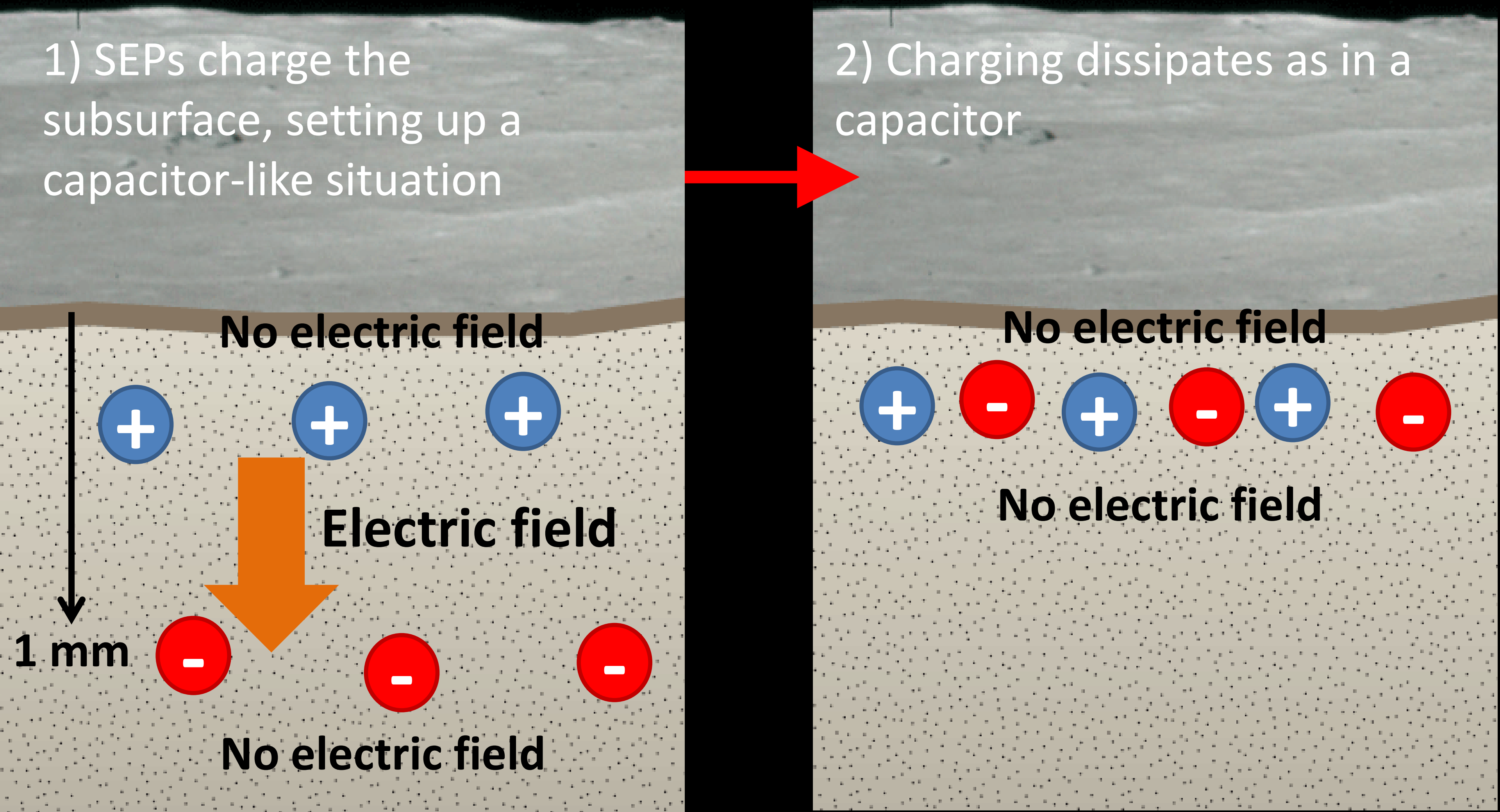


Solar Proton Fluence Important for Human Exploration and for Regolith Charging Effects

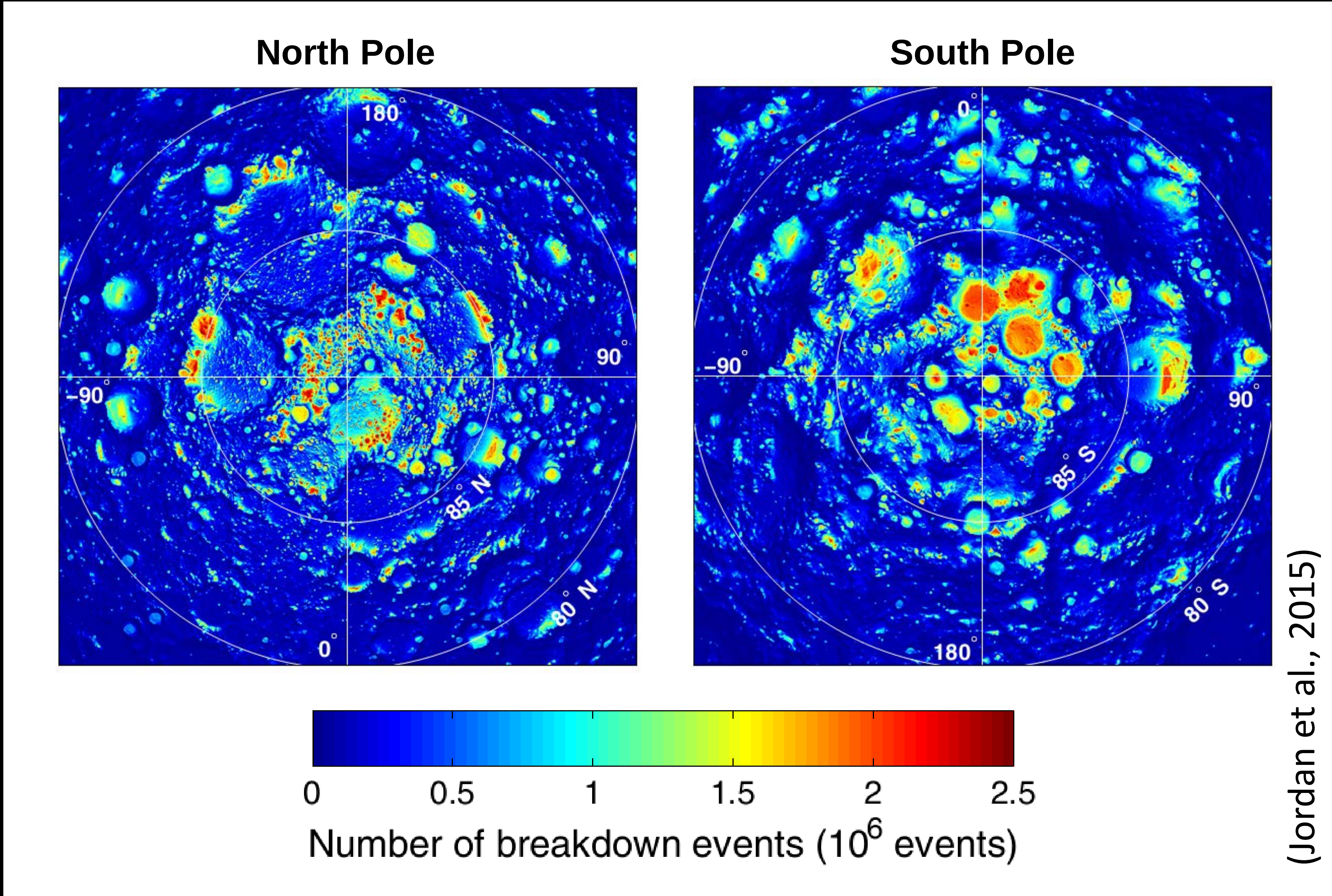


After Joyce et al., 2014

Solar Energetic Particles Produce Deep Dielectric Discharges That Modify Regolith



All gardened soil within Moon's PSRs has likely experienced ~10^6 SEP events capable of causing breakdown!!



Scaling GCR Intensity: Translating GCR-Related Effects at Moon to Other SS Objects

- Interplanetary magnetic field poses obstacle for incoming GCR (establishes radial gradient); acts out of phase with solar cycle (establishes time dependence)

Airless Object	Heliocentric Distance (AU)	Solar Max: 120-230 MeV p^+ intensity (#/m^2 sr s MeV)	Solar Min: 120-230 MeV p^+ intensity (#/m^2 sr s MeV)
Mercury	0.39	0.186	1.51
Moon	1.00	0.190	1.54
Mars/Phobos/Deimos	1.52	0.193	1.57
Asteroids (Ceres)	2.77	0.200	1.63
Pluto	~40	0.649	5.27

- GCR radiation environments (and effects) about same at Moon as throughout inner solar system; much higher (x3) at Pluto
- GCR radiation environments (and effects) considerably higher (x8) during solar minimum than at solar maximum (at all objects, including Moon)

Scaling SEP Intensity: Translating SEP-Related Effects at Moon to Other SS Objects

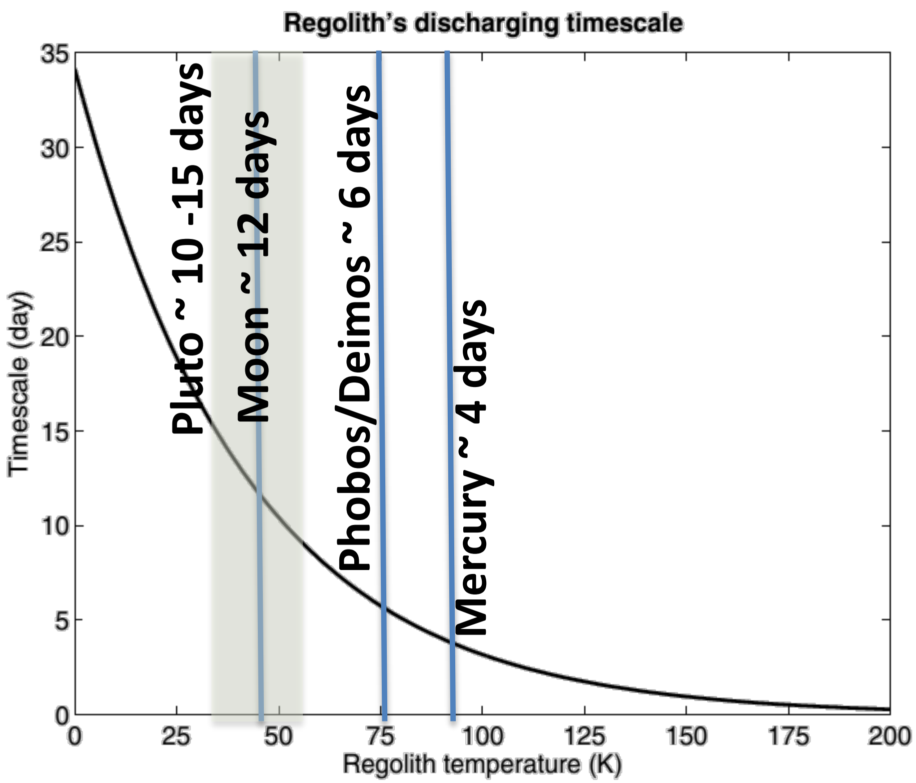
- Assume that SEP fluence scales with interplanetary magnetic field fluxtube area that scales like $1/r^2$ (Parker approximation)
- Take largest SEP event in LRO era and scale CRaTER measurements at Moon to other objects to estimate fluence

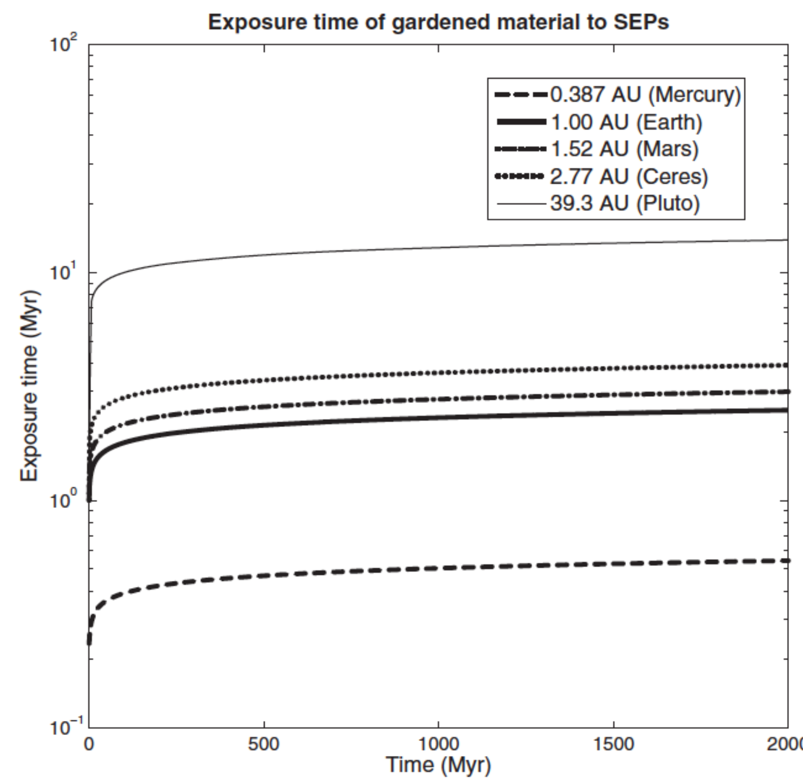
Airless Object	Heliocentric Distance (AU)	>10 MeV p^+ SEP fluence 7-day running avg. (cm^{-2})
Mercury	0.39	3.3e9
Moon	1.00	5.0e8
Mars/Phobos/Deimos	1.52	2.2e8
Asteroids (Ceres)	2.77	6.5e7
Pluto	~40	1.8e6

- SEP radiation environments much higher at Mercury (x7), about half as intense at Phobos/Deimos, and order of magnitude lower at Ceres, and ~200x lower at Pluto

Scaling Other Properties That Affect Effects: Temperature and Micrometeoroid Gardening

- Dielectric breakdown phenomenon is temperature dependent – favors regions that are colder than ~100K
- All effects moderated by radial dependent micrometeoroid gardening – need to compare versus gardening rates/exposure time

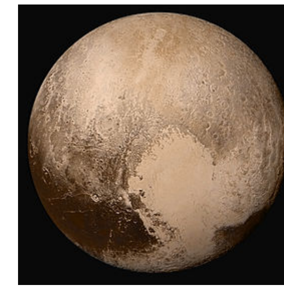




Putting it All Together: A Work in Progress…

- A summary of the environments follows below

Closer to the Sun	Farther from the Sun
Lower GCR intensity	Higher GCR intensity
Higher SEP fluence	Lower SEP fluence
Faster gardening	Slower gardening
Shorter exposure	Longer exposure
Generally warmer	Generally colder



- Overall, GCR-related effects (dose, chemical weathering, albedo production) much greater at greater distances (i.e., Pluto) than at Moon (x8)
- SEP-related effects much stronger closer to Sun, but also temperature dependent (which is less tied to distance owing to shadowing geometries)
- All effects moderated by gardening rates/exposure times
- Quantifying detailed effects is a work in progress…

LRO/CRaTER Results→ Future Exploration

- Ionizing radiation throughout heliosphere and at planets has both intrinsic science value (“truths”) and exploration applications (“consequences”)
  - LRO/CRaTER discovering roles that ionizing radiation plays in modifying planetary surfaces, for example, charging effects:
    - **SEPS causing deep dielectric discharges may be as important as meteoritic weathering at Moon, particularly in PSRs**
    - **Same space weathering effects may also be important in PSRs at Mercury and at Phobos and Deimos**
    - **Less likely an important effect in outer solar system (i.e., Pluto, KBOs, etc.) as SEP fluence greatly diminished**
- Example underscores how ionizing radiation studies, motivated initially by exploration, also provide insights on the scientific processes shaping solar system objects, which further fosters future exploration

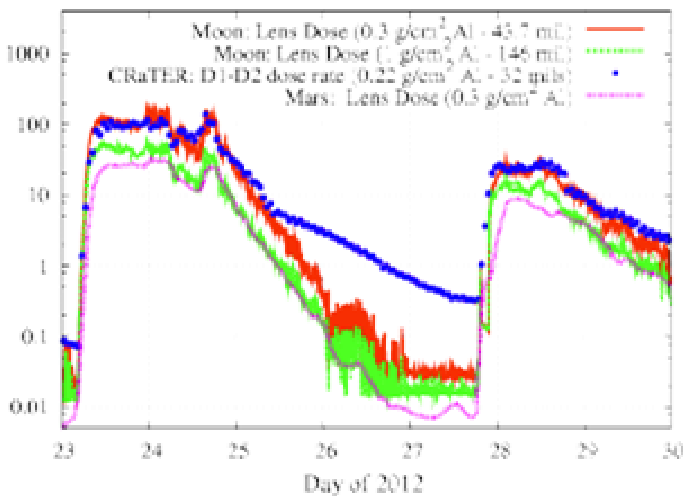
Backup Slides

Solar Proton Fluence Important for Human Exploration and for Regolith Charging Effects

SEP Events During 2012: Indicators of Larger SEP Events in the New Cycle (24)

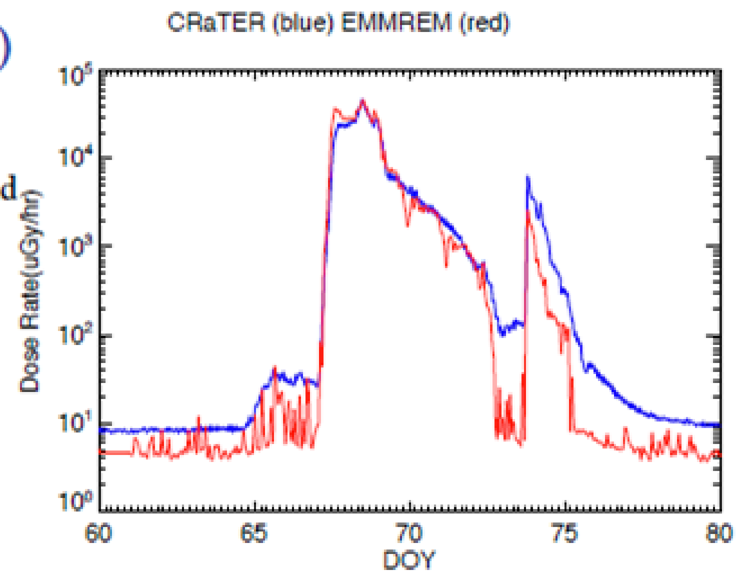
- Shown here are the major SEP events of 2012 and the comparisons between CRaTER observations (blue) and EMMREM/PREDICCs model predictions (red and green).
- Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER

Jan. 23rd 2012 Event

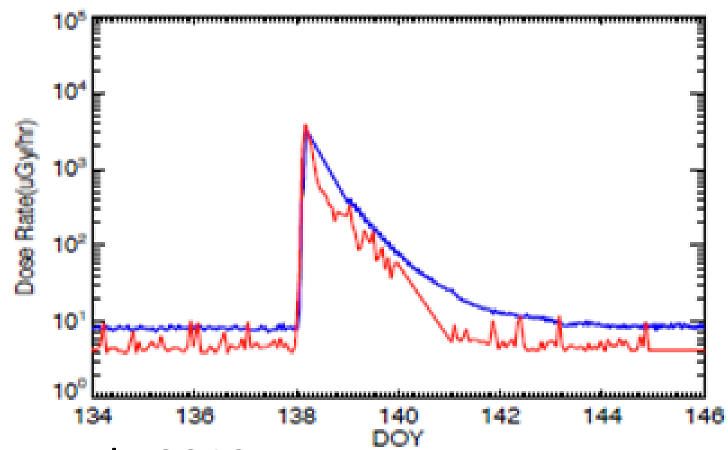


http://prediccs.sr.unh.edu

Mar 7, 2012 Event



May 16, 2012 Event



After Schwadron et al., 2012