Modeling Shielding in the Earth-Moon-Mars Radiation Environment using PREDICCS

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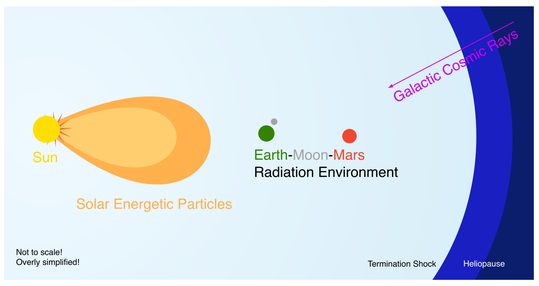
Motivation and Health Risks

One-liner - We use PREDICCS to demonstrate how shielding mitigates accumulated dose from three solar events in 2012 in order to prepare for future space exploration missions to the Moon and Mars.



Motivation - Radiation from SEPs and GCRs are risks to the short-term and long-term health of astronauts and success of space exploration missions to the Moon and Mars.

Short-term health risks - Prodromal effects (nausea, vomiting, anorexia, fatigue), skin injury, depletion of blood-forming organs (BFOs), and death.
Long-term health risks - Cataracts, cancer.

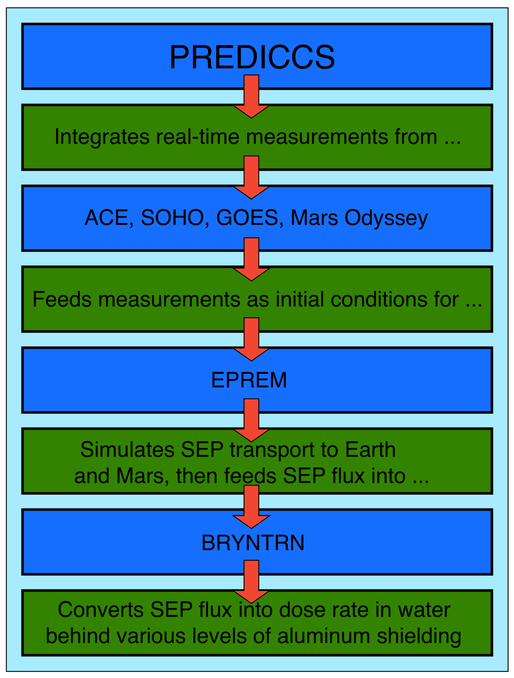
Dose Limits

Organ	30-day	1-year	Career
Lens	100 cGy-eq	2000 cGy-eq	4000 cGy-eq
Skin	150 cGy-eq	3000 cGy-eq	6000 cGy-eq
BFO	25 cGy-eq	500 cGy-eq	Not applicable
Heart	25 cGy-eq	500 cGy-eq	1000 cGy-eq
CNS	500 cGy-eq	1000 cGy-eq	1500 cGy-eq

Question - How much shielding is required to prevent short-term health risks to astronauts when experiencing solar events? (i.e. to prevent the accumulated dose-equivalent from exceeding the 30-day limit.)
Question - Is PREDICCS a valid tool beyond 1 AU?
Question - How does additional shielding reduce dose?

PREDICCS

PREDICCS is an online forecast tool that converts real-time measurements to dose rate data at Earth and Mars.



We consider the following depth of H_2O and aluminum as proxies for human tissue and protective shielding:

Proxies

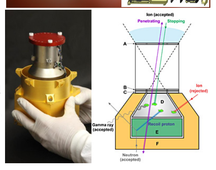
Aluminum shielding (g cm^{-2})	Proxy
0.3	Thin spacesuit
1.0	Thick spacesuit
5.0	Spacecraft
10.0	Storm shelter
H_2O (g cm^{-2})	Proxy
1.0	Lens, skin
10.0	Blood-forming organs (BFOs), heart, central nervous system (CNS)

LRO/CRaTER and MSL/RAD

PREDICCS dose rates are compared to CRaTER and RAD.

LRO/CRaTER
- Measures dose rate in silicon detectors.
- Located on the LRO spacecraft orbiting the Moon.

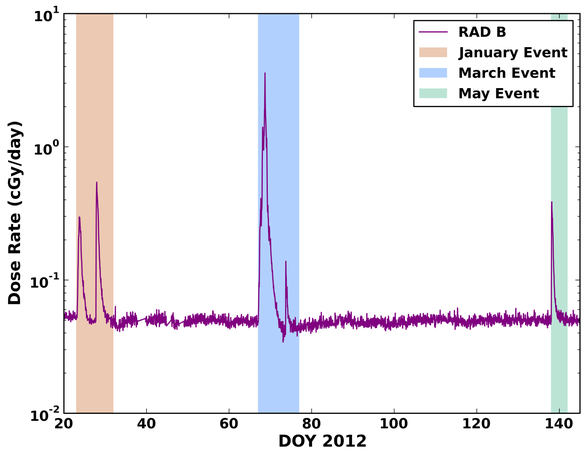
MSL/RAD
- Measures dose rate in silicon detectors.
- Located on the Curiosity rover housed in the MSL spacecraft during its cruise phase from Earth to Mars in 2012.



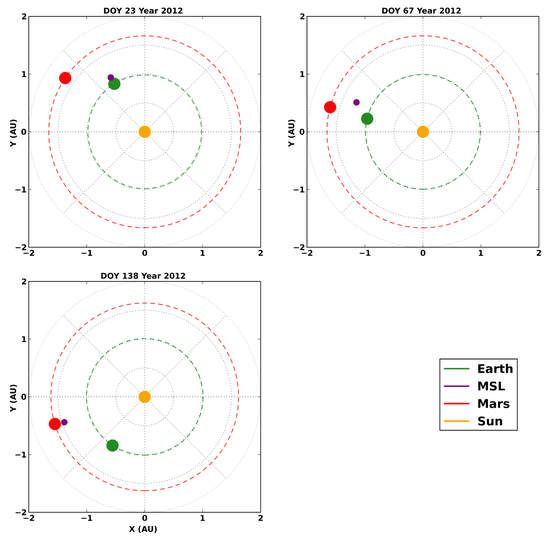
All dose rates from CRaTER and RAD are converted from silicon to water to compare to PREDICCS.

Solar Event Selection

MSL/RAD observed three solar events during its cruise phase from Earth to Mars.



The alignment of Earth, MSL/RAD, and Mars during the January (top left), March (top right), and May (bottom left) solar events allow for good comparisons between PREDICCS, RAD, and CRaTER.



MSL/RAD was located at approximately 1.12, 1.27, and 1.46 AU during the January, March, and May events respectively.

Gray and Gray-equivalent

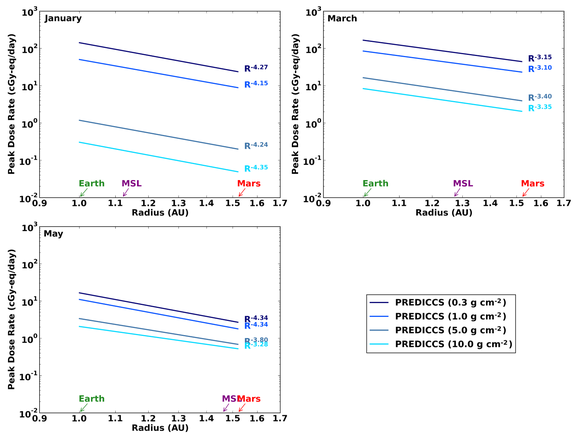
Dose (Gray)
- Amount of energy deposited by radiation in a material per unit mass.
- In this case, the material is human tissue.
- Units are Gray (Gy) = 1 J kg^{-1}.

Dose (Gray-equivalent)
- Used to determine the short-term radiation effects on humans due to penetrating protons.
- Defined as $D(\text{Gy-eq}) = D(\text{Gy}) \times RBE$, where RBE is the relative bioligical effectiveness – a measure of how damaging the radiation when compared to X-rays.
- For protons, $RBE = 1.5$.
- Units are Gray-equivalent (Gy-eq).

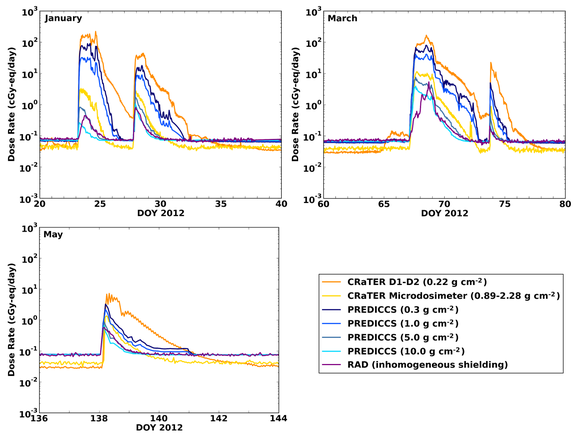
All dose in Gray are converted to dose in Gray-equivalent.

Dose Rates

PREDICCS peak shielded dose rates at Earth and Mars are fit to a power law.

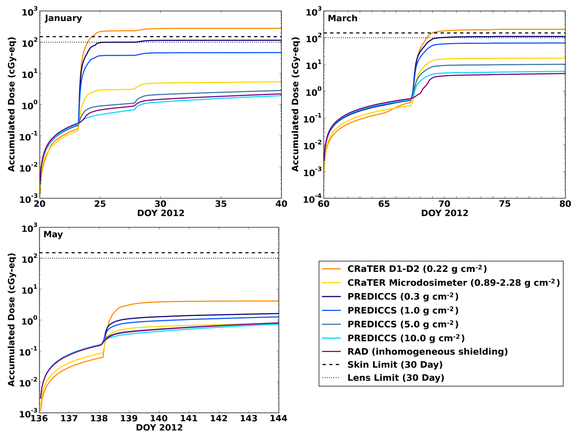


PREDICCS shielded dose rates are scaled to the location of MSL/RAD for each event.

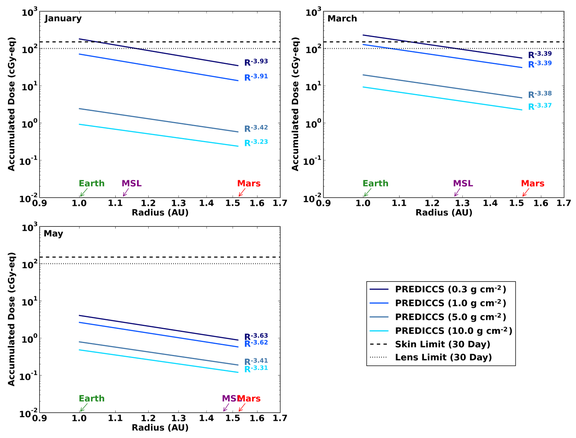


Accumulated Dose

- Dose rates are converted to accumulated dose to compare with the 30-day dose limits.
- At the location of MSL during each event, the accumulated dose for the January and March events exceed the 30-day limit – posing a health risk.

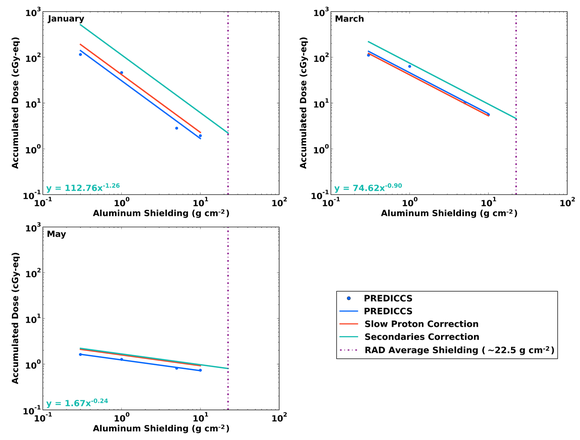


- The radial gradient of accumulated dose between Earth and Mars is fit to a power law.
- The indices compare well to the Halloween 2003 event.

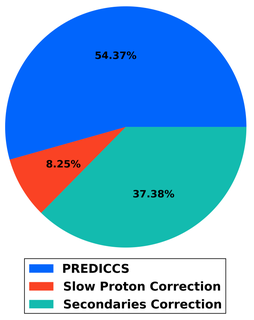


The radial gradient of accumulated dose shows:
- Lunar missions require shielding between 1.0 g cm^{-2} and 5.0 g cm^{-2}.
- No imminent health risks exist at Mars.

Verification of PREDICCS



- **Slow Proton Correction** - Descrepency between PREDICCS and CRaTER due to EPREM handling low energy protons poorly.
- **Secondaries Correction** - Increased dose rate measured by RAD due to inhomogeneous shielding. SEPs enter areas of low shielding and create secondaries in areas of high shielding.



Summary

Percent shielding mitigates accumulated dose beyond 0.3 g cm^{-2}

Al Shielding, H_2O = 1.0 (g cm^{-2})	January (%)	March (%)	May (%)	Average (%)
0.3	-	-	-	-
1.0	60	43	22	42
5.0	97	91	50	79
10.0	98	95	55	83
Al Shielding, H_2O = 10.0 (g cm^{-2})	January (%)	March (%)	May (%)	Average (%)
0.3	-	-	-	-
1.0	1	3	1	2
5.0	5	18	3	9
10.0	9	29	5	14

Radial dependence of dose rate and accumulated dose between Earth and Mars

Al Shielding, H_2O = 1.0 (g cm^{-2})	Dose Rate		
	January	March	May
0.3	$R^{-4.27}$	$R^{-3.15}$	$R^{-4.34}$
1.0	$R^{-4.15}$	$R^{-3.10}$	$R^{-4.34}$
5.0	$R^{-4.24}$	$R^{-3.40}$	$R^{-3.80}$
10.0	$R^{-4.35}$	$R^{-3.35}$	$R^{-3.28}$
Al Shielding, H_2O = 1.0 (g cm^{-2})	Accumulated Dose		
	January	March	May
0.3	$R^{-3.93}$	$R^{-3.39}$	$R^{-3.63}$
1.0	$R^{-3.91}$	$R^{-3.39}$	$R^{-3.62}$
5.0	$R^{-3.42}$	$R^{-3.38}$	$R^{-3.41}$
10.0	$R^{-3.23}$	$R^{-3.37}$	$R^{-3.31}$

Accumulated dose behind different levels of shielding at the location of MSL

Al Shielding, H_2O = 1.0 (g cm^{-2})	January (cGy-eq)	March (cGy-eq)	May (cGy-eq)
0.3	115.21	111.33	1.63
1.0	46.36	63.39	1.27
5.0	2.83	10.15	0.82
10.0	1.94	5.56	0.74
Al Shielding, H_2O = 10.0 (g cm^{-2})	January (cGy-eq)	March (cGy-eq)	May (cGy-eq)
0.3	1.87	5.03	0.73
1.0	1.85	4.86	0.72
5.0	1.77	4.13	0.70
10.0	1.71	3.56	0.69

We have utilized PREDICCS to study how shielding reduces the short-term health risks for human space exploration missions within the Earth-Moon-Mars radiation environment. Large SEP events pose a threat to the short-term health of astronauts during lunar exploration missions, requiring shielding between 1.0-5.0 g cm^{-2}. No imminent health risks appear near Mars, however accumulated dose may exceed the 30-day limits if multiple SEP events occur.