Space Radiation Risk Assessment for Future Lunar Missions

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Abstract

For lunar exploration mission design, radiation risk assessments require the understanding of future space radiation environments in support of resource management decisions, operational planning, and a go/no-go decision. The future GCR flux was estimated as a function of interplanetary deceleration potential, which was coupled with the estimated neutron monitor rate from the Climax monitor using a statistical model. A probability distribution function for solar particle event (SPE) occurrence was formed from proton fluence measurements of SPEs occurred during the past 5 solar cycles (19-23). Large proton SPEs identified from impulsive nitrate enhancements in polar ice for which the fluences are greater than 2×10^9 protons/cm^2 for energies greater than 30 MeV, were also combined to extend the probability calculation for high level of proton fluences. The probability with which any given proton fluence level of a SPE will be exceeded during a space mission of defined duration was then calculated. Analytic energy spectra of SPEs at different ranks of the integral fluences were constructed over broad energy ranges extending out to GeV, and representative exposure levels were analyzed at those fluences. For the development of an integrated strategy for radiation protection on lunar exploration missions, effective doses at various points inside a spacecraft were calculated with detailed geometry models representing proposed transfer vehicle and habitat concepts. Preliminary radiation risk assessments from SPE and GCR were compared for various configuration concepts of radiation shelter in exploratory-class spacecrafts.

Problem

- Continuous galactic cosmic rays (GCR) pose a serious health risk to humans and contribute to failure rates for electronics during space missions. The risks must be predicted accurately for future lunar missions.

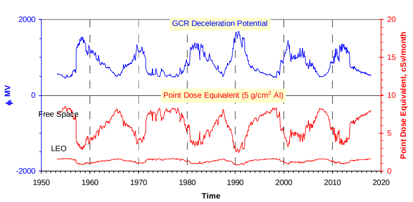
→ We develop a practical approach for the expected GCR environment.

- Solar particle events (SPEs) are a concern for space missions outside Earth's geomagnetic field.
- The sporadic occurrence of SPEs and number of large SPEs in a short period are major operational problems for planning space missions and protecting humans during missions.

→ We estimate the probability of large SPE for a given mission duration.

An integrated strategy for radiation protection on lunar exploration missions.

GCR Environment and Point Dose Equivalent

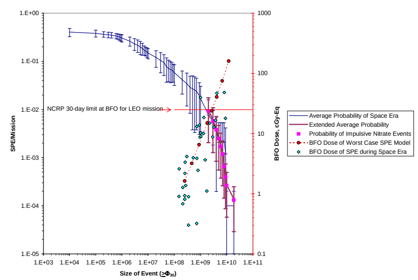


Database of Solar Particle Events

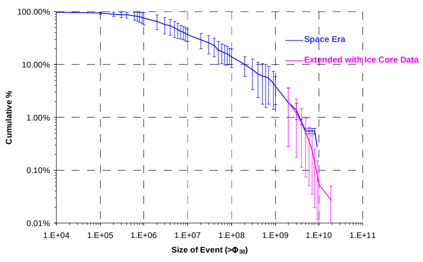
Solar Cycle	# of SPE	# of Day	Period	Fluence, Φ_E
Cycle 23	92	3897	5/1/1996-12/31/2006	$\Phi_{10,30,50,60,100}$ (1)
Cycle 22	77	3742	2/1/1986-4/30/1996	$\Phi_{10,30,50,60,100}$ (1)
Cycle 21	70	3653	2/1/1976-1/31/1986	$\Phi_{10,30}$ (2)
Cycle 20	63	4140	10/1/1964-1/31/1976	$\Phi_{10,30}$ (2) and $\Phi_{10,30,60}$ (3)
Cycle 19	68	3895	2/1/1954-9/30/1964	$\Phi_{10,30,100}$ (2) and $\Phi_{10,30}$ (4)
Impulsive Nitrate Events	71	390 years	1561 - 1950	Φ_{30} (5 and 6)
Energy Spectra(7 and 8) or Weibull Distribution Function(9 and 10)				

(1) GOES SEM data: http://goes.ngdc.noaa.gov/data/
(2) Feynman, Armstrong, Dao-Gibner, and Silverman, J. Spacecraft, **27**, No. 4, pp. 403-410, July-August, 1990.
(3) King, J. H., solar proton fluences for 1977-1983 space missions, J. Spacecraft, **11**, No. 6, pp. 401-408, June 1974.
(4) Shea and Smart, Solar Physics, **127**, pp. 297-320, 1990.
(5) McCracken, K. G., Dreschhoff, G. A. M., Zeller, E. J., Smart, D. F., and Shea, M. A., Solar cosmic ray events for the period 1561-1994, 1. Identification in polar ice, 1561-1950. J. Geophys. Res., **106**, No. A10, 21585-21598, October 1, 2001.
(6) Silverman, S., Silverman catalog of ancient auroral observations, 666BCE to 1951, http://nssdc.gsfc.nasa.gov/space/auroral/auroral.html, 2002.
(7) Freier, P. S. and Webber, W. R., "Exponential Rigidity Spectrums for Solar-Flare Cosmic Rays," *J. Geophys. Res.*, Vol. 68, No. 6, 1963, pp. 1605-1629.
(8) Biswas S., Fichtel, C. E., and Guss, D. E., "Study of the Hydrogen, Helium, and Heavy Nuclei in the November 12, 1960 Solar Cosmic-Ray Event," *Phys. Review*, Vol. 128, No. 6, 1962, pp. 2756-2771.
(9) Kim, M. Y., Cucinotta, F. A., and Wilson, J. W., A temporal forecast of radiation environments for future space exploration missions, Radiat. and Environ. Biophys., **46**, No. 2, pp. 95-100, June 2007.
(10) Xapsos et al., *IEEE Trans. Nuc. Sci.* **47**(6), 2218-2223, 2000.

SPE Probability in 2-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



Distribution of Sample SPE Population



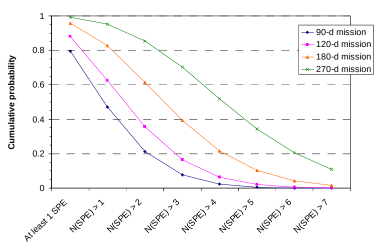
Probability of SPE with $\Phi_{30} > 2 \times 10^9$ cm^{-2}

1-Week Mission

	Sample	$P(\Phi_{30} \geq 2\times10^9$ cm$^{-2})$
Calculation	SPEs in Space Era	0.39 % ± 0.4 %
	SPEs in Space Era + the interval 1561-1950	0.49 % ± 0.39 %
Observation	SPEs in the interval 1561-1950	0.47 %

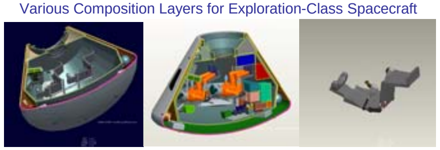
Probability of SPE for a Given Mission Duration

Event Threshold $\Phi_{30} > 10^7$ cm^{-2}

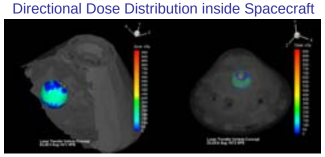


Structural Distribution Model Using ProE™

Various Composition Layers for Exploration-Class Spacecraft



Directional Dose Distribution inside Spacecraft

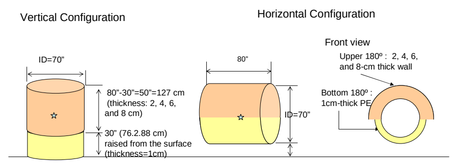


Organ Dose Quantities for Two Orientations

August 1972 SPE

		Random orientation				Aligned orientation			
		DLOC1	DLOC2	DLOC3	DLOC4	DLOC1	DLOC2	DLOC3	DLOC4
X-coordinate, cm		43.18	-43.18	40.64	-40.64	43.18	-43.18	40.64	-40.64
Y-coordinate, cm		119.38	119.38	119.38	119.38	119.38	119.38	119.38	119.38
Z-coordinate, cm		52.71	52.71	-79.34	-79.34	52.71	52.71	-79.38	-79.38
Al-Eq x_{avg}, g/cm^2		15.18	15.08	15.85	15.33	15.18	15.08	15.85	15.33
x_{min} - x_{max}		0 - 102.07	0 - 105.50	0 – 83.21	0 - 85.79	0 - 102.07	0 - 105.50	0 – 83.21	0 - 85.79
CAM organ dose, cSv	Avg skin	126.61	121.07	104.08	108.59	150.92	135.41	111.45	114.45
	Eye	86.76	84.36	73.58	77.06	89.71	89.94	81.62	79.72
	Avg BFO	16.91	16.82	15.2	15.88	18.14	18.20	16.05	15.98
	Stomach	7.38	7.37	6.77	7.03	6.94	6.89	6.59	6.63
	Colon	14.42	14.36	13.04	13.6	14.46	14.36	12.67	12.79
	Liver	10.37	10.33	9.41	9.8	9.43	9.60	8.92	9.23
	Lung	12.16	12.12	11.04	11.5	12.09	11.61	11.30	10.73
	Esophagus	11.61	11.57	10.54	10.98	11.25	10.78	10.52	9.93
	Bladder	7.54	7.53	6.9	7.17	7.64	7.25	6.98	6.84
	Thyroid	18.39	18.31	16.55	17.28	18.55	18.15	16.47	16.79
	Chest	72.23	70.58	61.85	64.83	74.88	73.95	67.60	66.37
	Gonads	35.27	34.74	30.76	32.24	37.72	32.64	31.19	27.74
	Front brain	29.54	29.32	26.31	27.53	28.72	27.60	25.32	25.32
	Mid brain	16.2	16.15	14.68	15.3	15.52	15.56	14.05	15.03
	Rear brain	28.93	28.72	25.79	26.98	27.49	27.96	24.98	27.84
Effective dose eq, cSv		21.45	21.16	18.89	19.75	22.42	21.09	19.43	18.64
Point dose eq, cSv		254.68	242.74	207.92	216.83	253.48	241.76	205.76	211.88

SPE Shelter Concepts on Rover



EVA Exposure Inside Shelter on Lunar Surface

August 1972 SPE and One Crew Member

Polyethylene cylinder shelter thickness (ID=70", H=80")	E, cSv							
	Horizontal Orientation				Vertical Orientation			
	Mass, kg	Astro	Spacesuit	MARKIII Spacesuit	Mass, kg	Astro	Spacesuit	MARKIII Spacesuit
2 cm (1.84 g/cm^2)	229	51.90	52.03	52.21	242	53.49	53.47	53.19
4 cm (3.68 g/cm^2)	389	24.76	24.88	25.16	429	25.06	25.03	24.83
6 cm (5.52 g/cm^2)	556	13.37	12.96	12.80	624	12.39	12.38	12.25
8 cm (7.35 g/cm^2)	729	8.22	8.36	8.74	825	7.74	7.73	7.64

Summary

- A temporal forecast of GCR has been derived from the GCR deceleration potential (ϕ) - Point dose equivalent in interplanetary space is influenced by solar modulation by a factor of 3
- The relationship between large SPE occurrence and ϕ is clearly shown.
- Exposure levels of 34 large SPEs and worst-case SPE are analyzed with differential energy spectra from Weibull distribution function.
- A probability of SPE at a given fluence level is obtained for various mission periods.
- Detailed distribution of directional risk assessment shows better protection for risk mitigation inside a habitable volume/shelter/ spacecraft during future exploration missions.