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Preliminary Estimates of Galactic Cosmic Ray Exposures for Manned Interplanetary Missions

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ABSTRACT

Preliminary estimates of radiation exposures resulting from galactic cosmic rays are presented for interplanetary missions. The calculations use the Naval Research Laboratory cosmic ray spectrum model as input into the Langley Research Center galactic cosmic ray transport code. The heavy ion portion of the transport code can be used with any number of layers of target material, consisting of up to five different constituents per layer. The nucleonic portion of the transport code can be used with any number of layers of target material of arbitrary composition except hydrogen. Calculated galactic cosmic ray particle fluxes, doses, and dose equivalents behind various thicknesses of aluminum shielding are presented for solar maximum and solar minimum periods.

INTRODUCTION

As time progresses, there is an ever-widening interest in launching a manned mission to the planet Mars. A major concern to interplanetary mission planners is the long-term radiation exposure of the crew to highly penetrating and damaging galactic cosmic rays. The purpose of the present report is to present preliminary estimates of radiation exposure from galactic cosmic rays (GCR) for interplanetary missions (e.g., a Mars mission). Calculations for both solar maximum and solar minimum periods are made using a previously developed GCR transport code (ref. 1). For the HZE (high-energy heavy ion) component, the transport code is valid for any number of layers of target material of arbitrary composition. Each layer can consist of up to five different constituent materials. For the nucleonic (proton and neutron) component, the transport code is valid for any number of layers of target material of arbitrary composition, except hydrogen. This restriction to non-hydrogenous materials for nucleonic transport will be rectified by incorporating the appropriate nucleon-nucleon cross sections and spectral distribution databases into the transport code. Nonetheless, the present code is useful for preliminary exposure estimates.

In this report, preliminary estimates of integral fluxes (particles/cm^2/year), doses (Rad/year), and dose equivalents (Rem/year) in tissue, behind various thicknesses of aluminum shielding, are presented according to particle composition (protons, neutrons, alphas, and HZE) and as LET (linear energy transfer) spectra. The calculations, which include both solar maximum and solar minimum periods, use as the input spectrum the analytical model of the GCR environment promulgated by the Naval Research Laboratory (Ref. 2).

CALCULATIONAL METHODS

The incident galactic cosmic ray spectrum (Ref. 2) for free space is propagated through the target material using the accurate analytical/numerical solutions to the transport equation described in reference 1. These highly accurate solution methods have been verified (to within 2 percent accuracy) by comparison with an exact, analytical benchmark solution to the ion transport equation (ref. 3).

These transport calculations include:

a. ICRP-26 quality factors (ref. 4).

b. Dose contributions from propagating neutrons, protons, alpha particles, and heavy ions (HZE particles).

c. Dose contributions resulting from target nuclear fragments produced by incident neutrons and protons.

d. Dose contributions due to nuclear recoil in tissue.

Major shortcomings of the calculations are:

a. Nucleon-hydrogen cross sections and spectral and angular distributions need to be added so as to enable transport of nucleons in tissue to be included.

b. Except for tissue targets, mass number 2 and 3 fragment contributions are neglected.

c. Target fragmentation contributions from incident HZE particles are neglected (although they are included for incident nucleons).

d. It is presently assumed that all secondary particles are produced with a velocity equal to that of the incident particle. For neutrons produced in HZE particle fragmentations this is conservative.

e. A quality factor of 20 is assigned to all target fragments. To improve this approximation, one needs to calculate target fragment spectra correctly.

RESULTS

Figure 1 displays "skin" dose equivalent (in Rem/year), as a function of aluminum shield thickness (in units of areal density, g/cm^2), for interplanetary missions during solar minimum and solar maximum periods. Note that the dose equivalent is reduced appreciably by the initial 5 g/cm^2 of shield thickness, but is not as dramatically affected for greater thicknesses. A likely explanation for this behavior can be deduced from figure 2 where contributions from individual radiation field components are displayed. Note that the main contribution to the radiation dose equivalent comes from the HZE particle component of the incident spectrum (~ 1% by number) and not from the more abundant protons ~ 88 % by number). The initial dose equivalent reduction is the result of a significant reduction in this HZE component, probably caused by the attenuation of the low-energy portion of the spectrum. Thereafter, the increase in proton and neutron contributions resulting from breakup (fragmentations) of the high energy portion of the HZE spectrum mitigates this attenuation and accounts for the slowly decreasing dose equivalent values as the shield thickness increases. The actual numerical values used in the figures are listed in Table I. Tables II and III list values for dose (Rad/year) and particle flux (particles/cm^2/year) as a function of shield thickness and particle type. Clearly there is a need to understand and accurately model the nuclear fragmentation process.

Because many damage mechanisms in biological systems, electronic components, and structural materials may be LET-dependent, Tables IV-VI display values of particle flux, dose, and dose equivalent as a function of LET (in MeV-cm^2/g) and aluminum shield thickness. Values are listed for both solar minimum and solar maximum periods. All dose and flux quantities are integral values.

To improve these estimates, the ability to transport nucleons through hydrogenous target materials must be included by incorporating the appropriate nucleon-hydrogen cross sections and angular/spectral distributions into the GCR transport code. Once this has been completed, the effectiveness of shields composed of water or organic composites (including polymers) can be evaluated. In addition, more meaningful biological doses/dose equivalents to the blood-forming-organs can be estimated for radiation protection purposes.

Recently, a fast, accurate nucleon transport code, capable of transporting either cosmic ray spectra or monoenergetic incident nucleons in all materials, including hydrogenous ones, has been developed. After completion of validation, this code will be joined with the HZE transport code (ref. 1) to provide a completely general, deterministic, accurate GCR transport code in a single, self-contained package.

CONCLUDING REMARKS

Preliminary estimates of radiation exposures resulting from galactic cosmic rays are presented for interplanetary missions. Particle flux, dose, and dose equivalent values are presented, for both solar maximum and minimum periods, as a function of aluminum shield thickness and as a function of linear energy transfer. The main contributions to the radiation doses arise from HZE particles. As the incident radiations attenuate in the shield material, there is a significant buildup of secondary particles resulting from nuclear fragmentation and Coulomb dissociation processes. A substantial fraction of these secondaries are energetic neutrons. Finally, additional improvements to the GCR transport code are described.

References

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2. Adams, J. H.; Silberberg, R.; and Tsao, C.H.: "Cosmic Ray Effects on Microelectronics, Part I: The Near-Earth Particle Environment", NRL Memorandum Report 4506-Part I, August 1981.

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4. International Commission on Radiological Protection: Recommendations of the ICRP. ICRP Publication 26, 1977.

Table I - Galactic Cosmic Ray "Skin" Dose Equivalent (Rem/Yr) in Tissue as a Function of Aluminum Shield Thickness for Interplanetary Missions

Thickness (g/cm^2)	Neutrons	Protons	Alphas	HZE	Total Dose Equivalent
SOLAR MINUMUM PERIOD					
0	0	9.44	7.38	107.85	124.67
5	2.49	8.90	3.23	50.91	65.53
10	5.02	10.37	2.83	36.24	54.46
15	7.56	11.46	2.46	26.77	48.25
20	10.12	12.33	2.14	20.27	44.86
25	12.67	13.07	1.87	15.63	43.24
SOLAR MAXIMUM PERIOD					
0	0	3.84	2.52	39.46	45.82
5	1.16	3.51	1.00	18.46	24.13
10	2.35	4.23	0.89	14.57	22.04
15	3.57	4.78	0.80	11.60	20.75
20	4.81	5.25	0.72	9.31	20.09
25	6.06	5.66	0.64	7.52	19.88

Table II - Galactic Cosmic Ray "Skin" Dose (Rad/Yr) in Tissue as a Function of Aluminum Shield Thickness for Interplanetary Missions

Thickness (g/cm^2)	Neutrons	Protons	Alphas	HZE	Total Dose
SOLAR MINUMUM PERIOD					
0	0	6.57	3.27	8.53	18.37
5	0.39	7.99	2.61	5.02	16.01
10	0.77	9.18	2.29	3.79	16.03
15	1.15	10.06	2.00	2.95	16.16
20	1.52	10.75	1.75	2.34	16.36
25	1.89	11.32	1.54	1.88	16.63
SOLAR MAXIMUM PERIOD					
0	0	2.43	1.11	2.17	5.71
5	0.18	3.09	0.88	1.93	6.08
10	0.36	3.67	0.79	1.58	6.40
15	0.55	4.13	0.71	1.31	6.70
20	0.73	4.50	0.64	1.09	6.96
25	0.91	4.83	0.57	0.91	7.22

Table III - Galactic Cosmic Ray Flux (particles/cm^2/year) as a Function of Aluminum Shield Thickness for Interplanetary Missions

Thickness (g/cm^2)	Neutrons	Protons	Alphas	HZE	Total Flux
SOLAR MINUMUM PERIOD					
0	0	1.62E+08	1.57E+07	1.75E+06	1.79E+08
5	3.44E+07	1.73E+08	1.39E+07	1.43E+06	2.23E+08
10	6.96E+07	1.80E+08	1.23E+07	1.19E+06	2.63E+08
15	1.05E+08	1.85E+08	1.09E+07	1.00E+06	3.02E+08
20	1.41E+08	1.88E+08	9.65E+06	8.49E+05	3.40E+08
25	1.78E+08	1.91E+08	8.57E+06	7.24E+05	3.78E+08
SOLAR MAXIMUM PERIOD					
0	0	6.38E+07	6.44E+06	7.20E+05	7.09E+07
5	1.59E+07	6.97E+07	5.77E+06	6.20E+05	9.20E+07
10	3.23E+07	7.38E+07	5.19E+06	5.37E+05	1.12E+08
15	4.93E+07	7.71E+07	4.67E+06	4.68E+05	1.32E+08
20	6.67E+07	7.98E+07	4.20E+06	4.08E+05	1.51E+08
25	8.44E+07	8.22E+07	3.78E+06	3.56E+05	1.71E+08

Table IV - Flux (Particles/cm^2/yr) vs LET in Aluminum

LET (MeV-cm^2/g)	Thickness in g/cm^2 0	5	10	15	20	25
			SOLAR MINIMUM PERIOD			
1.08E+00	1.79E+08	2.23E+08	2.63E+08	3.02E+08	3.40E+08	3.78E+08
5.03E+00	2.36E+07	6.56E+07	1.05E+08	1.44E+08	1.83E+08	2.21E+08
2.35E+01	3.94E+06	3.87E+07	7.40E+07	1.10E+08	1.46E+08	1.82E+08
1.09E+02	1.39E+06	3.54E+07	7.04E+07	1.06E+08	1.42E+08	1.78E+08
5.10E+02	2.55E+05	2.86E+05	3.94E+05	5.26E+05	6.73E+05	8.33E+05
2.38E+03	2.15E+04	3.48E+04	5.82E+04	8.49E+04	1.14E+05	1.44E+05
1.11E+04	2.39E+03	2.53E+04	5.23E+04	8.09E+04	1.11E+05	1.42E+05
5.16E+04	2.68E+01	2.50E+04	5.21E+04	8.08E+04	1.11E+05	1.42E+05
			SOLAR MAXIMUM PERIOD			
1.08E+00	7.10E+07	9.19E+07	1.12E+08	1.32E+08	1.51E+08	1.71E+08
5.03E+00	8.36E+06	2.79E+07	4.66E+07	6.53E+07	8.40E+07	1.03E+08
2.35E+01	1.34E+06	1.74E+07	3.41E+07	5.12E+07	6.78E+07	8.65E+07
1.09E+02	5.38E+05	1.63E+07	3.27E+07	4.96E+07	6.70E+07	8.47E+07
5.10E+02	9.03E+04	1.20E+05	1.79E+05	2.46E+05	3.19E+05	3.99E+05
2.38E+03	5.88E+03	1.44E+04	2.66E+04	3.98E+04	5.40E+04	6.90E+04
1.11E+04	1.08E+03	1.19E+04	2.47E+04	3.84E+04	5.30E+04	6.82E+04
5.16E+04	2.85E+01	1.18E+04	2.46E+04	3.84E+04	5.29E+04	6.82E+04

Table V - "Skin" Dose (Rad/yr) vs LET in Aluminum

LET (MeV-cm^2/g)	Thickness in g/cm^2 0	5	10	15	20	25
SOLAR MINIMUM PERIOD						
1.08E+00	1.84E+01	1.60E+01	1.60E+01	1.62E+01	1.64E+01	1.66E+01
5.03E+00	1.33E+01	1.08E+01	1.07E+01	1.08E+01	1.10E+01	1.12E+01
2.35E+01	1.06E+01	7.13E+00	6.54E+00	6.25E+00	6.15E+00	6.19E+00
1.09E+02	8.94E+00	5.20E+00	4.47E+00	4.09E+00	3.93E+00	3.91E+00
5.10E+02	5.64E+00	2.43E+00	1.71E+00	1.25E+00	9.45E-01	7.29E-01
2.38E+03	2.56E+00	5.50E-01	3.43E-01	2.27E-01	1.56E-01	1.11E-01
1.11E+04	1.42E+00	6.73E-02	4.09E-02	2.66E-02	1.80E-02	1.27E-02
5.16E+04	3.81E-04	3.32E-04	2.91E-04	2.57E-04	2.28E-04	2.04E-04
SOLAR MAXIMUM PERIOD						
1.08E+00	6.73E+00	6.09E+00	6.42E+00	6.69E+00	6.96E+00	7.23E+00
5.03E+00	4.84E+00	4.11E+00	4.37E+00	4.58E+00	4.80E+00	5.02E+00
2.35E+01	3.91E+00	2.71E+00	2.70E+00	2.72E+00	2.78E+00	2.87E+00
1.09E+02	3.32E+00	1.98E+00	1.87E+00	1.82E+00	1.82E+00	1.86E+00
5.10E+02	2.07E+00	8.74E-01	6.87E-01	5.46E-01	4.38E-01	3.55E-01
2.38E+03	9.65E-01	1.36E-01	1.00E-01	7.48E-02	5.63E-02	4.29E-02
1.11E+04	6.67E-01	1.63E-02	1.20E-02	8.92E-03	6.70E-03	5.10E-03
5.16E+04	4.05E-04	3.50E-04	3.05E-04	2.66E-04	2.34E-04	2.06E-04

Table VI - "Skin" Dose Equivalent (Rem/yr) vs LET in Aluminum

LET	Thickness in g/cm^2					
(MeV-cm^2/g)	0	5	10	15	20	25
			SOLAR MINIMUM PERIOD			
1.08E+00	1.25E+02	6.56E+01	5.45E+01	4.83E+01	4.49E+01	4.33E+01
5.03E+00	1.20E+02	6.04E+01	4.92E+01	4.29E+01	3.95E+01	3.78E+01
2.35E+01	1.17E+02	5.67E+01	4.50E+01	3.84E+01	3.47E+01	3.28E+01
1.09E+02	1.15E+02	5.40E+01	4.22E+01	3.55E+01	3.17E+01	2.98E+01
5.10E+02	9.75E+01	3.94E+01	2.73E+01	1.97E+01	1.46E+01	1.11E+01
2.38E+03	5.12E+01	1.10E+01	6.86E+00	4.53E+00	3.12E+00	2.21E+00
1.11E+04	2.84E+01	1.34E+00	8.16E-01	5.29E-01	3.59E-01	2.52E-01
5.16E+04	6.57E-03	5.75E-03	5.13E-03	4.67E-03	4.35E-03	4.13E-03
			SOLAR MAXIMUM PERIOD			
1.08E+00	4.61E+01	2.41E+01	2.21E+01	2.08E+01	2.01E+01	1.99E+01
5.03E+00	4.41E+01	2.22E+01	2.00E+01	1.87E+01	1.79E+01	1.77E+01
2.35E+01	4.31E+01	2.08E+01	1.83E+01	1.68E+01	1.59E+01	1.55E+01
1.09E+02	4.22E+01	1.97E+01	1.72E+01	1.56E+01	1.46E+01	1.42E+01
5.10E+02	3.58E+01	1.40E+01	1.08E+01	8.50E+00	6.73E+00	5.38E+00
2.38E+03	1.93E+01	2.71E+00	2.00E+00	1.49E+00	1.12E+00	8.52E-01
1.11E+04	1.33E+01	3.22E-01	2.37E-01	1.76E-01	1.32E-01	1.00E-01
5.16E+04	6.97E-03	5.97E-03	5.16E-03	4.51E-03	4.00E-03	3.60E-03

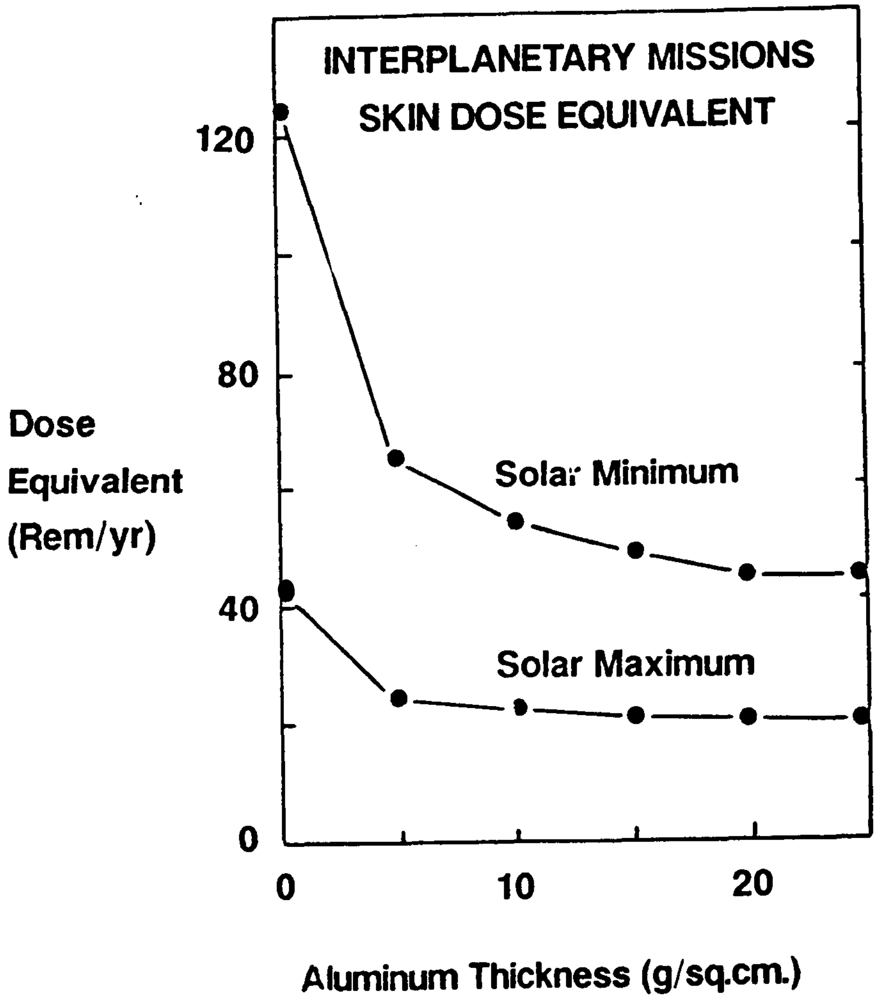

Figure 1. - "Skin" dose equivalent in tissue, as a function of aluminum shield thickness, resulting from galactic cosmic rays.

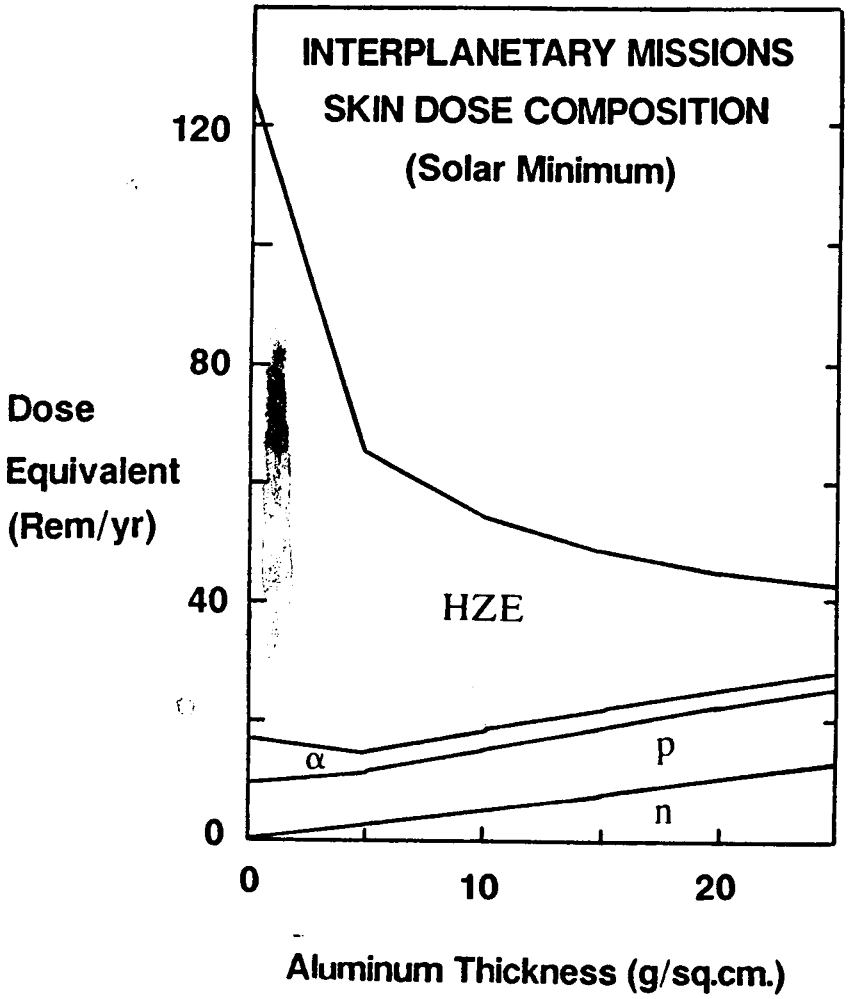

Figure 2. - Composition of the radiation field, as a function of aluminum shield thickness, resulting from galactic cosmic rays.

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16. Abstract

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