J. RADIAT. RES., 43: SUPPL., S119–S124 (2002)

Visualization of Particle Flux in the Human Body on the Surface of Mars

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Mars / Radiation / Human body / Visualization / GCR

For a given galactic cosmic ray (GCR) environment, information on the particle flux of protons, alpha particles, and heavy ions, that varies with respect to the topographical altitude on the Martian surface, are needed for planning exploration missions to Mars. The Mars Global Surveyor (MGS) mission with its Mars Orbiter Laser Altimeter (MOLA) instrument has been providing precise topographical surface map of the Mars. With this topographical data, the particle flux at the Martian surface level through the CO_2 atmospheric shielding for solar minimum and solar maximum conditions are calculated. These particle flux calculations are then transported first through an anticipated shielding of a conceptual shelter with several water equivalent shield values (up to 50 g/cm^2 of water in steps of 5 g/cm^2) considered to represent a surface habitat, and then into the human body. Model calculations are accomplished utilizing the HZETRN, QMSFRG, and SUM-MARS codes. Particle flux calculations for 12 different locations in the human body were considered from skin depth to the internal organs including the blood-forming organs (BFO). Visualization of particle flux in the human body at different altitudes on the Martian surface behind a known shielding is anticipated to provide guidance for assessing radiation environment risk on the Martian surface for future human missions.

INTRODUCTION

If the later part of the 20th century is considered to be a *small step* based on the human landing that occurred on the Moon, indeed, it will be a *giant leap* when the humans reach Mars in the early part of the 21st century. In planning human exploration missions, NASA and other space agencies involved in these endeavors will place a high priority on the health and safety of astronauts[1)]. A major area of concern is the possible detrimental effect on health, including cancer, a broad-range of degenerative tissue diseases including damage to the central nervous system, cataracts, and hereditary risks, caused by exposure to galactic cosmic rays (GCR). The GCR contain high-energy protons and highly ionizing heavy ions that have large penetration power in shielding and tissue and are unlike any radiation to which humans are exposed on Earth. It is not possible to completely shield the GCR environment with practical amounts of radiation shielding because of their ranges in materials and the production of secondary particles including neutrons as the GCR penetrate materials[2)].

In this report, we present the model calculations and predictions of the particle flux of protons, alpha particles, and heavy ions on the Martian surface at various solar cycle scenarios. As a particle passes through tissues, cells, or DNA, ionization events on biomolecules occur leading to the production of secondary electrons. Close to an ion track, particles directly excite biomolecules. Lower energy electrons produced in these events deposit a large amount of energy, however are confined to a small radial region about the ion track in the so called track core. Higher-energy electrons ejected by the ion are termed as γ-rays and impart energy in other areas of the cell or even in adjacent cells[3)]. The term *track structure* refers to the description of the spatial distri-

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bution of energy deposition events at the biomolecular level. Because the uncertainties in defining the dose equivalent for the GCR are large[4], alternate quantities to discuss risks for exploration missions are needed. Here we consider one basic property, the number of particle traversals or hits per cell. We note that other quantities will be discussed elsewhere.

In our present model calculations, we consider detailed calculations of the particle flux and organ dose equivalent values at several locations on the surface of Mars with the inclusion of static CO_2 atmospheric shielding model based on the MOLA data[5]. Particle fluxes are presented in terms of the probable number of cell hits by protons, alpha particles, and heavy ions ($3 \le Z \le 10$, $11 \le Z \le 20$, $21 \le Z \le 28$) in order to provide insights into the risks on the Mars surface from different GCR components. These calculations and model predictions are expected to provide requirements for radiation shield development and also influence the ongoing radiobiology research investigations to assess future human missions to Mars.

MATERIALS AND METHODS

GCR Spectra

Using the HZETRN transport code, GCR spectra for several solar maximum and solar minimum scenarios were generated. Following Badhwar and O'Neill model[6] the solar effects on the GCR are described in terms of the solar modulation parameter, Φ, with the results shown here are for the current solar maximum (Φ = 1075 MV) (anticipated for the year, 2002) and near solar minimum (Φ = 428 MV). The contribution from the Solar Particle Events (SPE) is not included in the present calculations. Calculations that include spectral data from past SPE will be presented elsewhere.

Particle Flux

Making use of the HZETRN transport code[7] and the QMSFRG nuclear interaction model[8] the particle flux, $\phi_j(x,E)$, of ion, j with energy, E and depth, x is obtained from

$$\Omega \cdot \nabla \phi_j(x,\Omega,E) = \sum\nolimits_k \int \sigma_{jk}(\Omega,\Omega',E,E') \phi_k(x,\Omega',E')dE'd\Omega' - \sigma_j(E)\phi_j(x,\Omega,E)$$

The methods of Wilson et al.,[7] for GCR transport is to use the straight-ahead and continuous slowing down approximation to solve the above equation for charged ions and to include angular effects for neutrons.

Martian CO_2 Model

For two different density models (16 and 22 g/cm^2), spherically distributed CO_2 atmosphere was considered[9]. In each atmospheric model, variation of CO_2 density with respect to altitude was also considered are available from ref.[9]. The variations in the CO_2 density due to sporadic temperature changes is not completely know and hence these changes are not incorporated in the current model. The resultant shielding offered by the CO_2 atmosphere at a given altitude location is calculated for a set of 512 rays using the relation

$$s(z,\theta) = \sqrt{(R+h)^2\cos^2(\theta) + [2R(z-h) + z^2 - h^2]} - (R+h)\cos(\theta)$$

Where, h is the altitude above the mean surface, s being the distance along the slant path with zenith angle, θ, (calculated between 0 and 90^0 with 10^0 increments) and z is the vertical height of the atmosphere above the identified location.

Visualization in the Human Body

Utilizing the SUM-MARS code[10], the intrinsic shield values offered by the human body for 12 different anatomical locations were calculated based on the CAM (Computerized Anatomical Male) shielding description. Then the flux of the particles (neutrons, alpha, low, medium, and heavy ions) that were generated for various solar cycle scenarios was transported through the human body shielding. Visualization of the organ dose-equivalent values (cSv/yr), along with probable particle-hits by protons and heavy-ions (particle-hits/cell/yr) are presented in the human body on the Martian mean surface. The cell dimension considered was 100 μm^2. Visualization of the interactive human model was accomplished using the SRHP (Space Radiation Health Project at NASA Johnson Space Center)[11] developed VIZ-MARS routines[12] utilizing the MATLAB-5.1 resources[13]. These human body visualization techniques are based on our earlier work reported in the year 2001[14].

Description of the CAM Model

Human body shield values are calculated utilizing the CAM model originally developed by Paul Kase in the 1970s[15]. The CAM model consists of about 1500 quadratic surfaces that result in about 2500 closed volumes[16]. Current resolution of the model is about 0.1 inch and is represented within 5% of organ size and body weight. Anatomical composition is modeled for 11 different tissue types. Typically, the CAM model represents a 50th percentile U. S. Air Force cohort of about 5' 9.25" (~ 176 cm) height and 155 lbs (70 kg) weight. In our current visualization, we have used a 19"

× 19" × 71" (~ 48 × 48 × 180 cm^3) 3D-lattice to represent our calculated data. Though at this time, the CAF (computerized anatomical female) model is available at the NASA Johnson Space Center, we have not used it for our calculations[17]. We intend to present our results for the CAF model in future publications.

RESULTS AND DISCUSSION

Projections of the particle-hits per cell on the Mars surface are estimated for 12 different organ depths in a human body behind a given conceptual vehicle with known water equivalent shielding. Radiation elemental fluxes on the Martian surface at 12 different anatomical locations inside of the human body for a given GCR environment are calculated (Table-1). Visualization of the dose-equivalent values and particle-hits per cell on the Martian surface are presented to illustrate the range of variation inside of the human body at the mean surface level on Mars (Fig. 1-3). Though not included in this report, variations of the particle flux distribution as a function of entire Martian topography above and below the mean surface were also calculated and presented by Cucinotta et al., in this volume[18]. The human body self-shielding from the outermost point level to the innermost organ level indicate a particle flux reduction of ~ 2% for the protons (Z=1) and ~ 35% for the heavy ions (Z≥2). The addition of water shielding for solar minimum condition indicates significant reduction for heavy ion flux, moderate reduction for alpha particles, and little or no reduction for neutron and protons. With a 40 g/cm^2 water shield at the mean surface level, the particle flux at skin level is noted as follows: heavy ion flux decreased by a factor of 30, medium ions by a factor of 12, light ions by a factor of 4, alpha particles by a factor of 3, the flux of protons essentially remained unchanged.

The models used here for the GCR particle flux predictions show good agreement with the cruise-phase (April-August, 2001) and orbital phase (April 2002 – present) data of the Martian Radiation Environment Experiment (MARIE) instrument of the 2001 Mars Odyssey mission as will be described elsewhere[19]. Also, in this report, we have not included any detailed calculations of the *albedo* neutrons produced in interactions with the Mars atmosphere or surface. Such data will be needed to make a complete estimate of the exposures to be encountered on Mars. Quantifying the radiation risk uncertainty[4] and mitigating the radiation risk on the Martian surface has been a priority for future manned missions to the Mars and for radiobiological investigations of the current era.

Table 1. Model calculations of probable particle-hits per cell at skin depth in one year near solar maximum (Φ = 1075 MV). Calculations are for 12 different organ locations in a human body at the mean surface level on Mars

Particle-Hits / Cell / Year near solar maximum						
Human Body on the Martian Surface (Mean Altitude)	Protons Z = 1	Alpha Particles Z = 2	Light Ions 3≤Z≤10	Medium Ions 11≤Z≤20	Heavy Ions 21≤Z≤28	All (Z≥2)
1 Skin	42.7	1.46	0.08	0.0067	0.0011	1.55
2 Eye	42.8	1.52	0.08	0.0069	0.0011	1.61
3 Blood Forming Organs (BFO)	42.6	1.32	0.06	0.0047	0.0006	1.39
4 Stomach	42.6	1.23	0.06	0.0038	0.0005	1.29
5 Colon	42.6	1.32	0.06	0.0046	0.0006	1.39
6 Liver	42.6	1.25	0.06	0.0041	0.0005	1.31
7 Lungs	42.5	1.29	0.06	0.0044	0.0006	1.36
8 Bladder	42.4	1.21	0.06	0.0037	0.0004	1.27
9 Thyroid	42.6	1.35	0.07	0.0050	0.0007	1.42
10 Esophagus	42.5	1.28	0.06	0.0043	0.0006	1.34
11 Gonads	42.4	1.31	0.06	0.0048	0.0007	1.37
12 POINT	43.2	1.84	0.10	0.0098	0.0017	1.95

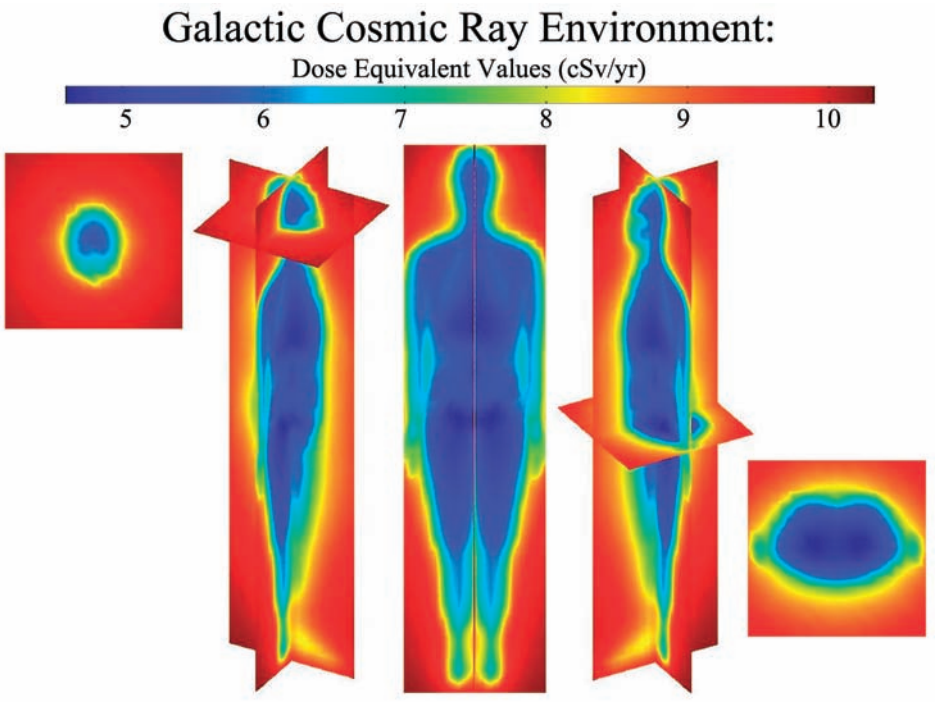

Fig. 1. Model predictions of the dose-equivalent values (cSv/yr) from the GCR at the mean surface level on the Martian surface. Calculations are shown at skin depth for a solar maximum scenario (Φ = 1075 MV).

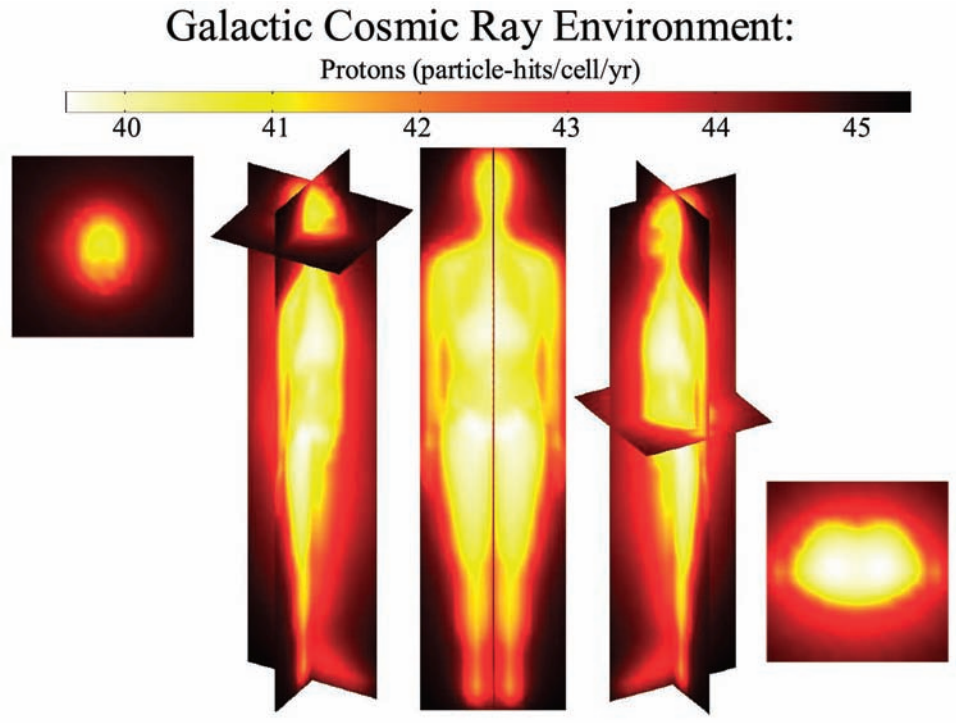

Fig. 2. Model predictions of proton flux (particle-hits/cell/yr) from the GCR contribution at the mean surface level on the Martian surface. Calculations are shown at skin depth for a solar maximum scenario (Φ = 1075 MV).

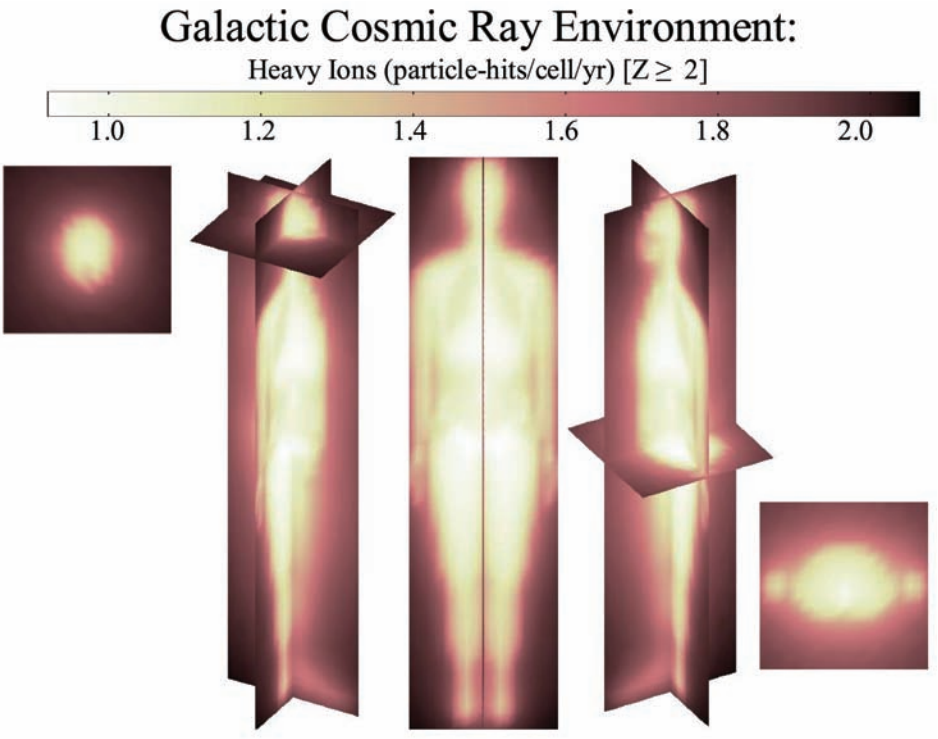

Fig. 3. Model predictions of all ions ($Z \geq 2$ shown as particle-hits/cell/yr) from the GCR contribution at the mean surface level on the Martian surface. Calculations are shown at skin depth for a solar maximum scenario ($\Phi = 1075$ MV).

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Received on June 10, 2002
Revision on August 26, 2002
Accepted on November 1, 2002