Surviving in space: the challenges of a manned mission to Mars

Lecture 3
Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars
Back to the Moon…
Then, On to Mars

- President Bush has committed the US Space Program to going to Mars…
- The first step will be a return to the Moon to develop and test the techniques needed eventually to go to Mars…
- Crew radiation exposure has been identified as one of the major problems that must be dealt with to make this possible…
Radiation Exposure Guidelines

• Recall that astronauts will be held to the same exposure limits in terms of risk to health that ground-based atomic workers are!

• Nominally, for chronic exposure threats the biggest risk is radiation-induced cancer, and the current exposure guideline is to keep the Excess Lifetime Risk (ELR) to under 3%...
NASA Revised Standard for Radiation Limits

- Revised standard applies a 95% confidence level to the career limit of 3% risk of lifetime fatal cancer
  - Approved by NASA Medical Policy Board
- 95% confidence is conservative
  - Takes specific risk probabilities of individuals into account
  - Narrows range of increased risk
  - Epidemiology, DDREF (Dose and Dose Rate Effectiveness Factor), quality (QF) and dosimetry uncertainties part of evaluation
- “Lack of knowledge” leads to costs and restrictions

ISS Mission Nominal Fatal Cancer Risk

Slide Courtesy of F. Cucinotta, NASA/JSC
Mars “Reference” Mission

Figure 1-1 Typical fast-transit trajectory.
Reference Mars Vehicles

Basic idea is to pre-position the ascent stage and habitats on Mars, along with the orbiting return vehicle before sending the crew with the descent stage… This is just a planning concept, and will likely be modified heavily in practice…
Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars
4-6 crew to lunar surface for extended-duration stay

**CEV:** Earth-moon cruise – 4 days
Low lunar orbit (LLO) operations - 1 day
Untended lunar orbit operations – 4-14 days
Low lunar orbit operations – 1 day
Moon-Earth cruise – 4 days

**Lunar Lander:** Lunar surface operations
60-90 days

4-6 crew to Low Earth Orbit

**Crew Exploration Vehicle:** Launch Environment
LEO Environment
Earth entry, water (or land) recovery

Crew TBD to Mars Vicinity

**Transit vehicle:** Earth-Mars cruise – 6-9 months
Mars vicinity operations – 30-90 days
Mars-Earth cruise – 9-12 months

Crew TBD to Mars surface

Surface Habitat

2020

2014

2015-2020

2025+

2030+

Spiral 1

Spiral 2

Spiral 3

Spiral 4

Spiral 5

Crew LTD to Mars surface

Surface Habitat

2020

Slide Courtesy of F. Cucinotta, NASA/JSC
Mars Mission Exposure Regimes

- Trans-Mars & Trans-Earth Vehicle
  - Normal Crew Compartment
  - “Storm Shelter” within Vehicle
  - Spacesuit EVAs

- Martian Surface
  - Within Surface Habitat
  - Possible “Storm Shelter” within Habitat
  - EVA Vehicle
  - Spacesuit EVAs
DEEP SPACE GCR DOSES
Trans-Mars & Trans-Earth

• Annual bone marrow GCR doses will range up to ~ 15 cGy at solar minimum (~ 40 cSv) behind ~ 2cm Al shielding
• Effective dose at solar minimum is ~ 45-50 cSv per annum
• At solar maximum these are ~ 15-18 cSv
• Secondary neutrons and charged particles are the major sources of radiation exposure in an interplanetary spacecraft
• No dose limits yet for these missions
Figure D.4. Relative Contribution of Different Components of Space Radiation to Dose Equivalent

From NASA 1996

Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars

CERN Course – Lecture 3
October 28, 2005 – L. Pinsky
Dose v. Shielding Depth
For Various Materials

From NASA CP3360, J.W. Wilson et al., eds.
Cosmic Rays and Nuclear Physics

- **NASA** Sponsors Nuclear Modeling to Obtain Nucleus-Nucleus EVENT GENERATORS for use in Monte Carlo Transport Codes…

- Like **FLUKA**…
  - We have embedded **DPMJET** 2.5 & 3 (for E > 5 GeV/A)
  - as well as **RQMD** (for 100 MeV/A < E < 5 GeV/A)
...And, There is an Ongoing NASA-Sponsored Program to Improve the Accuracy of the Event Generators

• There is a Dual Program to Both Model and Measure Cross Sections…
  – The Focus is on the E < 5GeV/A Region…
  – Several Approaches are being taken…
  – The NASA-FLUKA Team is developing a new Hamiltonian QMD Formalism (HQMD).

• These Improvements will Directly benefit many Cosmic Ray Applications…
  – Air Shower Calculations…
  – Galactic Transport Calculations…
  – Experimental Corrections…
The FLUKA Monte Carlo code

• hadron-hadron and hadron-nucleus interactions 0-100 TeV
• nucleus-nucleus interactions 5 GeV/u-10,000 TeV/u (DPMJET)
• electromagnetic and μ interactions 0-100 TeV
• neutron multigroup transport and interactions 0-20 MeV
• nucleus-nucleus interactions below 5 GeV/u down to 100 MeV/u (by coupling with the RQMD 2.4 code)
• parallel development of an original non-relativistic QMD code down to ~ 20 MeV/u

Courtesy of F. Balarini
New Methods

Quality factors

Yields of “Complex Lesions”

GCR and SPE spectra

FLUKA

Dose

Equivalent dose

“Biological dose”

(Complex Lesions/cell)

30 DNA base-pairs

“voxel” phantom (287 regions, > 2x10^6 voxels)

mathematical phantom (68 regions)

Courtesy of F. Balarini

Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars
FLUKA rQMD

Fragmentation Yields

Fe 1.05 GeV/nucleon on Al

Zeitlin et al
Cummings et al
FLUKA

Fe 1.05 GeV/nucleon on Cu

Zeitlin et al
Cummings et al
Westfall et al
FLUKA
FLUKA Simulations
FLUKA MIR TPEC Simulations

Charged Particle Fluences
(Note the albedo fluences outside of the phantom…)

Neutron Fluences

Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars
Future developments

Further validation of the FLUKA Monte Carlo code in space radiation protection problems with simple shielding geometry

Repetition for more realistic geometries of shielding and spacecraft

Ultimately, we will need to assess the risk from this kind of radiation field, and that is a Biology Problem, not a physics challenge…
## Annual GCR Doses

<table>
<thead>
<tr>
<th>Al Shield (g cm(^{-2}))</th>
<th>Skin</th>
<th>Bone Marrow</th>
<th>Bone Marrow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Dose (cGy)</td>
<td>Annual Dose Equiv. (cSv)</td>
<td>Annual Dose Equiv. (cSv)</td>
</tr>
<tr>
<td>1</td>
<td>6.2</td>
<td>27.4</td>
<td>5.7</td>
</tr>
<tr>
<td>5</td>
<td>6.4</td>
<td>24.6</td>
<td>5.8</td>
</tr>
<tr>
<td>10</td>
<td>6.5</td>
<td>21.8</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**1970-71 Solar Maximum**

(Courtesy of L. Townsend, US NCRP)
### Fatal Cancer Risk near Solar Maximum (Males)

*Phi=1100 MV (solar modulation) with Aug. 1972 SPE in transit

<table>
<thead>
<tr>
<th>Mission</th>
<th>D, Gy</th>
<th>E, Sv</th>
<th>%REID</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 g/cm² Al</td>
</tr>
<tr>
<td>Lunar (90 d)</td>
<td>0.45</td>
<td>0.69</td>
<td>2.7</td>
<td>[0.92, 7.4]</td>
</tr>
<tr>
<td>Lunar (600 d)</td>
<td>0.63</td>
<td>1.21</td>
<td>4.4</td>
<td>[1.5, 13.3]</td>
</tr>
<tr>
<td>Lunar (1000 d)</td>
<td>0.66</td>
<td>1.24</td>
<td>4.4</td>
<td>[1.5, 13.0]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20 g/cm² Al</td>
</tr>
<tr>
<td>Lunar (90 d)</td>
<td>0.042</td>
<td>0.09</td>
<td>0.35</td>
<td>[0.11, 1.2]</td>
</tr>
<tr>
<td>Mars (600 d)</td>
<td>0.22</td>
<td>0.54</td>
<td>2.0</td>
<td>[0.65, 6.8]</td>
</tr>
<tr>
<td>Mars (1000 d)</td>
<td>0.25</td>
<td>0.60</td>
<td>2.1</td>
<td>[0.69, 7.2]</td>
</tr>
</tbody>
</table>

* Slide Courtesy of F. Cucinotta, NASA/JSC

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CERN Course – Lecture 3  
October 28, 2005 – L. Pinsky  
Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars
### Solar Min Annual GCR Dose

<table>
<thead>
<tr>
<th>Al Shield (g cm(^{-2}))</th>
<th>Skin</th>
<th>Bone Marrow</th>
<th>1977 Solar Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Dose (cGy)</td>
<td>Annual Dose Equiv. (cSv)</td>
<td>Annual Dose (cGy)</td>
</tr>
<tr>
<td>1</td>
<td>18.4</td>
<td>79.8</td>
<td>16.4</td>
</tr>
<tr>
<td>5</td>
<td>18.3</td>
<td>66.9</td>
<td>16.3</td>
</tr>
<tr>
<td>10</td>
<td>18.0</td>
<td>56.2</td>
<td>16.1</td>
</tr>
</tbody>
</table>

Credit: Courtesy of L. Townsend, US NCRP
### Fatal Cancer Risk at Solar **Minimum** (20 g/cm² Aluminum Shielding)

<table>
<thead>
<tr>
<th>Mission</th>
<th>D, Gy</th>
<th>E, Sv</th>
<th>%REID</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Males</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar (90 d)</td>
<td>0.03</td>
<td>0.071</td>
<td>0.28</td>
<td>[0.09,0.96]</td>
</tr>
<tr>
<td>Mars (600 d)</td>
<td>0.36</td>
<td>0.87</td>
<td>3.2</td>
<td>[1.0,10.5]</td>
</tr>
<tr>
<td>Mars (1000 d)</td>
<td>0.41</td>
<td>0.96</td>
<td>3.4 (3.2)*</td>
<td>[1.1,11.0]</td>
</tr>
<tr>
<td><strong>Females</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar (90 d)</td>
<td>0.03</td>
<td>0.071</td>
<td>0.34</td>
<td>[0.11,1.2]</td>
</tr>
<tr>
<td>Mars (600 d)</td>
<td>0.36</td>
<td>0.87</td>
<td>3.9</td>
<td>[1.2, 12.8]</td>
</tr>
<tr>
<td>Mars (1000 d)</td>
<td>0.41</td>
<td>0.96</td>
<td>4.1 (4.5)**</td>
<td>[1.4, 14.4]</td>
</tr>
</tbody>
</table>

*Parenthesis exclude Prostate cancer; **Parenthesis LSS-report 12 (others report 13)

Slide Courtesy of F. Cucinotta, NASA/JSC
Material Shielding and GCR Risks

• Do materials rich in hydrogen and other light atomic mass atoms significantly reduce GCR risks?
• Possible advantages
  – High Z/A ratio increases stopping effectiveness
  – Higher projectile fragmentation per unit mass in hydrogen
  – Reduced target fragmentation per unit mass in hydrogen
• Possible physics limitations to GCR shielding approaches
  – GCR not stopped in practical amounts of shielding
  – Target fragmentation is largely short-range and correlated with projectile track
  – Target fragments in tissue occur for all materials and largely produced by relativistic ions not absorbed by shielding
• Do the biological uncertainties prevent us from knowing?
Significance of Shielding Materials for GCR Spiral 4 (40-yr Males): 20 g/cm² Shields

- Distribution aluminum: $E_{(alum)} = 0.87$ Sv, $R_{(alum)} = 3.2$ [1.0, 10.5] (%)
- Distribution polyethylene: $E_{(poly)} = 0.77$ Sv, $R_{(poly)} = 2.9$ [0.94, 9.2] (%)
- Distribution Liq. Hydrogen (H2): $E_{(H2)} = 0.43$ Sv, $R_{(H2)} = 1.6$ [0.52, 5.1] (%)

Probability vs. (% Fatal Cancer Risk)

Slide Courtesy of F. Cucinotta, NASA/JSC
GCR Risks

- Clearly, annual doses < 20 cGy present no acute health hazard to crews on deep space missions.
- Hence only stochastic effects such as cancer induction and mortality or late deterministic effects, such as cataracts or damage to the central nervous system are of concern.
- Unfortunately, there are NO DATA for human exposures from these radiations that can be used to estimate risks to crews.
- In fact, as noted yesterday, it is not clear that the usual methods of estimating risk by calculating dose equivalent are even appropriate for these particles.
CONCLUSIONS - GCR

- Cancer risks for exploration missions
  - Risks from GCR are 2 to 5 percent mortality with upper 95% C.I. exceeding 10% for both males and females
    - Shielding will not significantly reduce GCR risks
    - Materials have unknown benefits because of biological uncertainties
  - Risks from SPE are manageable with shielding approaches
    - Hydro-carbon shields offer a mass reduction over Aluminum shields of factor of two or more for acute effects from most SPE spectra
    - Benefits for cancer risk reduction are similar, however not significant for poly or similar materials again due to biological uncertainties
- Uncertainty factors of 4-fold for GCR and 2.5 fold for SPE do not include several model assumptions
  - Uncertainties for Mars mission likely higher than estimated here
- Exploration vehicle shielding should focus on SPE not GCR

Slide Courtesy of F. Cucinotta, NASA/JSC
August 1972 Solar Particle Event

<table>
<thead>
<tr>
<th>Depth</th>
<th>Alum</th>
<th>Poly</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>61.1</td>
<td>39.1</td>
</tr>
<tr>
<td>10</td>
<td>20.9</td>
<td>10.7</td>
</tr>
<tr>
<td>20</td>
<td>4.57</td>
<td>1.83</td>
</tr>
</tbody>
</table>

BFO Dose, rem (cSv)

Slide Courtesy of F. Cucinotta, NASA/JSC
GCR and SPE Dose: Materials & Tissue
- GCR much higher energy producing secondary radiation

### GCR and SPE Dose: Materials & Tissue

<table>
<thead>
<tr>
<th>Material</th>
<th>Shielding Depth, g/cm²</th>
<th>Dose Equivalent, rem/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCR L. Hydrogen</td>
<td>0</td>
<td>10000</td>
</tr>
<tr>
<td>GCR Polyethylene</td>
<td>5</td>
<td>1000</td>
</tr>
<tr>
<td>GCR Graphite</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>GCR Aluminum</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>GCR Regolith</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>SPE Graphite</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>SPE Regolith</td>
<td>30</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**No Tissue Shielding**

**With Tissue Shielding**

August 1972 SPE

*Slide Courtesy of F. Cucinotta, NASA/JSC*
### August 1972 SPE - comparison to NCRP limits

<table>
<thead>
<tr>
<th>Al shield (g/cm²)</th>
<th>Skin</th>
<th>Lens</th>
<th>BFO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erma</td>
<td>Golem</td>
<td>Erma</td>
</tr>
<tr>
<td>1</td>
<td>13.31</td>
<td>11.63</td>
<td>6.89</td>
</tr>
<tr>
<td>2</td>
<td>7.25</td>
<td>6.57</td>
<td>4.90</td>
</tr>
<tr>
<td>5</td>
<td>2.23</td>
<td>2.11</td>
<td>1.60</td>
</tr>
<tr>
<td>10</td>
<td>0.62</td>
<td>0.60</td>
<td>0.56</td>
</tr>
</tbody>
</table>

**NCRP limits for 30 days LEO missions:** 1.5, 1.0 and 0.25 Gy-Eq for skin, lens and BFO, respectively ⇒ a 10 g/cm² Al storm shelter would provide adequate protection

Courtesy of F. Balarini
August 1972 SPE - skin vs. internal organs

- much lower doses to liver than to skin (e.g. 1.0 vs. 13.3 Sv behind 1 g/cm² Al)
- larger relative contribution of nuclear reaction products for liver than for skin (e.g. 14% vs. 7% behind 1 g/cm² Al)

Courtesy of F. Balarini
Aug. 1972 and Oct. 1989 SPEs - Effective Dose (Sv)

<table>
<thead>
<tr>
<th>Al shield (g/cm²)</th>
<th>August 1972 (Erma)</th>
<th>October 1989 (Erma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>E*</td>
</tr>
<tr>
<td>1</td>
<td>2.04</td>
<td>1.35</td>
</tr>
<tr>
<td>2</td>
<td>1.43</td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td>0.63</td>
<td>0.43</td>
</tr>
<tr>
<td>10</td>
<td>0.23</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- Large contribution (33-50%) from gonads, especially with small shielding
- E* values (by neglecting gonads) very similar to those calculated with the BRYNTRN code and the CAM phantom (*Hoff et al. 2002, J. Rad. Res. 43*)

Courtesy of F. Balarini
Conclusions - SPEs

- calculation of:
  - dose decrease with increasing shielding
  - differences between internal organs and skin
  - relative contribution of primary protons and secondaries
  - contribution to effective dose from gonads

- Concludes that in case of an SPE similar to the August 1972 event, a 10 g/cm² Al storm shelter should allow us to respect the 30-days NCRP limit.

Courtesy of F. Balarini
Modeling Lunar & Martian Surface Radiation Environments

- We need to start with the Free Space Fluences.
- For the Moon, we can just calculate the albedo produced by the impact of the primary fluences and add one half the free space fluence to the albedo.
- For Mars, we have to propagate the free space fluence through the atmosphere to and into the surface materials. Then examine the field near and underneath the surface including all secondaries...
Free Space GCR Environments at 1 AU

1977 Solar Minimum (solid)
1990 Solar Maximum (dashed)

Particle Fluence (# particles/cm²·MeV/amu·year)

Energy (MeV/amu)

Courtesy of M. Clowdsley
Free Space Solar Particle Event
Proton Spectra at 1 AU

Particle Fluence (# particles/cm$^2$-MeV/amu)

Energy (MeV/amu)

Worst Case SPE
Feb. 1956
Aug. 1972
Sept. 1989

Courtesy of M. Clowdsley
Lunar Surface GCR Environments

1977 Solar Minimum (solid)
1990 Solar Maximum (dashed)

Courtesy of M. Clowdsley
Lunar Surface “Worst Case SPE” Environment

![Graph showing particle fluence vs. energy for Z=0 and Z=1.]

Courtesy of M. Clowdsley
Dose Equivalent on Lunar Surface Due to GCR

- AL2219 - 1977 min.
- Polyethylene - 1977 min.
- H Nanofibers - 1977 min.
- Liquid Hydrogen - 1977 min.
- AL2219 - 1990 max.
- Polyethylene - 1990 max.
- H Nanofibers - 1990 max.
- Liquid Hydrogen - 1990 max.

Annual BFO Dose Equivalent (cSv) vs. Sphere Thickness (g/cm²)

Courtesy of M. Clowdsley
Modeling the Martian Surface Radiation Environment
Mars Induced Fields

Planetary Surface Material and Atmosphere

~15% of the primary GCR flux reaches the Martian Surface…

(From Simonsen et al.)

Neutron albedos must be included in dose estimates…

Courtesy of M. Clowdsley
Mars Surface Environment

Courtesy of M. Clowdsley
Mars Surface Mapping

Charged Ions – 1977 Solar Minimum

Courtesy of M. Clowdsley
Mars Surface Mapping

Neutrons – 1977 Solar Minimum  Courtesy of M. Clowdsley

Neut/cm$^2$-day, E > 100.00 MeV

Latitude

Longitude

LEGEND

Modeling the Interaction of the Space Radiation Environment and Assessing the Risks on a Mission to Mars

http://sirest.larc.nasa.gov
Mars Surface Mapping

Neut/cm$^2$-day, $E > 1.00$ MeV

Longitude

Latitude

Legend

http://sirest.larc.nasa.gov

Courtesy of M. Clowdsley
Mars Surface GCR Environments

1977 Solar Minimum (solid)
1990 Solar Maximum (dashed)

Courtesy of M. Clowdsley
Mars Surface Neutrons

Fluence (\# neutrons/cm²-MeV/year)

Energy (MeV)

Regolith
\text{CO}_2
\text{H}_2\text{O}
Forward

Courtesy of M. Clowdsley
CERN Course – Lecture 3
October 28, 2005 – L. Pinsky
Mars Surface “Worst Case SPE” Environment

![Graph showing particle fluence versus energy for different nuclear charges (Z)]

<table>
<thead>
<tr>
<th>Z</th>
<th>Energy (MeV/amu)</th>
<th>Particle Fluence (# particles/cm² - MeV/amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10⁻²</td>
<td>10⁰</td>
</tr>
<tr>
<td>2</td>
<td>10⁻¹</td>
<td>10⁴</td>
</tr>
<tr>
<td>3</td>
<td>10⁰</td>
<td>10⁸</td>
</tr>
<tr>
<td>4</td>
<td>10¹</td>
<td>10⁷</td>
</tr>
</tbody>
</table>

Courtesy of M. Clowdsley
Dose Equivalent on Mars Surface Due to GCR

Courtesy of M. Clowdsley

Annual BFO Dose Equivalent (cSv)

Sphere Thickness (g/cm²)

AL2219 - 1977 min.
Polyethylene - 1977 min.
H Nanofibers - 1977 min.
Liquid Hydrogen - 1977 min.
AL2219 - 1990 max.
Polyethylene - 1990 max.
H Nanofibers - 1990 max.
Liquid Hydrogen - 1990 max.

Courtesy of M. Clowdsley
Summary and Conclusions

• SPE’s can probably be shielded against
  – …But only in “Storm-Shelters” or Protected Habitats on planetary surfaces.
  – Problematic during EVAs and in thinly shielded surroundings.

• GCR is more difficult to protect against in terms of keeping the Chronic Dose acceptable during a long mission, but enough shielding or a shorter mission could work…
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