Towards Radiation-Smart Structures and Designs

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Space Radiation: The Drive & The Challenges

The Problem

Å In deep space outside the protection of the Earth’s atmosphere and magnetic field, radiation levels are known to be a major hazard to our astronauts and our missions.

Å From space physics and from space-based observations, we know that Galactic Cosmic Rays (or GCR) and Solar Energetic Particles (SEP) are the two main sources of this high level of radiation.

Å But there are challenges!

The Challenges

Å Effective shielding against the combined effects of GCRs and SEPs can be mass prohibitive.

Å Shielding effectiveness of new, potential shielding materials (or combinations) is not that well characterized.

Å Little data to guide dose and risk assessment models.

Known, large uncertainties and variabilities in radiobiological effects.

Å Other uncertainties and variabilities? (e.g., in generalization and scale-up of shielding or protection solutions).
NASA's technology roadmaps call for an integrated approach in radiation protection.

- **TA02 and TA03**: coordination with radiation protection measures for nuclear propulsion and power systems;
- **TA03**: survivability of solar power cells and other power system components in extreme radiation environments;
- **TA06**: astronaut health;
- **TA08**: instrumentation for particles, fields, and waves;
- **TA10**: use of boron nitride nanotubes for protection against radiation; and
- **TA12**: materials and structures for radiation shielding.

No one center or group (in academia or in the private sector) can realistically implement this integrated approach on its own!
Dr. Svensmark (Danish National Space Center) and co-workers believe cosmic rays affect and impact our climate significantly and they should be considered more carefully in large-scale climate models. [Space Science Reviews 93, 175 (2000); Physical Review Letters 85, 5004 (2000).]

Cosmic rays-and-clouds connection has been made before as were cosmic rays and other geophysical phenomena, e.g., C-14

However, this recent conjecture goes farther!
Two main sources of ionizing radiation:

**Galactic Cosmic Rays (GCR)**
- Protons + almost all other nuclei
- Low intensity (~ 1 \(10^{-2}\) cm)
- High-energy (peaks at 500 MeV/N)
- Sun-modulated by a factor ~4
- Isotropic

**Solar Energetic Particles (SEP)**
- Mostly protons
- High intensity (~ \(10^7\) cm)
- Lower energy (~ 100–200 MeV)
- Random Directional

Space Radiation: Natural Sources
Motivation?

“Varying cosmic-ray flux may explain cycles of biodiversity”

By Bertram Schwarzschild, Physics Today
October 2007
Large uncertainties and variabilities in the radiation quality factor is seen as a main hindrance toward reliable dose and risk estimates.

These can be captured mathematically if we model the quality factor as an Ornstein-Uhlenbeck process,

$$dQ = C(\ell)Q d\ell + \sqrt{D(\ell)} dW$$

with a corresponding PDF of the form,

$$f_Q(Q; Q_0, 0) = \frac{1}{\sqrt{4\pi q_1(\ell)}} \exp \left\{ \frac{[Q \exp(q_2(\ell)) - Q_0]^2}{4q_1(\ell)} + q_2(\ell) \right\}$$
GCR near Earth: Observed Spectra

The ubiquitous Zipf-Pareto (power-law) distributions?
Materials vary in their ability to shield against GCR nuclei.

**Polymeric based materials tend to be most effective** - but their structural and safety properties remain poor or poorly known.

**Aluminum**, like all metals, is a **poor** GCR shield.

**Regolith** is not that much better either!
GCR near Earth: Observed Composition

GCR composition is altered from their source composition due to propagation in the interstellar medium (ISM).

Mostly spallation reactions with the ISM's protons producing secondaries like the light nuclei Li, Be, and B, and sub-Fe group.

These tell us much about the time GCRs spend and amount of matter they meet in the galaxy since their synthesis.
Space Radiation: Regolith as a shield material

TABLE I: 1999 NCRP-recommended dose limits by organ and exposure duration.

<table>
<thead>
<tr>
<th>Limit (cSv)</th>
<th>Bone Morrow (cSv)</th>
<th>Eye (cSv)</th>
<th>Skin (cSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-day Exposure</td>
<td>25</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Annual</td>
<td>50</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Career</td>
<td>50-300</td>
<td>400</td>
<td>600</td>
</tr>
</tbody>
</table>

TABLE II: Expected doses on the lunar surface with and without shielding (no nuclear power source assumed).

<table>
<thead>
<tr>
<th>Duration (days)</th>
<th>GCR (cSv)</th>
<th>SEP (cSv)</th>
<th>Mission (cSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.3/0.8</td>
<td>7.5/20.5</td>
<td>7.8/21.3</td>
</tr>
<tr>
<td>30</td>
<td>1.0/2.5</td>
<td>7.5/20.5</td>
<td>8.5/23.0</td>
</tr>
<tr>
<td>180</td>
<td>6.0/15.0</td>
<td>7.5/20.5</td>
<td>13.5/35.5</td>
</tr>
<tr>
<td>360</td>
<td>12.0/30.0</td>
<td>7.5/20.5</td>
<td>19.5/50.5</td>
</tr>
</tbody>
</table>

Use of regolith as a shield material in the presence of a small nuclear power source exposure of few cSv/yr

In-Space expected levels and limits
GCR near Earth: Interactions

Atomic and nuclear reactions of GCR with various media produce a host of secondary products. These reactions and products depend on many factors including GCR intensity, media properties, and atomic and nuclear physics parameters. A good amount of needed basic nuclear physics information is largely based on models. Most of these reactions can still be simulated with reasonable accuracy, except when it comes to radiobiological effects perhaps.
Space Radiation at Marshall

- Monitoring & Detection
  - protons- TaSEPS
  - neutrons- ANS

- Forecasting
  - Mag4

- Modeling & Simulation
  - Geant4-based

- Radiation-Smart Structures
  - Geant4-informed

Bastille Day (2000 July 14) Flare, Coronal Mass Ejection and Solar Energetic Particle Event
A Physicist’s View of Basic Processes

Particles & Fields

é and some rules!
Marshall scientists and engineers develop state-of-the-art charged particle and neutral particle detectors suitable for the harsh environments of space.

-Trapped and Solar Energetic Particle Spectrometer (TaSEPS): TaSEPS is a compact wide dynamic range charged particle spectrometer for measuring trapped and solar energetic protons by combing scintillation and Cherenkov techniques in a single CsI crystal that extends the dynamic range and reduces the mass and power requirements.

Planned for a balloon flight.
GCR near Earth: Solar Cycle Dependence
Marshall scientists and engineers develop state-of-the-art charged particle and neutral particle detectors suitable for the harsh environments of space:

**Advanced Neutron Spectrometer (ANS):** is a new instrument technique being developed to meet NASA’s requirements to monitor the radiation exposure due to secondary neutrons for future crewed missions. New instrument designs are needed to achieve the measurement performance requirements that fit within the resource limits of exploration missions beyond Earth’s protective magnetic field.

\[
\begin{align*}
    n + ^6\text{Li} &\rightarrow ^3\text{H} + ^4\text{He} \\
    Q &= 4.78 \\
    n + ^{10}\text{B} &\rightarrow ^7\text{Li} + ^4\text{He} \\
    Q &= 2.73 \text{ (93%)} \\
    &\quad \text{or} \quad 2.25 \text{ (7%)}
\end{align*}
\]

Plastic and Li-Gd-B scintillator

Planned for an ISS flight demonstration
Marshall scientists and engineers developed an automated prediction system that downloads and analyzes magnetograms from the HMI (Helioseismic and Magnetic Imager) instrument on NASA SDO (Solar Dynamics Observatory), and then automatically converts the rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events.

[Present cadence of new forecasts: 96 min; Vector magnetogram actual cadence: 12 min]

When the transverse gradient of the vertical (or line-of-sight) magnetic field is large, there is more free-energy stored in the magnetic field.

For each Active Region:
- The integral of the gradient along the neutral line is the free-energy proxy.

A magnetogram of an active region on the Sun.
Mag4: A Comparison of Safe and Not Safe Days

June 26, 2013
C1, C1.5 flares

March 7, 2012
X5.4, X1.3, C1.6
CME 2684, 1825 km/sec,
Solar Energetic Proton Event reaches
6530 $\phi$ particle flux unit $\geq$ 10 MeV
Marshall scientists and engineers use Geant4 for the design, analysis, and development of

*particle detector systems*
*exposures at accelerators and in-situ*
*dose estimates*
*shielding solutions*

Marshall scientists and engineers collaborate with experimental and theoretical and computational groups at Oak Ridge National Laboratory, Berkeley's Lawrence National Laboratory, Brookhaven National Laboratory, Indiana University's Cyclotron Facility, Japan's HIMAC facility, and others for basic and applied nuclear modeling, simulation, and exposure and shielding studies.
Marshall managed HEDS’ Space Radiation Shielding Project (SRSP) and ETDP’s Advanced Avionics and Processor Systems (AAPS) Project. Under these two radiation projects:

- Marshall developed the first generation of multi-functional shielding materials
- Marshall managed all accelerator-based testing of shielding materials
- Marshall managed the acquiring of basic nuclear-physics data needed for shielding and exposure risk assessment studies
- Marshall also developed a unique, sophisticated online simulation tools to reliably gauge the radiation effects on electronics (Crème-MC)

Virtual Irradiation Capabilities of Crème-MC
Complex geometry and material composition - in the presence of known physical uncertainties - are expected to produce sizable errors in any radiation protection solution.

A 2-D illustration:
Space Radiation: Modeling & Simulation

A 3-D illustration:

Unlikely?
Radiation-Smart Structures and Designs?

A: Adaptive Structures
B: Sensory Structures
C: Controlled Structures
D: Active Structures
E: Intelligent Structures
Smart Materials: Multi-functional

Smart Designs: Optimized

radiation shielding will most likely focus on MMOD shielding materials and core
Space Radiation: Contour-crafting technology

- A new technology (developed at the University of Southern California) for robotic and autonomous construction; allows for versatile design options & construction materials
- Current capabilities (at USC and MSFC) are for small structures only
- Current R&T efforts to improve TRL and space and terrestrial applicability (NIAC)
- Large-scale demonstration of the new technology just started
- Space applications focusing on remote lunar base construction, MMOD and radiation protection solutions
- Terrestrial applications for forward construction capability for military and for rapid, disaster relief efforts (FEMA)
NASA in collaboration with DoD, academia, and the private sector is embarking on a new and radical way in looking at the challenges and solutions of space-radiation exposure; from the ‘grounds-up’!

Marshall is at the heart of this ‘new paradigm’ shaping

Space-radiation protection solutions and strategies have evolved on many paths, but they may be converging on few?