Towards Radiation-Smart Structures and Designs

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Way Points

- Space Radiation  
  understanding the problem
- Few things about cosmic rays  
  from the problem solver perspective
- Few things about cosmic rays  
  from the astrophysicist perspective
- Space Radiation  
  engineering the solution

...if you have a question, please do interrupt me and ask...
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!
Space Radiation: What is it and why a problem?

The Problem

Â 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.

Â From space physics and from 50 years plus of space-based observations, we now know that Galactic Cosmic Rays (or GCR) and Solar Energetic Particles (SEP) are the two main sources of this high-level of so-called ionizing radiation but there are challenges!

The Challenges

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

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

Â Little data to guide dose and risk assessment models.

Â Known, large uncertainties and variabilities in radiobiological effects.

Â Other uncertainties and variabilities? (e.g., in generalization and scale-up of shielding or protection solutions).
Space Radiation: Natural Sources

Two main sources of ionizing radiation:

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

- **Solar Energetic Particles (SEP):**
  - Mostly protons
  - High intensity (~ $10^7$)
  - Lower energy (~ 100–200 MeV)
  - Random Directional
  - Space Radiation: Natural Sources
The radiation quality factor (or $Q'$ factor) is introduced to differentiate the radiobiological effects due to different radiation sources at the same energy.

Large uncertainties and variabilities in the radiation quality factor is seen as a main hindrance toward reliable dose and risk estimates.

These variabilities can be simulated (i.e., Monte Carlo-ed) or captured analytically using stochastic analysis tools.
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:
Others

A 3-D illustration:

Unlikely?
“Toyota recall might be caused by cosmic rays”

I have harnessed the cosmic rays and caused them to operate a motive device.

Some scientists and engineers as well as auto industry experts believe Toyota’s microprocessors, software and memory chips are more vulnerable to interference from radiation than others because of their advanced design.

Even less advanced microelectronics are known to be sensitive to radiation: Passage of energetic charged particles through sensitive volumes can lead to either physical damage of the device or change in its logic state—so-called soft errors.

Nikola Tesla
1856-1943
“Varying cosmic-ray flux may explain cycles of biodiversity”

By Bertram Schwarzschild, Physics Today

October 2007
GCR near Earth: Observed Spectra

The ubiquitous Zipf-Pareto (power-law) distributions?
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 and acceleration at their source(s).
GCR near Earth: Modulation by the Sun

Heliospheric magnetic field is altered significantly between quiet Sun (Solar minimum) and active Sun (Solar maximum) conditions.

Simplified models can capture this variation with a single ‘modulation parameter.’
GCR near Earth: Solar Cycle Dependence
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!
TABLE I: 1999 NCRP-recommended dose limits by organ and exposure duration.

<table>
<thead>
<tr>
<th>Limit (cSv)</th>
<th>Bone Marrow</th>
<th>Eye</th>
<th>Skin</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>

Surface expected levels vs. recommended limits

Distribution of terrestrial exposure of few cSv/yr
Typical Expected Dose levels: Mars Mission

Nominal risk is 3%

<table>
<thead>
<tr>
<th>Effective dose (cSv)</th>
<th>Risk of exposure-induced death, with uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35-year-old male</td>
</tr>
<tr>
<td>Ares I</td>
<td>30</td>
</tr>
<tr>
<td>Ares II</td>
<td>55</td>
</tr>
<tr>
<td>Ares III (crew)</td>
<td>72</td>
</tr>
<tr>
<td>Ares III (Watney)</td>
<td>41</td>
</tr>
</tbody>
</table>

From: "The Radiation Threat to the Martian" by R. Turner; http://www.anser.org/docs/The_Radiation_Threat_to_the_Martian.pdf
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!

Recall, $1^2 + 1^2 + 1^2 + \ldots + 1^2$ (26 times) is $< 26^2$
A Physicist’s View of Basic Processes

Particles \& Fields

\textit{plusé some (or sum, \&)} rules!
A Glimpse of Cosmic Rays Astrophysics

Origin of cosmic rays:
- supernovae remnants & ISM matter
- explosive nucleosynthesis:
  - H, He, and CNO burning cycles,
  - e- , r- , and s- processes;
  - nuclei heavier than Ni are unstable
  - stable ones (e.g., Fe) can be accelerated

Acceleration of cosmic rays:
- differentiation (ionization potential, volatility);
- supernovae shock (energetic, diffusive);
- First-order Fermi acceleration (turbulence)

Transport of cosmic rays:
- diffusive – tied to the galactic magnetic field
- propagation effects (re-acceleration; spallation reactions; radioactive decay…)

Modulation of cosmic rays:
- cyclic (dynamically coupled to the heliosphere);
- minor energy loss

Atomic number (Z) modulation of cosmic rays:

assiopeia A
SCO OB2

WSU; March 30, 2016
Theoretical Framework

Ginzburg-Syrovatskii Equation:

\[ \frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i} \left[ \kappa_{ij} \frac{\partial f}{\partial x_j} \right] - U_i \frac{\partial f}{\partial x_i} + \frac{1}{3} \frac{\partial U_i}{\partial x_i} \frac{\partial f}{\partial \ln(p)} + Q \]

-This equation is the basis of most theoretical/computational work on cosmic rays transport and acceleration

-It is a statistical (kinetic) description for isotropic distribution functions

-It applies to energetic particles whenever their speed >> Alfvén speed, if scattering (diffusion) is faster than macroscopic timecales

-Usual: **Without a theory the facts are silent.** - F.A. Hayek

and plasmas
GCR Acceleration

Fermi Second-Order Acceleration Mechanism


Collisions between an already energetic particle and a moving, massive cloud will on average result in an increase in the particle's energy according to:

\[
\frac{\langle \Delta E \rangle}{E} \propto \left( \frac{V}{c} \right)^2 \implies \frac{dE}{dt} = rE \implies f(E) \propto E^{-\eta}; \quad \eta = 1 + (r \tau)^{-1}
\]

Problem is that the rate of energy increase is too small!

The great tragedy of science is the slaying of an elegant theory by ugly facts. – Thomas Huxley
Fermi First-Order Acceleration Mechanism


Energetic particles are accelerated by a passing shock as they scatter and get isotropized in the turbulence before and ahead of the shock,

\[
\frac{\langle \Delta E \rangle}{E} \propto \left( \frac{V}{c} \right)^1
\]

\[
f(E) \propto E^{-2}
\]

All the richness in the natural world is not a consequence of complex laws, but arises from the repeated applications of simple laws.

-L.P. Kadanoff
GCR Acceleration

Diffusive shock acceleration (DSA) theory:

\[
\frac{\partial f}{\partial t} = \frac{\partial}{\partial x} \left[ \kappa(x, p) \frac{\partial f}{\partial x} \right] - u \frac{\partial f}{\partial x} + \frac{1}{3} \frac{\partial u}{\partial p} \frac{\partial f}{\partial p}
\]

\[
f(p, t) \bigg|_{x=0} \propto \left( \frac{p}{p_0} \right)^q \cdot \int_0^t \psi(t', p, p_0) Q(p_0, t - t') dt'
\]

\[
\langle t \rangle = \int_0^\infty t \phi(t) dt ; \quad \frac{\sigma^2(t)}{\langle t \rangle^2} \sim \alpha ; \quad \kappa \propto p^\alpha
\]

Only for \( \alpha \approx 0 \) is the accel.-time PDF sharp; \( \alpha \) is typically 1/4 to 1/2.

DSA: No characteristic acceleration time!
Anomalous Transport

**Brownian Motion in 2D**
Gaussian statistics; central limit theorem; well-behaved PDFs

**Continuous Time Random Walk**
Non-Gaussian statistics; generalized transport equation; fractional derivatives; PDFs with long (algebraic) tails!

Space Radiation at Marshall

- Monitoring & Detection
  - charged particles;
  - neutrons

- Forecasting
  - flares; CMEs

- Modeling & Simulation
  - propagation; effects; risk

- Radiation-Smart Structures Solutions

Bastille Day (2000 July 14) Flare, Coronal Mass Ejection and Solar Energetic Particle Event
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:

\[
\begin{align*}
\text{n} + ^6\text{Li} &\rightarrow ^3\text{H} + ^4\text{He} \\
\text{Q} & = 4.78
\end{align*}
\]

\[
\begin{align*}
\text{n} + \text{Gd} &\rightarrow \text{Gd}^* + \gamma \\
\text{Q} & = [0,2]
\end{align*}
\]

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

Plastic and Li-Gd-B scintillator

Planned for an ISS flight demonstration in 2017
**Mag4:** Marshall 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.

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
Radiation-Smart Structures and Designs

A: Adaptive Structures
B: Sensory Structures
C: Controlled Structures
D: Active Structures
E: Intelligent Structures
Radiation-Smart Structures and Designs

Smart Materials: Multi-functional

Smart Designs: Optimized

radiation shielding will most likely focus on MMOD shielding materials and core
Prototyping radiation-smart designs

- **Contour Crafting**: A new technology developed at the University of Southern California for robotic and autonomous construction; allows for versatile design options & construction materials

- 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 ûup! 

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

- Space-radiation protection solutions and strategies have evolved on many paths—é but they may be converging on a few!
Where to go for more info…

- NASA HQ and centers' websites all have lots of information and leads; for example:
  - http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html

- University physics, geophysics, astronomy departments; for example:
  - http://www.srl.caltech.edu/

- National laboratories; for example:

- Other space agencies; for example:
  - http://www.esa.int/esaSC/index.html

- Professional societies for example:
  - http://cosparhq.cnes.fr/