Spacecraft Radiation Shielding by a Dispersed Magnetic Field Array

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Spacecraft Radiation Shielding Using Dispersed Superconducting Loops

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Interplanetary Radiation Environment

**Galactic Cosmic Rays (GCRs)**
Isotropic and *constant*
1—1000 GeV
Protons $\leftrightarrow$ Fe

**Solar Particle Events (SPEs)**
Isotropic and *intermittent*
1—1000 MeV
protons, H, He, C, Si, Fe
Radiation Threat

Radiation Exposure Induced Death (REID)

NASA Standard of <3% increase (95% confidence)

Table 4-1. Example Career Effective Dose Limits in Units of milli-Sievert (mSv) for 1-year Missions and Average Life-loss for an Exposure-induced Death for Radiation Carcinogenesis (1 mSv = 0.1 rem)

<table>
<thead>
<tr>
<th>Age, yr</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>520 (15.7)</td>
<td>370 (15.9)</td>
</tr>
<tr>
<td>30</td>
<td>620 (15.4)</td>
<td>470 (15.7)</td>
</tr>
<tr>
<td>35</td>
<td>720 (15.0)</td>
<td>550 (15.3)</td>
</tr>
<tr>
<td>40</td>
<td>800 (14.2)</td>
<td>620 (14.7)</td>
</tr>
<tr>
<td>45</td>
<td>950 (13.5)</td>
<td>750 (14.0)</td>
</tr>
<tr>
<td>50</td>
<td>1,150 (12.5)</td>
<td>920 (13.2)</td>
</tr>
<tr>
<td>55</td>
<td>1,470 (11.5)</td>
<td>1,120 (12.2)</td>
</tr>
</tbody>
</table>
“The NASA PELs for fatal cancer risk may be exceeded for several lunar scenarios including a large SPE, cumulative career exposure, and mission length dependent on crew age and gender. In addition, the NASA PELs for fatal cancer risk are projected to be violated under all possible Mars scenarios at this time.”

-NASA Human Research Roadmap
Curiosity Rover

253-day cruise to Mars

SPEs

GCRs

Shortest round-trip: $660 \pm 120$ mSv

Fig. 1. Dose rates recorded in a silicon detector (black circles) and in a plastic scintillator (red circles) during the MSL’s cruise to Mars.
Why magnetic shielding?
**Threat Mitigation**

**Deal with consequences**
- Molecular/DNA level
- Enterade
- Not a “showstopper”

**Prevention**
- Absorption
- Deflect
Absorption - MaterialShielding

Secondary particles *increase* exposure

Top of the atmosphere

Proton collides with an atmosphere molecule.

Youngquist et al. (2014)

*Fig. 5. This plot shows the atmospheric radiation shielding function at the 06/09 solar minimum.*
Deflection - Mimic Earth's Shield
Magnetic Shielding
Previous Designs

Superconducting magnets attached directly to spacecraft


Drawbacks

- Thermal management of superconductors
- Danger of quench in proximity of habitat
- Hinders EVAs
- Re-designing Orion

Increase of secondary radiation! (Vuolo et al. 2014)
New Concept
New Concept

GCRs

Protected Volume

Magnetic Fields
Goals

1. Optimize Design
2. First approximation
3. Good News
4. Great News
5. Bad News

Better solution?
Create Isotropic Environment

$-1 < \cos \theta < 1$

$0 < \phi < 2\pi$
Equation of Motion

\[
\frac{d\vec{u}}{dt} = \frac{300}{E_n[\text{MeV}]} \frac{Z}{A} (\vec{u} \times \vec{B}[T])
\]

Energy space

Particle Advancement

\[
\begin{align*}
    u[n + 1] &= u[n] + a \cdot dt \\
    r[n + 1] &= r[n] + u[n + 1] \cdot dt
\end{align*}
\]

4th order Runge Kutta
Form of the Magnetic Shield

\[ B_x = \frac{Cxz}{2\alpha^2\beta\rho^2} \left[ (a^2 + r^2)E(k^2) - \alpha^2K(k^2) \right] \]

\[ B_y = \frac{Cyz}{2\alpha^2\beta\rho^2} \left[ (a^2 + r^2)E(k^2) - \alpha^2K(k^2) \right] \]

\[ B_z = \frac{C}{2\alpha^2\beta} \left[ (a^2 - r^2)E(k^2) + \alpha^2K(k^2) \right] \]

CIRCULAR CURRENT LOOPS

Exact magnetic field solutions outside conductor

(Simpson et al. 2001)

Remove particles that hit loops

Energy loss

\[ P = \frac{dE_n}{dt} = \frac{\mu_0 q^2 \gamma^6 \omega_0^2}{6\pi c} \left[ c^4 a' r^2 + |\vec{n} \times c^2 \vec{a}'|^2 \right] \]

\[ r_{cs} < R^2 + a^2 - 2a(R^2 - z^2)^{1/2} \]

\[ \mu = I A \]
High Temperature Superconductors

YBCO

\[ I = 300 \text{ A} \]
\[ J_e = 50 \text{ kA/cm}^2 \]
\[ T_c = 90 \text{ K} \]
\[ T_o = 40-50 \text{ K} \]

Loop dimensions

\[ r_{cs} = \sqrt{\frac{\mu}{\pi^2 a^2 J_e}} \]
\[ m = \frac{2\mu \rho}{a J_e} \]
Configuration

Sample Particle Tracks

Incident Particle Locations

Shield Loops

Spacecraft
Dispersed Shield – Large Loops

Shepherd & Kress (2007)

\[ \mu = 1.1 \times 10^{13} \, \text{A} \, \text{m}^2 \]

“Forbidden Zone”
Single Loop Simulations

1 GeV protons

$\mu = 5 \times 10^{11} \text{ A m}^2$

$^1\text{H} : 1\text{GeV}$

Distance (m)

Distance (m)
Single Loop Simulations

1 GeV iron nuclei

$a = 10 \text{ m}$
First Approximation

Two-loop magnetic “null”
Magnetic Field Environment

Deflect protons

Deflect iron nuclei
Simulations

Good news!
Diagnostics

Track
- Number of entering particles
- Total track length
Diagnostics

Total Particle Track Length

- Loop Offset Distance
- Protected Volume Distance

$L_{\text{tot}} ; \mu = 0.0 \text{ A m}^2$

$L_{\text{tot}} ; \mu = 5\times10^{11} \text{ A m}^2$
Particle Hits to Test Volumes

- Loop Offset Distance
- Protected Volume Distance

- Hits; \( \mu = 0.0 \ \text{A m}^2 \)
- Hits; \( \mu = 5 \times 10^{11} \ \text{A m}^2 \)

Diagnostics
## Diagnostics

### Protected Volume

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\mu$ (A m$^2$)</th>
<th>$n_{avg}$</th>
<th>% Reduction</th>
<th>$l_{tot-avg}$ (m)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>0</td>
<td>44 ± 0</td>
<td>–</td>
<td>290 ± 0</td>
<td>–</td>
</tr>
<tr>
<td>$^1$H</td>
<td>$5 \times 10^{11}$</td>
<td>22 ± 0</td>
<td>50 ± 0%</td>
<td>142 ± 1</td>
<td>51 ± 1%</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>0</td>
<td>55 ± 0</td>
<td>–</td>
<td>349 ± 0</td>
<td>–</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>$1 \times 10^{12}$</td>
<td>15 ± 0</td>
<td>73 ± 0%</td>
<td>100 ± 1</td>
<td>71 ± 1%</td>
</tr>
</tbody>
</table>

Great news!
# Superconducting Loop Properties

## Simulation Loops

<table>
<thead>
<tr>
<th>$\mu$ (A m$^2$)</th>
<th>$a$ (m)</th>
<th>$r_{cs}$ (m)</th>
<th>Mass (kg)</th>
<th>I (A)</th>
<th>$B_{max}$ (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{11}$</td>
<td>10</td>
<td>1.02</td>
<td>$1.84 \times 10^6$</td>
<td>$1.59 \times 10^9$</td>
<td>323</td>
</tr>
<tr>
<td>$1 \times 10^{12}$</td>
<td>10</td>
<td>1.44</td>
<td>$3.67 \times 10^6$</td>
<td>$3.18 \times 10^9$</td>
<td>559</td>
</tr>
</tbody>
</table>

## NASA SLS Block 2 Payload = 130,000 kg

## Alternative Loop Properties

<table>
<thead>
<tr>
<th>$\mu$ (A m$^2$)</th>
<th>$w$ ($\mu$m)</th>
<th>$J_e$ (A m$^{-2}$)</th>
<th>$r_{cs}$ (m)</th>
<th>Mass (kg)</th>
<th>I (A)</th>
<th>$B_{max}$ (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{11}$</td>
<td>3.50</td>
<td>$7.14 \times 10^9$</td>
<td>0.27</td>
<td>$1.26 \times 10^5$</td>
<td>$1.59 \times 10^9$</td>
<td>1068</td>
</tr>
<tr>
<td>$1 \times 10^{12}$</td>
<td>1.75</td>
<td>$14.29 \times 10^9$</td>
<td>0.27</td>
<td>$1.26 \times 10^5$</td>
<td>$3.18 \times 10^9$</td>
<td>2136</td>
</tr>
</tbody>
</table>
Optimization

1. “Decentralize” magnetic energy
   - more dispersed = more loops
2. Reduce overall loop $I, B, \text{mass}$
3. Maximize the use of “forbidden zones”

Further use of superconductors?
Superconductors in Space

- Superconducting magnetic energy storage (SMES)

- Docking and stability (magnetic levitation)

- Motors and MRIs
Charging Superconductors

Flux pumps

1. DC Motor
2. Rotor with Permanent Magnets (Red)
3. HTS Stator Loop With Soldered Joints
4. HTS Main Loop
5. Thermally Isolated Assembly
Conclusions

- Radiation mitigation is required for long duration exploration of space by humans

- Dispersed magnetic shield concept works, but needs optimization

- Synergistic combination of material shielding, magnetic shielding, and efficient propulsion
Thank You

orangewavedc@gmail.com
Thermodynamics

Cryogenic Select Surfaces

Reflects 99.9% solar irradiance

Transmits long infrared radiation from interior

Result: Cryogenic temperatures below 50K

\[ J = \sigma A (T^4 - T_0^4) \]

\[ \Delta E = C \Delta T + \sigma A (T^4 - T_0^4 ) \Delta t \]

Attenuation coefficient \( \alpha = \frac{J}{J_0} \)

\[ J = \frac{\Delta E}{\Delta t} \]

Limits of passive cooling

Youngquist & Nurge (2016)
Secondary Particle Threat

\[ \Omega_{PV} = \int F_\Omega d\phi \]
\[ \Omega_{PV} = \frac{A_{PV}}{r_{\text{off}}^2} \int d\phi \]
Other Solution?

In the absence of a radiation shield – reduce exposure time

Increase thrust!

\[ T = \dot{m} v_{ex} \]

What is the most efficient particle acceleration process in the solar system?
Magnetic Reconnection

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Toward laboratory torsional spine magnetic reconnection

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