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D. L. Chesny  
National Space Biomedical Research Institute (NSBRI)

S. T. Durrance  
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Spacecraft Radiation Shielding by a Dispersed Array of Superconducting Magnets

D. L. Chesny¹,²,³, S. T. Durrance¹, G. A. Levin¹, N. Brice Orange³

¹Florida Institute of Technology
²National Space Biomedical Research Institute
³OrangeWave Innovative Science, LLC
Interplanetary Radiation Environment

**Galactic Cosmic Rays (GCRs)**
- Isotropic
- 1—1000 GeV particles
- protons, H, He, C, O, Ne, Fe
- $Z = 1, 2, 6, 8, 10, 26$

**Solar Particle Events (SPEs)**
- Uni-directional
- 1—1000 MeV particles
- protons, H, He, C, Si, Fe
- $Z = 1, 2, 6, 14, 26$
Radiation Threat

Radiation Exposure Induced Death (REID)

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

Mean REID = 3.2%
95% Confidence Level = 10.5%
REID Probability = 10.5%

Equivalent Dose (Sv)

\[ H_T = \sum_{R} W_R \cdot D_{T,R} \]

Radiation (R) Weighing Factor
protons \( W_R = 2 \)
heavy nuclei \( W_R = 20 \)

Absorbed Dose in Tissue (T) by Radiation (R)
Measured in Gray (Gy)
1 Gy is the absorption of 1 J/kg
Previously Proposed Safeguards

Superconducting magnets attached directly to spacecraft

Shielding efficiencies: 90% for 1 GeV
57% for 2 GeV

Drawbacks
- Screen interior from field
- Thermal management
- Hinders EVAs
- Re-designing Orion


Magnetic Shielding
New Concept

Dispersed Array of Superconducting Magnetic Satellites

Exploit the Integral Field Parameter

\[ \int \vec{B} \times d\vec{l} \]

Small vs large deflections
**Code Formulation**

### Magnetic Dipole

\[
\vec{B}_{\text{dipole}} = \frac{\mu_0}{4\pi} \left( \frac{3\vec{r}(\vec{r} \cdot \vec{m})}{|\vec{r}|^5} - \frac{\vec{m}}{|\vec{r}|^3} \right)
\]

**Translation, Rotation, and Superposition**

**Equation of Motion**

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

\[
u[n + 1] = \nu[n] + a \cdot dt \\
r[n + 1] = r[n] + u[n + 1] \cdot dt
\]

**Plane of Solar System**

y towards spacecraft

Throw away regions of divergence
Effective Shields

Momentum “Maps”

Limit for small deflections

\[ \Delta \vec{p} \left[ \frac{\text{MeV}}{c} \right] = \frac{300Z}{A} \int \vec{B} \times d\vec{l} \]

\[ \Delta p_x = 300 \frac{Z}{A} \int (B_y dz - B_z dy) \]

\[ \Delta p_y = 300 \frac{Z}{A} \int (B_z dx - B_x dz) \]

\[ \Delta p_z = 300 \frac{Z}{A} \int (B_x dy - B_y dx) \]

For \( +y \) velocity charged particles in a magnetic field

\[ \Delta p_x = -300 \frac{Z}{A} \int B_z dy \]

\[ \Delta p_z = 300 \frac{Z}{A} \int B_x dy \]

How do different magnetic dipole configurations affect particle momenta?
Momentum Map

Single Dipole

\[ E_n = 1 \text{ MeV} \]
\[ m = \pi \times 10^4 \text{ A m}^2 \]
Momentum Map

4-dipole circle

4-dipole Circle momentum map - Protons
Shield Optimization

2D Gaussian fits
Superconducting Magnets

For $m=\pi \times 10^4$ Am$^2$ (20 cm radius loop) – 5.6 kg

High-temperature superconducting wires (YBCO coated conductors)

Critical temperature 90 K - operating temperature 40-50 K, maintained using sunshield, similar to JWST, or “Solar White” coating

Magnets operate in persistent mode.

A closed loop made out of coated conductor. An assembly of 100 loops.
Protected Volumes

Orion Multi-Purpose Crew Vehicle

Sphere of 5 m diameter

Deep-Space Habitat

Cylinder of 5 m diameter and 15 m length
Simulation – Single Dipole \( (m=\pi \times 10^4 \text{ Am}^2) \)

Orion Capsule

21 hits

No field

6 hits

\( E_n=1 \text{ MeV} \)

8 hits

\( E_n=10 \text{ MeV} \)

Protected Volume

Dipole Location \([0, 0, 0]\)
% Reduction = \frac{\text{No field hits} - \#\text{hits}}{\text{No field hits}}

### 1x resolution (21 hits)

<table>
<thead>
<tr>
<th>( E_n ) (MeV)</th>
<th>1</th>
<th>10</th>
<th>30</th>
<th>60</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi \times 10^3 ) A m(^2)</td>
<td>61.9</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>( \pi \times 10^4 ) A m(^2)</td>
<td>71.4</td>
<td>61.9</td>
<td>47.6</td>
<td>23.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>( \pi \times 10^5 ) A m(^2)</td>
<td>85.7</td>
<td>71.4</td>
<td>61.9</td>
<td>66.7</td>
<td>61.9</td>
<td>52.4</td>
<td>61.9</td>
<td>4.8</td>
</tr>
</tbody>
</table>

### 2x resolution (81 no field hits)

<table>
<thead>
<tr>
<th>( E_n ) (MeV)</th>
<th>1</th>
<th>10</th>
<th>30</th>
<th>60</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi \times 10^3 ) A m(^2)</td>
<td>60.5</td>
<td>14.8</td>
<td>7.4</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>( \pi \times 10^4 ) A m(^2)</td>
<td>65.4</td>
<td>60.5</td>
<td>51.9</td>
<td>24.7</td>
<td>14.8</td>
<td>12.3</td>
<td>11.1</td>
<td>9.9</td>
</tr>
<tr>
<td>( \pi \times 10^5 ) A m(^2)</td>
<td>71.6</td>
<td>65.4</td>
<td>65.4</td>
<td>64.2</td>
<td>60.5</td>
<td>59.3</td>
<td>58.0</td>
<td>14.8</td>
</tr>
</tbody>
</table>

### 3x resolution (177 no field hits)

<table>
<thead>
<tr>
<th>( E_n ) (MeV)</th>
<th>1</th>
<th>10</th>
<th>30</th>
<th>60</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi \times 10^3 ) A m(^2)</td>
<td>58.8</td>
<td>10.2</td>
<td>1.7</td>
<td>1.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>( \pi \times 10^4 ) A m(^2)</td>
<td>66.7</td>
<td>58.8</td>
<td>45.2</td>
<td>22.6</td>
<td>10.2</td>
<td>6.8</td>
<td>5.1</td>
<td>0.6</td>
</tr>
<tr>
<td>( \pi \times 10^5 ) A m(^2)</td>
<td>70.1</td>
<td>66.7</td>
<td>63.3</td>
<td>62.1</td>
<td>58.8</td>
<td>55.4</td>
<td>51.4</td>
<td>10.2</td>
</tr>
</tbody>
</table>
Simulation – Halbach Array

Deep Space Habitat

Halbach Array

Increased B energy

Decreased B energy

$E_n = 10 \text{ MeV}$

Halbach 5-dipole location

11 hits
Simulation Results – Halbach Array

\[ \% \text{ Reduction} = \frac{\text{No field hits} - \#\text{hits}}{\text{No field hits}} \]

1x resolution (75 hits)

<table>
<thead>
<tr>
<th>(E_n) (MeV)</th>
<th>1</th>
<th>10</th>
<th>30</th>
<th>60</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi \times 10^3) A m(^2)</td>
<td>64.0</td>
<td>5.3</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>(\pi \times 10^4) A m(^2)</td>
<td>85.3</td>
<td>64.0</td>
<td>34.7</td>
<td>17.3</td>
<td>5.3</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>(\pi \times 10^5) A m(^2)</td>
<td>94.6</td>
<td>85.3</td>
<td>77.3</td>
<td>66.7</td>
<td>64.0</td>
<td>50.7</td>
<td>46.7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Velocity Errors: \(1.002 \pm 0.020, 1.013 \pm 0.032, 1.052 \pm 0.078\)
Robust Simulations

**Plasma** – an electrically neutral collection of a large number of positively and negatively charged particles

For accurate description of shields, we must account for BOTH ions and electrons
Particle-in-cell Method

Ion charge density (C m\(^{-3}\))

Ion electric potential (V)

\[
\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})
\]
Particle-in-cell Method

Total Plasma Charge Density (C m\(^{-3}\))
From Idea to Mission

Increase **Technology Readiness Level (TRL)**

- Superconductors in Space
- Technology Demonstration
- On-board Control in Deep-space
Increase TRL

NASA Space Radiation Laboratory

Digital Beam Imager

PIC prediction
Superconductors in Space

Cryogenic Select Surfaces

Reflects 99.9% solar irradiance

Transmits long infrared radiation from interior

Result: Cryogenic temperatures below 50K
Technology Demonstration

Nanoracks CubeSat deployment

South Atlantic Anomaly

0.04 – 10 MeV inner Van Allen Belt particles
On-board, Deep-space Control

- Magnetic Shield Optimization -

Input:
- Solar Flare Class
- Solar Origin Coordinates

Process:
- Particle-in-cell Transport
- Shield Optimization

Output:
- Energy Spectra
- Shield Array Positions
- Shield Array Δρ

Visuals:
- Heliospheric current sheet
- Spacecraft with deployed shields
GCR Defense

For an isotropic distribution \( f(\vec{r}, \vec{p}) \) in a magnetic field,
a first-order perturbation \( f = f_0 + \sigma \) gives

\[
\vec{v} \cdot \frac{\partial \sigma}{\partial \vec{r}} = -(\vec{F} \cdot \vec{p}) \frac{\partial f_0}{\partial |\vec{p}|} \frac{1}{|\vec{p}|} = 0
\]

Evenly spherical distribution of dipoles

Create isotropic distribution
20-pt Buckyball Simulation

- Arbitrary number of particles per injection
- Arbitrarily narrow beam

Sphere of isotropic distribution

Protected Volume
GCR Deflection

E = 1000 MeV

Code validation run
Robust Simulations

Approximate GCRs with random distribution of input particles

$\cos \Theta \rightarrow 0, 1$
$\phi \rightarrow 0, 2\pi$
Results

GCR Deflection

Normalized Hits

Magnetic Moment (A m$^{-2}$)

- No field
- 8dp-Skyrmion Cube (100 off)
- 8dp-Two Circles (100 off)
- 20dp-6 Halbach (100 off)
- 20dp-Cage (100 off)

6-Halbach “cage”

20-dipole “cage”
Percent reductions in SPE radiation show **feasibility**

Existing technology shows **viability**
Fig. 13. Effective Dose Equivalent (milli-sieverts) in an astronaut as a result of extreme SPEs compared to the recommended ESA career limit for the four SPEs shown in Figure 9.

Jiggens, P., et al. (2014)
Consider 12 mm wide and 50 μm thick (no stabilizer) coated conductor.

Critical current at 77 K is 300 A. Lift factor at 50 K in 2 T field is about 2.

Then the critical current at 50 K is about 600 A.

We can take persistent current to be 50% of the critical.

Then, the engineering current density of persistent current is approximately

\[ J = 50 \text{ kA/cm}^2 \]

Consider a loop of 20 cm radius creating a dipole moment \[ d=\pi x 10^4 \text{ Am}^2 \].

This required current of 250 kA or 5 cm\(^2\) cross-section of the loop.
Enabling Technology

Mass density of Hastelloy (the substrate) is about 9 g/cm^3.

The total volume of a torus 20 cm in radius and 5 cm^2 cross-section is 630 cm^3.

The mass of the superconducting material then is 5.6 kg.

For greater or smaller dipole of the same size the mass is scaled proportionally.

Increasing the size of the loop decreases the required current and the amount of the superconducting material inversely proportional to the radius.

These estimates do not take into account the support structure, power supply, electronics, sunscreen, etc.