Progress Toward Electrostatic Radiation Shielding of Interplanetary Spacecraft

Strategies, Concepts and Technical Challenges of Human Exploration Beyond Low Earth Orbit

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Space Radiation: A Key Challenge

- We **cannot** explore the solar system until the space radiation problem has been solved

- Three principle sources of space radiation
Galactic Cosmic Radiation (GCR)

- Charged particles accelerated in the shock waves surrounding supernovae.
- Ever-present, low-level flux of high-energy particles.
- Large cumulative dose over the course of a mission.
- Penetrate our solar system isotropically.
Solar Particle Events (SPEs)

- Particles accelerated by solar phenomena
- Sporadic
- High flux when it does occur
- Lower-energy spectrum than GCR
- Approximately isotropic flux due to magnetic interactions in the solar system
2 Types of SPEs

• Impulsive
  – Occur over a period of several hours
  – Associated with Solar Flares

• Gradual
  – Occur over a period of several days
  – Associated with Coronal Mass Ejections

SOHO (ESA/NASA)
Coronal Mass Ejections

1999/08/01 00:18

SOHO (ESA/NASA)
Space Radiation Spectrum

Sporadic but extremely high flux when SPE occurs

Solar Particle Events

Cosmic Rays

Continuous, low-level flux → unacceptable mission dose

Ref. Silberberg et al., 1984
Planetary Radiation Belts

- Earth
- Jupiter and other giant gas planets
  - Significant radiation belts
  - Especially bad at Europa

Measured by Cassini spacecraft
Image courtesy JPL
Our Protection on Planet Earth

Global Magnetic Field

Thick Atmosphere

NASA/MSFC Space Plasma Physics (Adapted)
Effects in Spaceflight

• Biological Effects
  – Delayed: cumulative effects of total dose
  – Acute: immediate effects of intense exposure
    - A single SPE may be lethal

• Electronic Effects
Passive (Material) Shielding

• The most successful method, to date
• Foams or other materials on outside of spacecraft
• The spacecraft structure, itself
• Consumables placed strategically
  – food
  – drinking water
Passive Shielding, continued

- Problems
  - Spacecraft Mass may become excessive
  - Secondary radiation
  - Some radiation gets through, which is not acceptable during the high flux of SPEs

- "Storm-Shelter approach"
Problems with Storm Shelters

• Excessive time in cramped quarters
  – Gradual SPE may last 4 or 5 days
  – Psychologically and physically distressing

• Provides no protection for spacecraft electronics
  – May suffer irreparable damage resulting in eventual loss of mission and crew

• Crew unable to attend to the spacecraft
  – During the precise time when it needs the most attention (due to radiation effects)
  – May need quick response to manage spacecraft
Magnetostatic Shield

- Attempt to mimic the shielding due to Earth’s magnetic field
- Requires heavy, superconducting coils to produce sufficient magnetic field
- Hazard that coil could explode under the energy of the fields
- Better to use the mass of the coil as foam on the outside of the spacecraft
Electrostatic Shield
Multipole Expansions

- An arbitrarily-complex electric field can be described as an infinite sum of these terms.

Monopole  Dipole  Quadrupole  etcetera
Multipole Electrostatic Shield

- Each term in the multipole expansion falls off with respect to distance more quickly than the previous term
  - Monopole term dominates far away
  - Higher-order terms dominate in close
- Assign different functions to different terms
- Result: Spherical zones of protection to repel both protons and electrons
  - But no charges need to be physically deployed around the spacecraft
Positive barrier deflects protons

Negative barrier deflects electrons

Damaging high-energy protons kept out of this region

Vast quantities of low-energy electrons kept out of this region

\[ \Phi(x=\xi, y=\xi, z=\xi) \]
Diagram of Isotropic Radiation, Showing Initial State of Charged Particle.
A bunch of math...

\[ A_x = (c_{23}c_{33}E_x - c_{22}c_{33}E_y, c_{12}c_{33}E_y + c_{13}c_{22}E_x - c_{12}c_{23}E_z)Q \]
\[ A_y = (-c_{23}c_{31}E_x + c_{21}c_{33}E_x + c_{13}c_{31}E_y - c_{13}c_{21}E_z + c_{11}c_{23}E_z)Q \]
\[ A_z = (c_{21}c_{32}E_x - c_{13}c_{32}E_y + c_{12}c_{31}E_y + c_{12}c_{21}E_z - c_{11}c_{22}E_z)Q \]

\[ E(r) = \sum_{i=1}^{N} V_i R_i \frac{r - r_i}{|r - r_i|^3} \]
\[ \gamma \equiv (1 - v^2 / c^2)^{-1/2} \]

\[ \alpha = \begin{bmatrix} R_0 \sin \theta \cos \phi - R'_0 \sin \theta' \cos \phi' \\ R_0 \sin \theta \cos \phi - R'_0 \sin \theta' \cos \phi' \\ R_0 \cos \theta - R'_0 \cos \theta' \end{bmatrix} \]
\[ \beta = \begin{bmatrix} R_0 \sin \theta \sin \phi - R'_0 \sin \theta' \sin \phi' \\ R_0 \sin \theta \sin \phi - R'_0 \sin \theta' \sin \phi' \\ R_0 \cos \theta - R'_0 \cos \theta' \end{bmatrix} \]
\[ \gamma = \begin{bmatrix} R_0 \cos \theta - R'_0 \cos \theta' \\ R_0 \sin \theta \cos \phi - R'_0 \sin \theta' \cos \phi' \\ R_0 \sin \theta \sin \phi - R'_0 \sin \theta' \sin \phi' \end{bmatrix} \]
\[ r_0 = R'_0 \begin{bmatrix} \sin \theta' \cos \phi' \\ \sin \theta' \sin \phi' \\ \cos \theta' \end{bmatrix} \]
\[ v_0 = \frac{\sqrt{2T}}{m_0 c} \left( \sqrt{1 + \left( \frac{m_0 c^2}{T} \right)^2} - 1 \right)^{1/2} \]
Model Length Parameters

\[ \rho_0 = 10 \, [\text{m}] \quad D = 1.0 \, [\text{AU}] \]
\[ R_0 = 20 \, [\text{m}] \quad R_s = 695990.0 \, [\text{km}] \]

Charged Particle Energy

\[ E_0 = 33.0 \, [\text{keV}] \quad \sigma_{E} = 1.0 \, [\text{keV}] \]

Particle Composition

\[ N_e = 0 \quad N_p = 2 \quad N_n = 2 \]

Monte Carlo Parameters

\# of particles = 900 \quad \text{seed} = 425001

Classical / Relativistic Mechanics

- Relativistic Acceleration ON

Program Output Log

\[ v_0 = 0.00421 \quad [c] \quad \text{(initial particle velocity, fraction of } c\text{, corresponding to } E_0) \]
\[ q_0 = 2 \quad [q] \quad \text{(total number of unit charges on particle)} \]
\[ f_c = 3.77777 \quad [%] \quad \text{(total particle / sphere collisions)} \]
\[ f_t = 25.77777 \quad [%] \quad \text{(percentage of particles arriving inside } \rho_C \text{ sphere)} \]
\[ v_{\text{min}} = 0.00405 \quad [c] \quad \text{(minimum particle } v \text{ of all particles, as a fraction of } c) \]
\[ v_{\text{max}} = 0.00441 \quad [c] \quad \text{(maximum particle } v \text{ of all particles, as a fraction of } c) \]
\[ v_{\text{avg}} = 0.00421 \quad [c] \quad \text{(average particle } v \text{ of all particles, as a fraction of } c) \]

Run Status: Done Processing
\[ \Phi(x = \xi, y = \xi, z = \xi) \]

Positive barrier deflects protons

Negative barrier deflects electrons
Cutoff Energy

• All particles unable to get over the "hump" are deflected
  – The hump's magnitude is the cutoff energy

• Particles with energy above cutoff may strike the spacecraft
  – But many are turned slightly and therefore "miss" the spacecraft
  – The number that "miss" is a function of energy
Deflection of Over-Cutoff Particles
Above Cutoff Energy
Increased Penetration with Increased Particle Energy
Shield Efficiency as a Function of Particle Energy

Fraction Deflected

50 100 150 200 250 300 MeV
Space Radiation Spectrum

- Sporadic but extremely high flux when SPE occurs
- Continuous, low-level flux → unacceptable mission dose

Ref. Silberberg et al., 1984
Maximizing Cutoff Energy

• Geometry of Shield
  – Arrangement of Spheres
  – Bigger Spheres
  – More Spheres

• Higher Voltage!

Developing higher-voltage, space-based power supplies is the key technology challenge

These affect shielding efficiency, but not cutoff energy
Shield Efficiency
as a Function of Particle Energy

Fraction Deflected

A nominal shield configuration

Same shield configuration but double the voltages

MeV
Power Supplies

• Van de Graaf generators
  – 10 to 20 MV for particle accelerators
    • But very large!
  – 500 kV for inexpensive desktop versions
    • Limited by charge bleed-off into the atmosphere
Achievable Voltages

• Take advantage of the space environment
• No atmosphere
  – Breakdown voltage in space is 20 to 30 times higher than on Earth
  – *Should achieve 10 – 15 MV in space with a small power supply*
• No gravity or ground plane
  – Easier spatial arrangement
  – Daisy-chaining 7 – 10 small power supplies along an insulating truss can achieve over 100 MV
Integration with the Spacecraft

• Ion Thrusters
  – Ion exhaust cannot escape radiation shield
  – Incompatible with electrostatic shield!

• Strategy
  – Use passive shielding only, except during SPEs
  – Also use electrostatic shield in planetary orbit
Conclusion

• The radiation problem is a serious obstacle to solar system exploration
• Electrostatic shielding was previously dismissed as unworkable
  – This was based on the false assumption that radial symmetry is needed to provide isotropic protection
• KSC recently demonstrated the feasibility of asymmetric, multipole electrostatic shielding

• Combined with passive shielding it might solve the radiation problem