Radiation exposure and mission strategies for interplanetary manned missions and interplanetary habitats

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Spectra of energetic c-rays (indicative)

Solar Wind (flux = $10^{16}$ flux$_{GCR}$)

SCR (flux$_{max}$ = $10^6$ flux$_{GCR}$)

GCR (ACR)

Dangerous

Sporadic, unpredictable

Mainly protons

Penetrating SS from outside

$\approx$ constant flux

Mainly protons

Comparison purpose
We are protected from GCR by:

At 1 AU (Earth orbit) by solar magnetic field (solar wind) $10^{-1} \ @ \ 1\text{GeV}$
$10^{-2} \ @ \ 500\text{ MeV}$

Near the Earth (about 10 R$_{\text{Earth}}$) by terrestrial magnetic field $10^{-1} \ @ \ 1\text{GeV}$
At 45º latitude

On the Earth surface by the Earth atmosphere a further $10^{-2} \ @ \ all\ latitudes$
Showers of CR in the atmosphere

- Outside of the atmosphere
- Top of the atmosphere (ballooning ≈ 40 km)
- 10 km on the sea level
- 4 km on the sea level

Energy of the primary CR (90% p, 9% Nuclei, <1% e,γ)

- ≈ 1 GeV
- ≈ 1 TeV
- ≈ 1 PeV
- ≈ 1 EeV
- ≈ 1 PeV

Showers of CR (x10^{-6} of bulk)

1 GeV (bulk)
depth through atmosphere gr/cm²

Km above the sea level

particles/(m² s sr)

10
100
1000

primary (≈ p)

soft (≈ e)

hard (≈ μ)

soft n

soft p

π

≈ x 10⁻²

2720 K

≈ x 10⁻²
Shielding in space is problematic:

**Passive shielding** (absorbers)
- enough for SCR (but huge masses needed)
- GCR very penetrating
- absorbers inefficient (secondary production)

**Active systems** are necessary for
- long duration manned missions
Active protection from CR: historical introduction

60s → 90s  several ideas were considered, no technical projects (mainly in USA) (URSS: some work on superconductivity in space).

(1985-90  two feasibility study of the ASTROMAG facility for CR on board of the Freedom SS.)
2000 review of available techniques and optimization of the working point for superconducting magnets for space applications

(INFN-Milan (L.Rossi and L. Imbasciati))

2002-2004 ESA international **Topical Team** on “Shielding from the cosmic radiation for interplanetary missions: active and passive methods”

2003-2004 WP “Review and development of active shielding concepts” of the contract **REMSIM** (Radiation Exposure and Mission Strategies for Interpl. Manned Missions)

ESA-Alenia (+EADS Astrium, REM, RxTec, INFN).
Continuous cylindrical conductor

Lumped conductors

Inside: \( B = 0 \)

Outside: \( B = 0 \)

Electric current: \( B \propto \frac{1}{R} \)

\( R_1 \) to \( R_2 \)
'Shelter' (Φ=2m, length 3m): shield masses for H₂O & Toroid

- H₂O
- Toroid R²=3m cold mass
- Toroid R²=3m envisaged total mass
- Toroid R²=3m maximum total mass

Hp:
NbSn sc cable Al sabilized
sc cable current ≤500 A/mm²
CFSM (cryocoolers)
Fig. 6.14 - Toroidal shelter (Ø 2m, length 3m) integrated in the habitat scheme of the AURORA CDF concept. At the outer diameter the electric current can be supposed to be returned by a few conductors.
'Habitat' (Φ=4m, length 5m):

$H_2O$ & Toroid shield masses

- H2O shield
- Toroid R2=4m cold mass
- Toroid R2=4m envisaged total mass

Hp:
- NbSn sc cable Al sabilized
- sc cable current ≤500 A/mm2
- CFSM (cryocoolers)
The studies of the past must be updated for several reasons:

Realization and operation of **huge volume and stored energy superconducting magnets** for elementary particle physics experiments

Remarkable technical developments of **high temperature superconductors** (in particular MgB2 material) and of the **cooling technique** (cryocoolers for the N2 shielding of AMS-2)

Future missions will be more and more addressed to the use of **space as a ‘forth dimension’**, such as a collective property for implementing services of economical and social benefit involving more and more **private investments**, with the Space agencies supplying the needed technical competences, guaranties and controls in conformity with the political indications of the respective governments
Signals in this direction:

First instances of space tourism

Successes of the SpaceShipTwo private spacecraft

Studies for the use of Moon for extraction of useful materials (e.g. He3)

Studies for the ‘production’ of large quantity of water on the Moon

‘MoonBase’ initiative activities

Awareness of the importance of using the Lagrange points for achieving scientific results and for supporting commercial activities (e.g. L1 for Moon, and Space Highways for transfer of materials)
Expected evolution of human presence in space:

- Space Stations → astronauts
- Space bases → astronauts and specialized personnel
- Space ‘complexes’ → astronauts, specialized personnel and common citizens
further step in GCR protection:

Long permanence in ‘deep’ space
not only
for a relatively small number of astronauts
but also
for citizens conducting ‘normal’ activities

Minimum basic assumptions for the ‘habitat’:

Volume to be protected: $\varnothing \geq 6m$, $L=10m$
Shroud of the transportation system: $\varnothing 10m$, $L>16m$
\[ B(R) = \frac{B(R_1) \times R_1}{R} \]

- **Shielded volume**
- **Transverse section**
- **Longitudinal section**
- L ≈ 16–20 m
- R₁, R₂
- B⁺, B⁻
p flux with H2O and toroidal cuts

GCR: dose reduction between absorber cut and toroid cut 28%
galactic proton flux in the 'habitat' (R1=3m, R2=5m)

- Flux [p/(cm²s·MeV)]
- KE [MeV]

<table>
<thead>
<tr>
<th>R1=3m R2=5m B1=0T</th>
<th>R1=3m R2=5m B1=1T</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1=3m R2=5m B1=2T</td>
<td>R1=3m R2=5m B1=4T</td>
</tr>
<tr>
<td>R1=3m R2=5m B1=6T</td>
<td>R1=3m R2=5m B1=8T</td>
</tr>
</tbody>
</table>

GCR dose (Gy) reduction

- 15% 34% 59% 75% 80% 85%
Technological criteria

- **Cryogen Free** Superconducting Magnet → *cryocoolers*

-‘ideal cable’ for space applications (Turin university + Alenia)  
  *thin MgB2 cable* produced by the in-situ method in a titanium sheath stabilized outside in aluminum:

- Medium operating temperature (20k)
- Low density (3 g/cm3)
- Small section: cables less suffering current and temperature instability, and distributing current in the surrounding cables in case of bad functioning.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Averaged density</td>
<td>2.96 g/cm³</td>
</tr>
<tr>
<td>Diameter of the cable</td>
<td>200 μm</td>
</tr>
<tr>
<td>Section of MgB2</td>
<td>6.28×10⁻³ mm²</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>20 K</td>
</tr>
<tr>
<td>Critical current at 2 T</td>
<td>1.3×10³ A/mm²</td>
</tr>
</tbody>
</table>

MgB₂ ≈ 20 %  
Ti ≈ 25 %  
Al ≈ 55 %
Cold mass for current density in sc cable 1kA/mm² @ 2T
Minimum basic assumptions for the ‘habitat’:

Volume to be protected: $\Omega \geq 6\, \text{m}$, $L=10\, \text{m}$
Shroud of the transportation system: $\Omega \, 10\, \text{m}$, $L>16\, \text{m}$

However:

deployment of return current circuit
must be considered
from the very beginning
- in a **toroidal configuration** the field diminishes at the increasing of the radius, making easier to support the ponderomotive forces.
- the outer part of the system must be **deployed or assembled** in space.
Basic philosophy for the ‘Space Complex’:

All the modules linked to the protected ‘habitat’
Protected ‘habitat’ can be reached in a few minutes
from any point of the Space Complex
‘Habitat’ fully protected from SCR’s.
‘Habitat’ guaranties a factor 5 reduction of GCR dose @ solar minimum

Furthermore:

Journeys during periods of maximum solar activity
Long permanences (>1 year) during periods of maximum solar activity
Cross section of the habitat protected against SCR and GCR

Units protected only against SCR events

Communication tunnels

Cross section of the habitat protected against SCR and GCR
Shelters against SCR events
Conclusions

An adequate protection from GCR to a large human community in space is a complex problem, which can be solved in an adequate time provided that a long program of study and R&D will be set up in due time and with the due resources.

It is therefore urgent a professional approach toward the study, project, realization and test of materials, mechanisms, systems, and finally ‘space demonstrators’, and their integration in manned exploration programs.

Furthermore protection from CR is
- a ‘niche’ where physicists can contribute
- an occasion of collaboration between labs and space agencies
- new technologies to be developped for space propulsion
  (magnetic lenses to control divergence and density of charged material for real-time control of thrust and direction, to concentrate it in small volume for further acceleration, magnetic bottle for suitable reactions, etc..)