Biological Effects of Space Radiation

Honglu Wu
Outline of the presentation

• Brief introduction to the space radiation environment
• Space radiation health risks
• Challenges in radiation countermeasures
• Biodosimetry analysis
Space Radiation

- Space radiation consists of energetic charged particles (atoms with all of the electrons stripped)

- Astronauts are exposed to secondary neutrons as well
Representation of the major sources of ionizing radiation of importance to manned missions in low-Earth orbit. Note the spatial distribution of the trapped radiation belts.
Trapped Radiation (Van Allen Belt)

James Van Allen (1914 - )

Energy spectrum of trapped protons
Galactic Cosmic Radiation (GCR)

![Birth of a Neutron Star and Supernova Remnant](image)

**Figure D.1. Abundances (a) and Energy Spectra (b) of GCR**

- **Relative Abundance**
  - Atomic Number $(Z)$
  - Elements: C, O, Mg, Ne, Si, Fe

- **Differential Flux $(m^{2}\cdot s^{-1}\cdot sr^{-1})$**
  - Kinetic Energy $(MeV/Nucleon)$
  - Elements: H, He, C, Fe
Solar Particle Event (SPE)

Sunspot Activity vs. Solar Flare Proton Flux
D.S. Nachtwey, NASA Johnson Space Center

Space Radiation Environment
(Courtesy of NASDA)
Secondary Neutrons
Summary of the Space Radiation Environment

- Major sources: Trapped protons, GCR, solar particle events
- Radiation type: Protons and heavy ions (high-LET), and secondary neutrons
- Dose rates vary from low (Trapped protons and GCR) to intermediate (SPE)
- Small amount of X-rays and gamma rays
- Ultraviolet radiation
Definitions

- **Absorbed dose:** The energy imparted per unit mass by ionizing radiation to matter at a specified point. The SI unit of absorbed dose is the joule per kilogram. The special name for this unit is the Gray (Gy).

- **Equivalent dose:** A quantity used for radiation protection purposes that takes into account the different probability of effects that occur with the same absorbed dose delivered by radiations with different radiation weighting factors. Effective dose is measured in Sv.

- **Linear energy transfer (LET):** The amount of energy deposited by radiation per unit length of travel, expressed in keV per micron. High energy gamma, x-rays or light charged particles have low LET values, whereas heavy charged particles have high LET values.

\[ H = D \cdot Q(\text{LET}) \]
Acute radiation syndrome
(Acute whole body dose > 50 cSv)

- Vomiting
- Diarrhea
- Reduction in the number of blood cells
- Bleeding
- Hair loss
- Temporary sterility in males
- Lens opacity
- Others
Radiation in Daily Life

- Living in Houston for one year: 0.09 cSv/yr
- Living in Denver for one year: 0.3 cSv/yr

<table>
<thead>
<tr>
<th>Radiation source</th>
<th>Dose (cSv/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation dose in Guaraparí (Brazil) per year</td>
<td>~10,000 μSv/year</td>
</tr>
<tr>
<td>Space</td>
<td>0.39</td>
</tr>
<tr>
<td>Ingestion</td>
<td>0.29</td>
</tr>
<tr>
<td>Earth</td>
<td>0.48</td>
</tr>
<tr>
<td>Radon absorbed in air</td>
<td>1.25</td>
</tr>
<tr>
<td>Natural radiation average</td>
<td>5 cSv/yr</td>
</tr>
<tr>
<td>Maximum difference of the average of natural radiation dose in each prefecture</td>
<td>~2,400 μSv/year</td>
</tr>
<tr>
<td>An air travel between Tokyo and New York (RT)</td>
<td>~200 μSv/round trip</td>
</tr>
<tr>
<td>Evaluated dose of radiation from radioactive substance emitted from the nuclear fuel reprocessing plant per year</td>
<td>22 μSv/year</td>
</tr>
<tr>
<td>Standard radiation dose from Clearance level</td>
<td>10 μSv/year</td>
</tr>
<tr>
<td>Chest CT scan</td>
<td>6,900 μSv/each time</td>
</tr>
<tr>
<td>Dose limit for public per year (except for medical care)</td>
<td>1,000 μSv/year</td>
</tr>
<tr>
<td>Gastrointestinal X-ray examination</td>
<td>600 μSv/each time</td>
</tr>
<tr>
<td>Chest X-ray examination</td>
<td>50 μSv/year</td>
</tr>
<tr>
<td>Standard dose of radiation around a nuclear plant (light water reactor)</td>
<td>50 μSv/year</td>
</tr>
</tbody>
</table>
Doses Received from Spaceflight

Figure 4-7. Summary of mission personnel dosimetry from all past NASA crews (Cucinotta et al., 2008). Effective dose and population average biological dose-equivalent for astronauts on all NASA space missions, including Mercury, Gemini, Apollo, Skylab, Apollo-Soyuz, space shuttle, shuttle-Mir, and ISS missions.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Altitude (nm)</th>
<th>Inc. (deg)</th>
<th>Duration (days)</th>
<th>Dose (cSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-94</td>
<td>160</td>
<td>28.5</td>
<td>15.7</td>
<td>0.27</td>
</tr>
<tr>
<td>STS-95</td>
<td>310</td>
<td>28.5</td>
<td>8.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Cucinotta, HRP Evidence Book
Space Radiation Health Risks

**Carcinogenesis** -- Increased cancer morbidity or mortality risk in astronauts may be caused by occupational radiation exposure

Low-LET -- Atomic bomb victims

High-LET – Miners exposed to alpha particles

Preston et al. 2003
Cucinotta, Evidence book

Lubin et al. 1995
## Evidence from spaceflight??

<table>
<thead>
<tr>
<th>Category</th>
<th>NASA January 1959-Feb 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft Accidents</td>
<td>14</td>
</tr>
<tr>
<td>Non-Spacecraft Accidents</td>
<td>12</td>
</tr>
<tr>
<td>Cancer</td>
<td>9</td>
</tr>
<tr>
<td>Circulatory Disease</td>
<td>5</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>44</strong></td>
</tr>
</tbody>
</table>

Cause of death of astronauts; Data from Mary Wear
• **Acute and late CNS risks** -- Acute and late radiation damage to the central nervous system (CNS) may lead to changes in motor function and behavior, or neurological disorders.

Budinger, Lyman and Tobias 1972

![Light flash forms](image)

**Light flashes**
• **Chronic and degenerative tissue risks** -- Radiation exposure may result in degenerative tissue diseases (non-cancer or non-CNS) such as cardiac, circulatory, or digestive diseases, as well as cataracts.

**FIG. 2.** Cumulative cataract rates (see text) for cataracts of grade 2 at 67 weeks postirradiation. □, X rays; ▲, iron ions. The lines joining the points are to guide the eye only.

Cucinotta et al. 2001

- Acute radiation risks -- Acute radiation syndromes may occur due to occupational radiation exposure

Intermediate dose rate
Kim et al. 2006

- Prodromal effect
- Skin damage
- Fatigue
- Immune function
Goals

- What are the risks from exposure to space radiation?
  - Radiation quality, dose and dose rate
  - Other spaceflight factors

- How to reduce the risks?
  - Physical
  - Biomedical
The **NASA Space Radiation Laboratory** now provides a ground-based facility to study the effects/mechanisms of damage from space radiation exposure.
Challenges in space radiation risk assessment: Risks due to space radiation exposure can be different from those due to exposures to gamma or X-rays.

**DSB induction**

- **Low-LET**
  - X-rays
  - Gamma rays

- **High-LET**
  - Space radiation

**Severity of DSB**

DSB: Double strand break
Assessing the risks from space radiation exposure

Gamma/X ray (low-LET) exposure to human at high dose and high dose rate

Charged particle (High-LET) exposure to human at low dose and low dose rate

\[
R(\text{High LET, LD, LDR}) = \sum \frac{R(\text{Low LET, HD, HDR}) \times Q(\text{LET})}{\text{DDREF(LET)}}
\]

Gamma/X ray (low-LET) exposure to human cells/animals

Charged particle (High-LET) exposure to human cells/animals

\[
Q(\text{LET}) \quad \text{DDREF(LET)} \quad \text{for cells/animals}
\]
The quality factor can be cancer type specific.

Weil et al. 2009

FIG. 1. Percentage incidence of AML (±SE) as a function of dose after exposure to $^{137}$Cs $\gamma$ rays (solid circles) or 1 GeV/nucleon $^{56}$Fe ions (open circles).

FIG. 2. Percentage incidence of hepatocellular carcinoma as a function of dose after exposure to $^{137}$Cs $\gamma$ rays (solid circles) or 1 GeV/nucleon $^{56}$Fe ions (open circles).
Challenges in space radiation risk assessment:
The doses are low

- Japanese atomic bomb survivals
- Chernobyl nuclear power plant accident
- Radiation workers
- Others
Challenges in radiation protection with shielding

Dose-depth relationship (Bragg curve)

Shielding for heavy ions generates secondary particles including neutrons

Wilson et al.
Effectiveness of shielding for GCR exposures

Wilson et al. 2001

Figure D.1. Abundances (a) and Energy Spectra (b) of GCR
Dose and dose equivalent may not accurately predict biological damages around the Bragg peak

Wu et al. 2006
Challenges in Biomedical Countermeasures

• Drugs used on patients undergoing radiotherapy
  - e.g., Amifostine

• Dietary supplements
  - e.g., Vitamin A

• New developments
  - e.g., Nanoparticles
Dendro[C_{60}]fullerene DF-1 provides radioprotection to radiosensitive mammalian cells

Corey A. Theriot · Rachael C. Casey · Valerie C. Moore · Linsey Mitchell · Julia O. Reynolds · Madeline Burgoyne · Ranga Partha · Janice L. Huff · Jodie L. Conyers · Antony Jeevarajan · Honglu Wu

DF-1 protects against 150 MeV proton-induced micronucleus formation in human lymphocytes
Biodosimetry

• What is biodosimetry?
  – The use of biological markers to estimate radiation exposure and dose

• Why do you need biodosimetry?
  – Complement the measurement using physical dosimeters
  – Take into account the individual susceptibility
  – Take into account the self-shielding of the body
  – Take into account the possible synergistic effect of other spaceflight factors
  – Hopefully use as a marker to predict risk

• What are the methods for biodosimetry?
  – Chromosome aberrations in astronauts’ blood cells
  – Other biological markers
Biodosimetry

Simple exchange

Complex exchange

Fig. 3. The frequency of stable aberrations by age. Circles and squares represent females and males, respectively. Filled and open symbols represent smokers (both previous and current) and nonsmokers, respectively. The solid line represents the line-of-squares regression fit to the data, as described in Statistical methods.
Biodosimetry procedure

Blood draw

PHA

Incubate for 48 hours

Colcemid

Incubate 2 hours

Harvest condensed cells

Calyculin-A

Incubate 30 min
### Frequencies of Chromosome Aberrations Measured before and after Flight for Six Crew Members of Long-Duration Mir Missions (1–6), and for Two Crew Members (7 and 8) before and after a 10-Day Shuttle Mission

<table>
<thead>
<tr>
<th>Crew member</th>
<th>Sample collection</th>
<th>Cells scored</th>
<th>Chromosomes analyzed</th>
<th>No.</th>
<th>Frequencies $\pm$ SD $(\times 10^{-3})$</th>
<th>No.</th>
<th>Frequencies $\pm$ SD $(\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Before flight</td>
<td>4404</td>
<td>1 + 2</td>
<td>19</td>
<td>4.3 ± 1.0</td>
<td>1</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>10 days after flight</td>
<td>6556</td>
<td>1 + 2</td>
<td>27</td>
<td>4.1 ± 0.8</td>
<td>7</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>2</td>
<td>Before flight</td>
<td>1892</td>
<td>1, 2 + 4</td>
<td>5</td>
<td>2.6 ± 1.2</td>
<td>1</td>
<td>0.5 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>12 days after flight</td>
<td>4677</td>
<td>2 + 1</td>
<td>20</td>
<td>4.3 ± 1.0</td>
<td>2</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>3</td>
<td>Before flight</td>
<td>3995</td>
<td>2 + 4</td>
<td>4</td>
<td>1.0 ± 0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Day of return</td>
<td>4056</td>
<td>2 + 4</td>
<td>9</td>
<td>2.2 ± 0.7</td>
<td>2</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>240 days after flight</td>
<td>4745</td>
<td>2 + 1</td>
<td>14</td>
<td>2.9 ± 0.8</td>
<td>2</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td>4</td>
<td>Before flight</td>
<td>3792</td>
<td>2 + 4</td>
<td>12</td>
<td>3.2 ± 0.9</td>
<td>3</td>
<td>0.8 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>9 days after flight</td>
<td>4843</td>
<td>2 + 4</td>
<td>30</td>
<td>6.2 ± 1.1</td>
<td>3</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>114 days after flight</td>
<td>3604</td>
<td>2 + 4</td>
<td>20</td>
<td>5.5 ± 1.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Before flight</td>
<td>742</td>
<td>2 + 4</td>
<td>3</td>
<td>4.0 ± 2.3</td>
<td>2</td>
<td>2.7 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>9 days after flight</td>
<td>2630</td>
<td>2 + 4</td>
<td>19</td>
<td>7.2 ± 1.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Before flight</td>
<td>2852</td>
<td>2 + 4</td>
<td>7</td>
<td>2.4 ± 0.9</td>
<td>1</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>Day of return</td>
<td>4672</td>
<td>2 + 4</td>
<td>26</td>
<td>5.6 ± 1.1</td>
<td>1</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>9 days after flight</td>
<td>3147</td>
<td>2 + 4</td>
<td>13</td>
<td>4.1 ± 1.1</td>
<td>1</td>
<td>0.3 ± 0.3</td>
</tr>
<tr>
<td>7</td>
<td>Before flight</td>
<td>2962</td>
<td>1, 2 + 5</td>
<td>5</td>
<td>1.7 ± 0.7</td>
<td>1</td>
<td>0.3 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Day of return</td>
<td>4287</td>
<td>1, 2 + 5</td>
<td>7</td>
<td>1.6 ± 0.6</td>
<td>1</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>8</td>
<td>Before flight</td>
<td>712</td>
<td>1, 2 + 5</td>
<td>1</td>
<td>1.4 ± 1.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Day of return</td>
<td>2529</td>
<td>1, 2 + 5</td>
<td>4</td>
<td>1.6 ± 0.8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Summary

- Space radiation health risks include carcinogenesis, CNS, degenerative tissue and acute radiation
- Accurate assessment of health risks from space radiation exposure is a highly complex task
- Both physical and biological countermeasures are non-trivial issues
- The JSC Biophysics Laboratory provides operational support by evaluating the biological dose received by the astronauts during long-duration missions
Thank you!