Galactic Cosmic Ray
Simulator Design at NSRL

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Outline

• Brief overview

• Reference field specification
  - External (free space) vs. internal (shielded tissue) environments

• General beam selection strategy

• Discussion and summary

Note: Most of the content described in this presentation can be found in:
Full reference list and citations for models used can also be found in the document (not included here)

Overview

• Long term exposure to GCR presents a serious health risk to astronauts with large uncertainties connected to the biological response
  - Main focus of radiobiology experimental research program is to reduce these uncertainties

• In order to reduce these uncertainties, radiobiology experiments are performed to understand basic mechanisms for carcinogenesis, CNS and cardiovascular effects
  - Most experiments have been performed with individual ion species and/or energies
  - Approach is guided in part by desire to understand basic mechanisms but also heavily influenced by facility constraints and cost

• Complicating feature of the GCR problem is that broad range of energies and particles found in space are difficult to provide in a laboratory

• NSRL has matured to a point where simulating a “broad” spectrum of particles and energies in a single experiment is feasible from a facility and cost perspective
  - Still can’t simulate full GCR spectrum in one experiment but can do better than a single particle and energy (e.g. $^{56}\text{Fe}$ at 1 GeV/n)
Overview

• Important to understand that development of a “GCR simulator” does not mean single beam studies are not useful or needed
  - Single beam studies are needed to examine and improve understanding of basic mechanisms where limited knowledge currently exists
  - Also needed to test, develop, and validate theoretical and computational models

• Instead, the simulator design should be viewed as the development of a new technology that provides new capabilities
  - Provides opportunity to test models derived from single beam studies in more realistic exposure scenario
  - Improves operational efficiency of NSRL, which in turn, improves efficiency for single beam studies

• The notion of a GCR simulator is not new – it has been discussed for decades, and was always a development goal of the space radiobiology program
  - What is new is that the accelerator facility has matured to a point where preliminary implementation is now realistic
Overview

• The GCR simulator at NSRL is intended to deliver deep space, shielded tissue environment to biological targets in a laboratory setting
  - Used to study a range of space radiobiology questions

• Many of the details associated with GCR simulator design will depend on biological question and endpoints being studied

• Some aspects may be “standardized” across experiments
  - Enables subsequent cross comparisons and validation
  - Saves time and cost

• Two aspects allow for some standardization
  - Reference field specification: which environment are we simulating with beams
  - General beam selection strategy: how can we pick beams to simulate the environment
External and Internal Fields

- The external GCR field is modified as it passes through shielding and tissue
  - Slowing down due to atomic processes
  - Attenuation and breakup of heavy ions due to nuclear collisions
  - Secondary particle production
  - Plot below (right) for minimal shielding (5 g/cm²) and average tissue (30 g/cm²)

Selected particle spectra in free space (left pane) and behind 5 g/cm² of aluminum and 30 g/cm² of water (right pane) during solar minimum
External and Internal Fields

- An important question is whether to design the simulator using the free space, external field or local tissue field.
External and Internal Fields

- **External field approach**

  Beams selected to represent external, free space field before shielding

- **Local tissue field approach**

  Beams selected to directly represent shielded tissue field
External and Internal Fields

• Facility constraints have a significant impact on choosing the approach

• NSRL Energy constraints
  - Current: protons (2.5 GeV) and heavier ions (1.0 GeV/n)
  - Upgrade: protons (4.0 GeV) and heavier ions (1.5 GeV/n)

• Table below gives fraction of effective dose delivered by energies within NSRL energy constraints
  - Female phantom behind 20 g/cm² of aluminum shielding during solar minimum
  - Other scenarios and exposure quantities lead to qualitatively similar results

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<tr>
<th>Energy cutoff description</th>
<th>Free space approach</th>
<th>Local field approach</th>
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<td>Current NSRL energy constraints</td>
<td>47%</td>
<td>88%</td>
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<tr>
<td>Upgrade NSRL energy constraints</td>
<td>63%</td>
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External and Internal Fields

• Results indicate that energy constraints at NSRL limit the feasibility of simulating the external, free space GCR field
  - Missing ~half of the exposure

• GCR simulator will focus on directly reproducing the shielded tissue field

Local tissue field approach

Beams selected to directly represent shielded tissue field

Biological target
Reference Field Specification

- Shielded tissue field in space depends on many factors
  - Tissue location within body
  - Shielding material, thickness, and geometry
  - Solar activity

- Looked at variation associated with each of these factors and concluded that a single reference field for deep space can be identified

- Observed variation is within
  - GCR environmental model uncertainty (at least 20%)
  - Combined physics and transport modelling uncertainty
  - Experimental design uncertainty: representing broad GCR spectrum with relatively few mono-energetic beams
Variation in Local Field

- Variation in local tissue field will be examined as a function of
  - Tissue location
  - Shielding configuration
  - Shielding material
  - Solar activity

- Models
  - GCR environment computed with the 2010 Badhwar-O’Neill GCR model
    - Solar minimum: June 1976
    - Solar maximum: June 2001
    - All results shown for solar minimum except for comparisons focused on solar activity
  - HZETRN transport code with π/EM and bi-directional neutron transport (ray-by-ray)
  - Female phantom (FAX)
  - NASA-Q and effective dose tissue weights implemented where applicable
  - Q-factor uncertainties from NSCR2012 implemented where applicable
Variation in Local Field

• Will consider spherical aluminum shielding (5 g/cm², 20 g/cm², 40 g/cm²) along with four realistic shielding geometries
  - Habitat demonstration unit (HDU) adapted for 1-year free space mission
  - Cislunar vehicle concept
  - ISS location in US Lab near overhead racks
  - STS location in mid-deck (often referred to as DLOC 2)
Variation in Local Field – Shielding

- Plots below show tissue doses and dose equivalents behind shielding
  - Variation is within even the GCR environmental model uncertainty (~±20%)
  - Increased variation in dose equivalent associated with HZE breakup
  - Bladder, BFO and breast appear as representative tissues
  - 20 g/cm² aluminum appears as representative shielding
Variation in Local Field – Shielding

- Shielding material also contributes to variation in exposure quantities
  - Current technology suggests deep space vehicle will be comprised of mainly aluminum with some parasitic shielding mass (polyethylene)
  - Plot below shows tissue exposure values behind 20 g/cm² of aluminum or polyethylene
  - Variation is within experimental design uncertainty
Variation in Local Field – Shielding

- Plots below show relative contribution to dose and dose equivalent for various charge groups
  - Protons and alphas account for more than half of the exposure
  - Breakup of HZE component can be clearly seen in breast dose equivalent
  - Relative contributions of particles types show some variation, but likely within experimental design uncertainty
Variation in Local Field – Shielding

- LET spectral comparisons in different shielding configurations and tissues
  - Variation associated with shielding appears small below 200 keV/µm
  - Variation is likely within experimental design uncertainty
  - Spectra appear as qualitatively similar
Variation in Local Field – Solar Activity

- During solar max, the GCR spectrum is attenuated below several GeV/n
  - Plots below compare solar minimum and solar maximum results
  - Solar maximum results have been scaled by 1.85
  - Constant factor of 1.85 nearly corrects discrepancies associated with solar activity across the entire LET domain
  - Suggests main difference between solar extremes is magnitude of exposure, not the shape of the LET spectrum
Reference Field Specification

- Reference field specification for GCR simulator
  - Female BFO (blood forming organ) behind 20 g/cm² spherical aluminum shielding during solar minimum conditions

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<th>Avg. hits per cell nucleus</th>
<th>Dose (mGy)</th>
<th>Dose Eq. (mSv)</th>
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**Annual reference field quantities**
General Beam Selection Strategy

- Plots below show physical quantities that describe the charged particle components of the reference field
  - neutrons and π/EM component not included

Hydrogen and helium energy spectra

Heavy ion (Z > 2) LET spectrum
General Beam Selection Strategy

- Hydrogen and helium are explicitly represented in energy domain and HZE ions are collectively represented within the LET spectrum
  - Greater emphasis/fidelity in simulator design for hydrogen and helium
  - Account for 81% of dose and 67% of dose equivalent
  - Other ions could be explicitly represented as well (trade against time/cost)
For hydrogen and helium
- Break energy domain into two pieces
- Low energy particles that might stop in mouse (<150 MeV/n)
- Higher energy particles that will pass through mouse (>150 MeV/n)
General Beam Selection Strategy

- For hydrogen and helium
  - Bin the low and high energy domains separately
  - Each bin represented by a mono-energetic ion beam
  - Protons and alphas used to represent hydrogen and helium, respectively
General Beam Selection Strategy

- High energy beams provided directly from accelerator (i.e. energy switching)
- Low energy beams achieved by using polyethylene degraders
  - Similar procedure as previously implemented for SPE simulator
  - Allows finer resolution for stopping particles thereby reducing exposure gradients within animals
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• Low energy beams achieved by using polyethylene degraders
  - Similar procedure as previously implemented for SPE simulator
  - Allows finer resolution for stopping particles thereby reducing exposure gradients within animals
General Beam Selection Strategy

- A similar binning procedure is used to represent HZE component
  - Bin the LET domain for HZE particles
  - Each bin represented by mono-energetic HZE beam
  - Can use look-up tables and energy constraints to determine which ion/energy to use for each bin
General Beam Selection Strategy

- Energies are now constrained below
  - Do not want rapid variation (Bragg peaks) occurring within animals
  - Not implementing degrader approach for each heavy ion (time/cost constraints)
  - Ions need to be energetic enough to reach at least ~9 cm
General Beam Selection Strategy

- General beam selection strategy is now set
  - Allows for precise beam specification (ion, energy, intensity) tied directly to physical spectrum of reference field
  - Convergence testing performed to see how many bins are needed
  - Convergence testing also provides cost-benefit information of using more beams
General Beam Selection Strategy

• Lower energy portion of hydrogen and helium spectra is being represented by using polyethylene degrader system
  - Similar procedure as previously implemented for SPE simulator
  - Need to determine number of low energy bins required to achieve reasonably smooth internal exposure profiles

• Considered an ellipsoidal tissue phantom to represent mouse
  - Mass: 33 grams, major axis length: 7 cm, minor axis length: 3 cm
  - Exposed phantom to isotropic irradiation of low energy proton beams (<150 MeV/n)
  - Systematically increased number of bins used to represent low energy spectrum
General Beam Selection Strategy

- Plots below show dose profiles within phantom
  - Internal variation measured as relative difference between min/max values
  - Local variation appears to be controlled with as few as 10 bins
  - Using more than 25 bins starts to reach limits of polyethylene degrader fidelity (0.025 cm)
Example Beam Selection

- Remaining analyses will consider the following case
  - 10 low energy bins for protons and alphas
  - 5 high energy bins for protons and alphas
  - 14 LET bins for HZE component
Example Beam Selection

- Internal exposure variation in ellipsoidal phantom under isotropic irradiation is shown below
  - Relatively smooth internal dose profile
  - Previously established that 10 low energy bins for hydrogen and helium are sufficient
  - Higher energy hydrogen and helium beams will not range out in phantom
  - HZE beams explicitly chosen to reach at least 9 cm

±4% variation in internal dose values
Example Beam Selection

- Left pane shows the differential LET spectrum of reference field compared to spectrum induced by beams at center of phantom (isotropic irradiation)
  - Qualitatively good agreement across the LET spectrum
Example Beam Selection

- Right pane shows the differential $X_{tr} = (Z'/\beta)^2$ spectrum of reference field compared to spectrum induced by beams at center of phantom (isotropic irradiation)
  - $(Z'/\beta)^2$ spectrum provides somewhat of an independent check since beam selection was not guided by this quantity
  - Qualitatively good agreement across the $(Z'/\beta)^2$ spectrum
Example Beam Selection

- Tables below show integrated quantities from reference field and beams
  - Cell nucleus hits computed by assuming cross sectional area of 100 µm²
  - Hits/cell results consistent with previous calculations by Curtis et al.

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Summary

• Current (and upgraded) facility constraints limit the ability to simulate the external, free space field directly
  - Proposed simulator design instead focuses on reproducing the local tissue field

• Variation in the induced tissue field was examined, and it was determined that a single reference environment for deep space is reasonable at this time

• An approach for beam selection in the simulator was presented
  - The approach is tied directly to the reference environment flux and allows systematic improvements to be made
  - Spectral quantities and integrated quantities are reasonably well represented
  - Optimization procedures could be developed to improve overall agreement across all quantities

• Drawbacks of the proposed strategy include
  - Possible lower energy constraints for HZE particles associated with animal models
  - Neutron and π/EM components
  - These drawbacks could be addressed by augmenting the existing design if necessary
Backup: Example Beam Info

- Proton beam information for example study

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### Backup: Example Beam Info

- Alpha beam information for example study

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Backup: Example Beam Info

- HZE beam information for example study

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<td>256.9</td>
<td>1.1 x 10⁴</td>
<td>0.76</td>
</tr>
<tr>
<td>32</td>
<td>16</td>
<td>755</td>
<td>66.7</td>
<td>369.4</td>
<td>5.7 x 10³</td>
<td>0.55</td>
</tr>
<tr>
<td>39</td>
<td>19</td>
<td>781</td>
<td>93.2</td>
<td>514.0</td>
<td>3.6 x 10³</td>
<td>0.48</td>
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<tr>
<td>47</td>
<td>22</td>
<td>682</td>
<td>130.2</td>
<td>728.1</td>
<td>3.0 x 10³</td>
<td>0.56</td>
</tr>
<tr>
<td>56</td>
<td>26</td>
<td>682</td>
<td>181.8</td>
<td>1016.8</td>
<td>2.8 x 10³</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Backup: External and Internal Fields

- Plots below show fraction of effective dose as a function of boundary and local energies for thicknesses of aluminum shielding
  - Current NSRL constraints appear to be restrictive if external, free space field is simulated
  - Appears energy domain of local tissue field can be well represented
Backup: Sensitivity Analysis

- Plots below show relative contribution to dose and dose equivalent from various particles in the reference field
- $Z = 1$ and $Z = 2$ contributions dominate
  - 81% of dose and 67% of dose equivalent
- $Z > 2$ contributes 7% to dose and 21% to dose equivalent
  - $Z = 6, 7, 8, 10, 12, 14, 20, 26$ appear amplified compared to other heavy ions
Backup: Sensitivity Analysis

- Another point to consider is the self-shielding provided by an animal model
  - May want to avoid Bragg peaks or rapid exposure gradients within mice
  - Localized tissue exposures may be difficult to reproduce in subsequent studies
  - Table below gives energies needed to reach 9 cm

<table>
<thead>
<tr>
<th>Z</th>
<th>E to reach 9 cm (MeV/n)</th>
<th>E to reach 80 cm (MeV/n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>109</td>
<td>393</td>
</tr>
<tr>
<td>2</td>
<td>109</td>
<td>393</td>
</tr>
<tr>
<td>6</td>
<td>204</td>
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<td>224</td>
<td>898</td>
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<tr>
<td>8</td>
<td>242</td>
<td>987</td>
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<tr>
<td>10</td>
<td>277</td>
<td>1166</td>
</tr>
<tr>
<td>12</td>
<td>308</td>
<td>1336</td>
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<td>14</td>
<td>339</td>
<td>1499</td>
</tr>
<tr>
<td>26</td>
<td>475</td>
<td>2334</td>
</tr>
</tbody>
</table>
BACKUP: LET and $X_{tr}$ spectra

- LET spectrum is computed from flux

$$\frac{d\phi(L)}{dL} = \sum_Z \frac{d\phi(Z, E)}{dE} \frac{dE}{dL} = \sum_Z \frac{d\phi(Z, E)}{dE} \frac{dL}{dE}^{-1}$$

- $X_{tr}$ spectrum is computed from flux

$$\frac{d\phi(X_{tr})}{dX_{tr}} = \sum_Z \frac{d\phi(Z, E)}{dE} \frac{dE}{dX_{tr}} = \sum_Z \frac{d\phi(Z, E)}{dE} \frac{dX_{tr}}{dE}^{-1}$$
Backup: Discussion

• Proposed strategy for beam selection provides a systematic approach for reproducing the reference field LET spectrum and related quantities
  - Sensitivity analyses and energy constraints provide supplementary information
  - Integrated quantities such as a dose, dose eq., and $<Q>$ well represented
  - Track structure spectrum reasonably well represented even though it wasn’t targeted
  - Optimization strategies could be pursued to improve overall agreement across all quantities considered

• Proposed strategy does have some drawbacks
  - Track structure characteristics
  - Lower energy constraint associated with ion stoppage in animal model
  - Neutron and $\pi$/EM components
• Track structure
  - Proposed strategy represents $F(X_{tr})$ spectrum reasonably well
  - Due to energy constraints, most beam energies were focused in the 200 MeV/n – 600 MeV/n range
  - Unclear if track structure characteristics of simulator will closely represent what might be expected in space
  - Especially important given ~half of the exposure is delivered by energies below 100 MeV/n
Backup: Discussion

- Lower energy constraint
  - Lower energy ions contribute significantly to exposure but are not explicitly included in simulator design
  - For cell cultures, the lower energy constraint could be relaxed
  - Proposed strategy could be modified to include a spectrum of low energy ions (degraders) but would require further analysis to integrate into the simulator design
  - Could leave design as-is and augment with increased complexity at a later date
Backup: Discussion

• Neutrons
  - Neutron spectrum of reference field shown below
  - Neutron dose is defined here as energy deposited by heavy target fragments ($Z > 2$) produced in nuclear collisions (elastic recoil and inelastic products)
  - Most of the exposure comes from neutrons between 1 MeV and 1 GeV
Backup: Discussion

• Neutron beam not currently available at NSRL
  - Even if it were, a pure neutron spectrum would induce a different exposure than what is defined presently

• Could represent heavy target fragment spectrum in some way, but might be difficult
  - Could use models to predict heavy target fragment spectrum (<10 MeV ions) and implement degraders to provide continuous spectrum
  - Could replace low energy target fragments with high energy ions with much higher Z value (i.e. same LET)

• Could also just ignore neutron component for now (and π/EM cascade)
  - Neutrons contribute small amount to dose and 7% to dose equivalent for reference environment
  - Likely this much error in any simulator design
  - Could again view the neutron and π/EM components as augmentations to the existing design to be added at a later date