Space Radiation Research for Human Space Missions

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Human mission to Mars presents unique challenges
- ~9 months to reach Mars
- Radiation environment is more severe in deep space than in low Earth orbit

Radiation exposure identified as a key risk for Mars
- Radiation risk estimates exceed NASA limits
- Exceeding limits does not preclude mission from occurring
- Risks for cancer, central nervous system, and cardiovascular system
- Major driver is biological uncertainty

Efforts to reduce risk and uncertainty
- Improve physics and biology models
- Countermeasure development
- Vehicle design and optimization
Outline

- Background
- Space radiation environments
- Physical interactions
- Radiation Transport
- Biological consequences and risk
Aeronautics Research Mission Directorate

Human Exploration and Operations Mission Directorate

Space Technology Mission Directorate

Science Mission Directorate

Human Research Program

Advanced Exploration Systems

Game Changing Division

• Identify and rapidly mature innovative and high impact technologies
  - Advanced radiation protection project focused on thick shielding for deep space environments

• Develop prototype systems, future systems, and validate operational concepts for future missions
  - Radiation protection (Radworks) project

• Discover best methods and technologies to support safe human space travel
  - Environmental, physics, transport and measurements project
  - Risk assessment project
Background

- Shielding models
- Environment models
- Radiation transport models
- Exposure & Biological response
- Physics models
Background

• A multi-scale problem spatially and temporally
  - Particle transport is described across the solar system, through complex vehicle shielding and tissue, down to cellular levels
  - Solar activity includes daily variation and longer term cycles
  - Physical interactions occur in nanoseconds
  - Biological consequences can extend many years after the exposure

• Relevant energies and particles in space radiation applications
  - Energies ranging from keV/n up to TeV/n
  - Particles include heavy ions, neutrons, e⁻, e⁺, gammas, and some mesons

- **keV/n**: Stopped by thinnest shielding (skin)
  - Important energy region for delta rays and some target fragments
- **MeV/n**: Able to penetrate to some tissue sites
  - Important energy region for local energy deposition in tissue and solar particle events
- **GeV/n**: Able to penetrate spacecraft shielding and tissue
  - Important energy region for galactic cosmic rays
- **TeV/n**: Able to penetrate just about everything, even through Earth atmosphere (1000 g/cm²)
• The galactic cosmic ray (GCR) environment is omnipresent in space and fluctuates between solar extremes
  – Exposures differ by a factor of ~2 between nominal solar extremes
  – Broad spectrum of particles (most of the periodic table) and energies (many orders of magnitude)
  – Difficult to shield against due to high energy and complexity of field
Space Radiation Environment

- Solar particle events (SPE) are intense bursts of protons from the Sun
  - Difficult to predict occurrence, spectral shape, or magnitude
  - More likely to occur during periods of heightened solar activity (solar max)
  - Energies up to several hundred MeV (may extend up to GeV)
  - Presents serious acute risk to astronauts if not adequately shielded
Physical Interactions

- The ambient radiation field is modified as it passes through bulk matter
  - Charged particles are slowed down
  - Secondary particle production can occur

- Atomic interactions
  - Well known with existing models
  - Interaction between positive ions and orbital electrons of target
  - Main physical mechanism for ion energy deposition
  - ~10^6 atomic interactions occur in a cm of matter
  - Production of delta ray e^- along the ion track (track structure)

- Nuclear interactions
  - Significant uncertainties remain in nuclear models
  - Nuclear elastic: think of classical “pool-ball” collision
  - Nuclear inelastic: think of “pool-balls” breaking apart into pieces and some new pieces possibly being created
  - May be separated by a fraction to many cm of matter
  - Nuclear interactions are critical in describing space radiation transport

Artist depiction of cosmic ray induced atmospheric cascade. [Simon Swordy (U. Chicago), NASA]
Radiation Transport - Beams

- Low energy (E < 500 MeV/n) proton and carbon beams are sometimes used in cancer therapy
  - Atomic interactions precisely specify where charged particles stop in matter
  - Leads to a localized energy deposition site referred to as the Bragg peak

- Monte Carlo methods are typically used in clinical applications to describe beam interactions with tissue
  - Green’s function methods have been developed at ODU in support of NASA applications
  - Tweed, Rockell, Walker, et al.
Radiation Transport - Space

• NASA has distinct requirements for radiation analysis models
  - Need to optimize vehicle design and minimize costs
  - Radiation constraints are included throughout the design process
  - Analysis tools need to be highly efficient to facilitate rapid turnaround in design cycle
  - Most of the end-to-end runtime is spent in radiation transport procedures

• Radiation transport methods are classified into two main categories
  - Deterministic: solve the relevant transport equations using analytical and numerical methods
  - Monte Carlo: use random-number generators to sample interactions and track particle trajectories
Radiation Transport - Space

• For space applications, it is recognized that Monte Carlo methods are computationally restrictive
  - Monte Carlo simulations in simple slab geometries required \(~200\) CPU years
  - Fully detailed geometries like ISS would present an even greater challenge

• Monte Carlo codes used in space applications
  - PHITS, Geant4, FLUKA, MCNP6
  - These codes are “general purpose”
  - Sometimes used in treatment planning, nuclear reactor design, accelerator design, and high energy physics experiments

• Deterministic codes used in space applications
  - HZETRN
  - Not a “general purpose” code
  - Developed specifically for space applications with some applicability in beam-line analysis
  - Most space application analyses run on a single CPU in seconds-minutes
Deterministic Methods: HZETRN

• ~40 years ago, Wilson et al. (NASA Langley)\textsuperscript{1,2} begin investigating deterministic methods for space radiation transport applications
  - Starting point was the 3D linear Boltzmann transport equation

\[
\left[ \Omega \cdot \nabla - \frac{1}{A_j} \frac{\partial}{\partial E} S_j(E) + \sigma_j(E) \right] \phi_j(x, \Omega, E) = \sum_k \int \sigma_{jk}(E, E', \Omega, \Omega') \phi_k(x, \Omega', E') d\Omega' dE'
\]

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Flux of type \( j \) particles at position \( x \) with kinetic energy \( E \) moving in the direction of \( \Omega \)

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\]

Drift operator for rate of change of flux with respect to position

Continuous slowing down operator representing ion energy loss due to atomic interactions

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\begin{bmatrix}
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\]

- Reaction cross section for type \(j\) particles with kinetic energy \(E\)
- Production cross section for type \(k\) particles with direction \(\Omega'\) and energy \(E'\) producing type \(j\) particles with direction \(\Omega\) and energy \(E\)

Deterministic Methods: HZETRN

- Solution methodology allows for converging sequence of physical approximations to be implemented
  - Simple and highly efficient solutions can be used in early design when vehicle is not well defined
  - Increasing fidelity of solution methodology can be matched to fidelity of vehicle design

- Straight ahead approximation: \( \sigma_{jk}(E,E',\Omega,\Omega') = \tilde{\sigma}_{jk}(E,E')\delta(1 - \Omega \cdot \Omega') \)
  - Reduces 3D equation to 1D
  - Most accurate for heavier ions where produced particles are forward directed

\[
\left[ \frac{\partial}{\partial x} - \frac{1}{A_j} \frac{\partial}{\partial E} S_j(E) + \sigma_j(E) \right] \phi_j(x,E) = \sum_k \int \tilde{\sigma}_{jk}(E,E')\phi_k(x,E')dE'
\]

- Solution method for 1D transport equation
  - Invert Boltzmann equation and write as a Volterra integral equation
  - Solution to homogeneous equation is valid over sufficiently small step-sizes, \( h \)
  - Homogeneous solution is inserted into Volterra equation to allow \( O(h^2) \) marching procedures
  - High speed computational procedures implemented\(^{1-4}\) and resulted in first HZETRN code

Bi-directional Transport Methods

• Verification and validation for straight ahead approximation (HZETRN)
  - Extensively validated using space-flight measurements on ISS and shuttle\textsuperscript{1,2}
  - Compared to recent data from the Mars Science Laboratory Radiation Detector (MSL/RAD)\textsuperscript{3}
  - Verification against Monte Carlo simulations have been performed\textsuperscript{2,4}

• Shortcomings:
  - Straight ahead approximation is less accurate for light ions ($Z \leq 2$) and neutrons
  - Light ions and neutrons are produced in all directions following a nuclear collision
  - Will not predict back-scattered leakage or build-up effects within matter

• Next level of approximation: bi-directional transport
  - Neutron transport was extended to evaluate forward and backward directions\textsuperscript{5}
  - Further improvements fully coupled forward/backward transport through multiple elastic collisions\textsuperscript{4}
  - Light ion semi-analytic solution also implemented for low energies\textsuperscript{4}

\textsuperscript{1} Wilson et al., Verification and validation: High charge and energy (HZE) transport codes and future development. NASA TP-2005-213784, 2005.
\textsuperscript{2} Slaba et al., Pion and electromagnetic contribution to dose: Comparisons of HZETRN to Monte Carlo results and ISS data. \textit{Adv. Space Res.} \textbf{52}: 62-78; 2013.
\textsuperscript{3} Matthia et al., Particle Spectra on the Martian Surface. \textit{SWSC}, accepted; 2015.
Bi-directional Transport Methods

- Neutron production is separated into forward and isotropic components\(^1\)
  - Forward component associated with higher energies
  - Isotropic component associated with lower energy target de-excitation

- Fluxes are similarly separated into forward and isotropic components
  - Forward component of flux is solved using the straight ahead approximation
  - Isotropic neutron solution obtained by solving a coupled set of equations\(^2\)

\[
\begin{align*}
\left[ \frac{\partial}{\partial x} + \sigma_n(E) \right] \phi_n^{(f)}(x,E) &= \int \tilde{\sigma}^{(f)}_{nn}(E,E') \phi_f(x,E') dE' + \int \tilde{\sigma}^{(b)}_{nn}(E,E') \phi_b(x,E') dE' \\
- \left[ \frac{\partial}{\partial x} + \sigma_n(E) \right] \phi_n^{(b)}(x,E) &= \int \tilde{\sigma}^{(f)}_{nn}(E,E') \phi_f(x,E') dE' + \int \tilde{\sigma}^{(b)}_{nn}(E,E') \phi_b(x,E') dE'
\end{align*}
\]

- Solution method for coupled equations\(^2\)
  - Neumann series solution
  - Each term in series solved using collocation methods and back-substitution for matrix inversion

Verification and Validation

- Planetary surfaces have albedo environments
  - Incoming GCR/SPE interact with soil and back-scattered neutrons are emitted
  - Mars also has a thin atmosphere which further complicates the albedo environment

1. Matthia et al., Particle Spectra on the Martian Surface. SWSC, accepted; 2015.
3D Transport Methods

• Neutron production is separated into forward and isotropic components\(^1\)
  - Forward component associated with higher energies
  - Isotropic component associated with lower energy target de-excitation

• Fluxes are similarly separated into forward and isotropic components
  - Forward component of flux is solved using the straight ahead approximation

• Forward flux generates isotropic neutron source
  - Evaluated at any point within arbitrary geometry

• Isotopic neutron field solved over \( N \) stream directions\(^1\)
  - Bi-directional neutron transport (\( N = 2 \)) implemented along opposing streams
  - Final step evaluates light ion target fragments produced from isotropic neutrons

\(^1\) Wilson et al., Advances in NASA space radiation research: 3DHZETRN, Life Sci. Space Res. 2: 6-22; 2014.
• First verification of 3D methods utilized simple spherical geometry
  - Directed (instead of isotropic) boundary conditions to emphasize 3D features

• 3DHZETRN agrees with Monte Carlo to the extent they agree with each other
  - Significant improvement over straight ahead approximation (N=1)
  - Main difference between codes is runtime: seconds for 3DHZETRN and years for Monte Carlo
• Second verification utilized simple spherical geometry with two materials
  - Tissue sphere (astronaut proxy) embedded in spherical aluminum shell

• 3DHZETRN agrees with Monte Carlo to the extent they agree with each other
  - Significant improvement over straight ahead approximation (N=1)
  - Main difference between codes is runtime: seconds for 3DHZETRN and years for Monte Carlo

• Latest verification utilized complex combinatorial geometry
  - Tissue sphere (astronaut proxy) embedded in cylindrical aluminum shell with internal boxes

• 3DHZETRN agrees with Monte Carlo to the extent they agree with each other
  - Significant improvement over straight ahead approximation (N=1)
  - Main difference between codes is runtime: seconds for 3DHZETRN and years for Monte Carlo

Impact of Transport Code Updates

- Recent updates in transport code development have had a significant impact on shielding strategies for deep space missions
  - Previous paradigm: shielding for GCR was ineffective but did not make problem worse
  - New paradigm: local minimum provides engineers with an optimal design range
  - Places renewed emphasis on shield design and material development

![Graph: Total dose equivalent versus aluminum thickness for a GCR boundary condition](image-url)
Exposure Quantities

- **Flux or fluence**
  - Example units: particles/(cm²-MeV/n-day)

- **Linear energy transfer (LET)**
  - Energy deposited per unit distance travelled
  - Space radiation is “high LET” compared to “low LET” gammas
  - Example units: keV/µm

- **Dose**
  - Energy deposited per unit mass (energy/mass) and per unit time
  - Example units: mGy/year

- **Dose equivalent**
  - Radiation quality factor is used to quantify increased biological effectiveness of high LET particles compared to gamma rays
  - Example: mSv/year

- **Effective dose**
  - Weighted sum of tissue averaged dose equivalent values
  - Tissue weights quantify relative radiosensitivity of individual tissues
  - Provides a measure of human mortality risk from radiation exposure

- **Risk of Exposure Induced Death/Cancer (REID/REIC)**
NASA Cancer Risk Model

- NASA cancer risk model
  - Based on epidemiological data from Atomic bomb survivor cohort
  - Utilizes background cancer incidence and mortality rates for general population
  - Distinction drawn between average US population and never smokers
  - Survival probabilities for general population also included

\[
REID = \sum_T \int_{a_E}^{\infty} \frac{\tilde{S}(a)}{\tilde{S}(a_E)} \lambda_T^{(M)}(a, a_E, H_T)e^{-\int_{\theta_E}^{a} \lambda_T^{(M)}(t, a_E, H_T)dt} \, da
\]

- Dose and dose rate reduction factor (large uncertainties)
  - Scales biological response from acute A-bomb exposure to lower dose rates
  - Mars mission exposures will reach over 1 Sv but at a low rate of \(~1\) mSv/day
  - \(~4-5\) Sv is the acute whole body exposure with 50% lethality rate (LD_{50})
  - Therapy regimens deliver \(~20\) Sv but protracted over time

- Quality factor (large uncertainties)
  - Scales biological response from low LET gammas to response for high LET radiation
  - Derived mainly from limited animal studies with accelerator beams
  - Increased tumor lethality and other factors not accounted for in present model
  - Preliminary model for cardiovascular risk (non-cancer) being considered (larger uncertainties)
Risk Estimate – 1 year mission

• NASA permissible exposure limits
  - Astronaut career REID does not exceed 3%
  - Protect against uncertainties in such projections at a 95% CL
  - Detriments to central nervous system and cardiovascular systems being studied

• Risk assessment for 1 year mission is 1.83% with upper 95% confidence level of 7.57%
  - NASA radiobiology program is focused on reducing these uncertainties

Probabilistic REID for 35 year old female astronaut (never smoker) on a 1 year mission during solar minimum behind 20 g/cm² of aluminum

20 g/cm² aluminum spherical shell shielding geometry with astronaut
Biological Consequences and Risk

- Exposure to the space radiation environment presents a serious health risk to astronauts on deep space missions
  - Large uncertainties connected to the biological response
  - Detriments to central nervous system and cardiovascular systems being studied

- In order to reduce these uncertainties, radiobiology experiments are performed
  - Experiments performed at ground based accelerators
  - Goal is to elucidate biological mechanisms (stress, damage, repair, mutation)
  - Difficult to reproduce the full space radiation environment on the ground
  - Effort underway to develop a GCR simulator at the NASA Space Radiation Laboratory

nasa.gov/centers/johnson/hacd/about/divisions/hacd/hrp/about-space-radiation.html
humanresearchroadmap.nasa.gov/evidence/reports/Carcinogenesis.pdf
Summary

• Radiation exposure to astronauts on long duration deep space missions is a serious concern

• NASA continues to improve models to better characterize the radiation fields
  – Measurement gaps on the ground and in space are being addressed

• 3DHZETRN is a significant step forward for radiation transport at NASA
  – Computational efficiency has been maintained despite added complexity
  – Transport code agrees with Monte Carlo to the extent they agree with each other in most cases
  – Nuclear physics models/databases need to be updated

• Radiobiology research being pursued to reduce uncertainties
  – Cancer risk model continues to be improved with emphasis on dose-rate and quality factor
  – CNS effects are being studied experimentally with some modeling efforts as well
  – Preliminary model for cardiovascular risk exists, but is highly uncertain
  – GCR simulator efforts will provide a more realistic exposure scenario for accelerator studies

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