Space Radiation Research for Human Space Missions

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#JOURNEYTOMARS

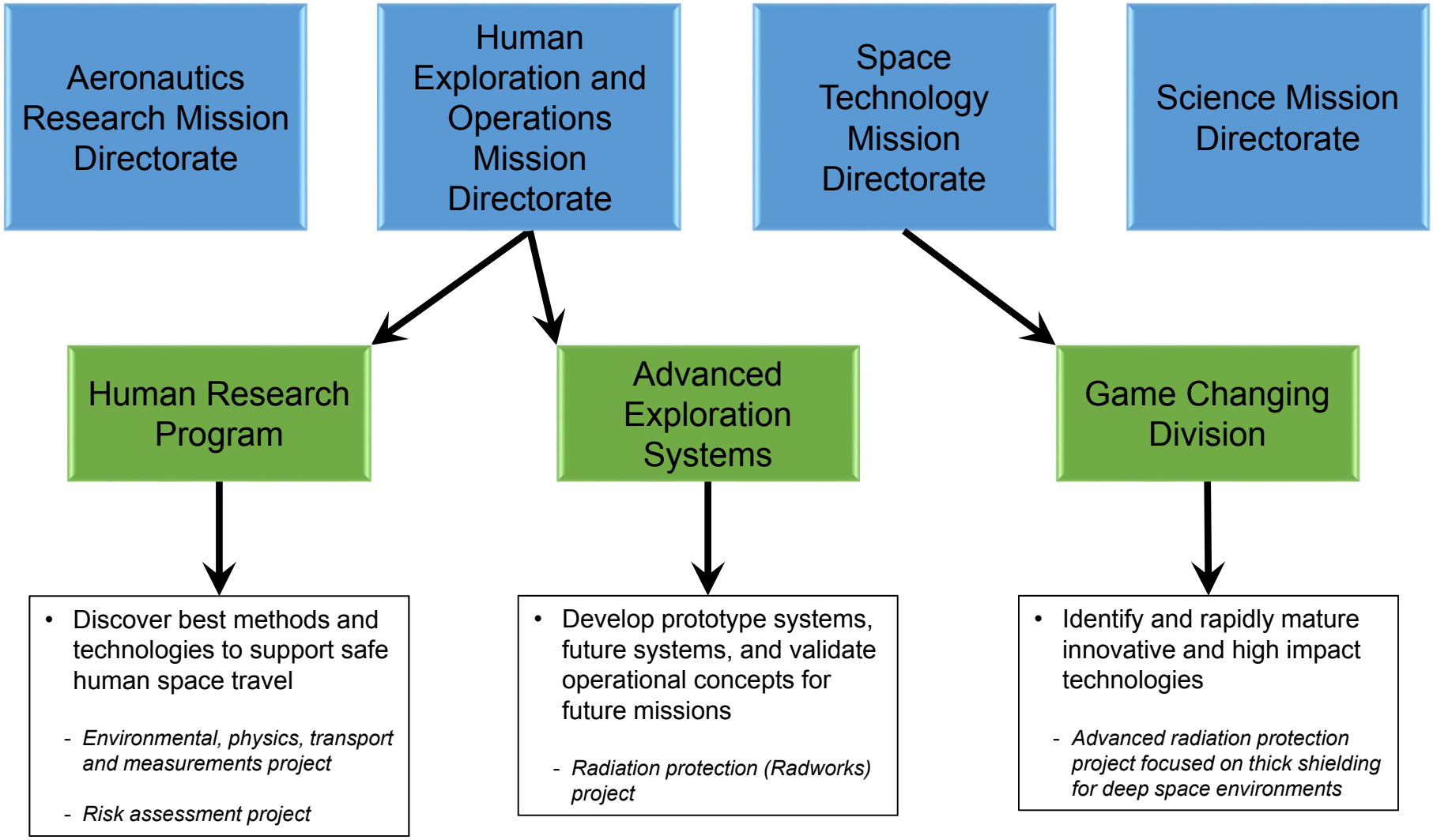
- Human mission to Mars presents unique challenges
  - ~9 months to reach Mars
  - Radiation environment is more severe in deep space than in low Earth orbit
- Radiation exposure identified as a key risk for Mars
  - Radiation risk estimates exceed NASA limits
  - Exceeding limits does not preclude mission 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

NASA'S JOURNEY TO MARS

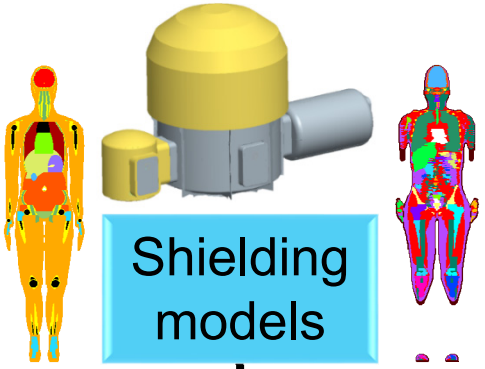
Outline

- Background
- Space radiation environments
- Physical interactions
- Radiation Transport
- Biological consequences and risk

Organization

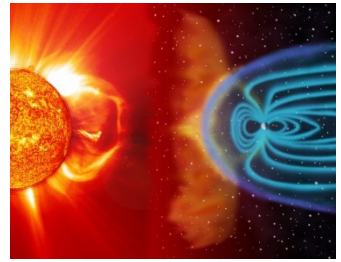


Background

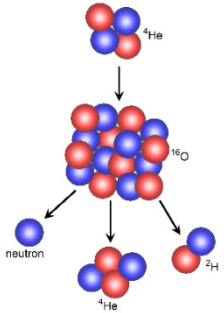


Shielding models

nasa.gov/sites/default/files/14-271.jpg

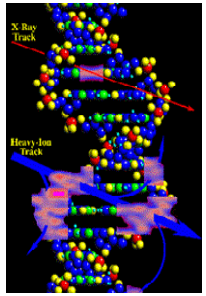


Environment models



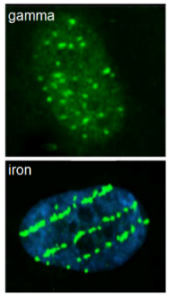
Physics models

Radiation transport models



nasa.gov/centers/johnson/slsd/about/divisions/hacd/hrp/about-space-radiation.html

Exposure & Biological response

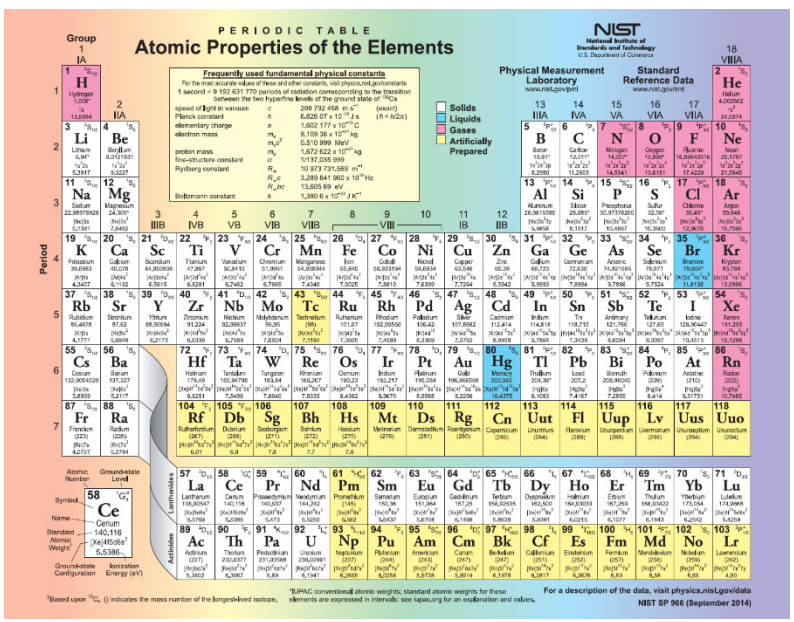


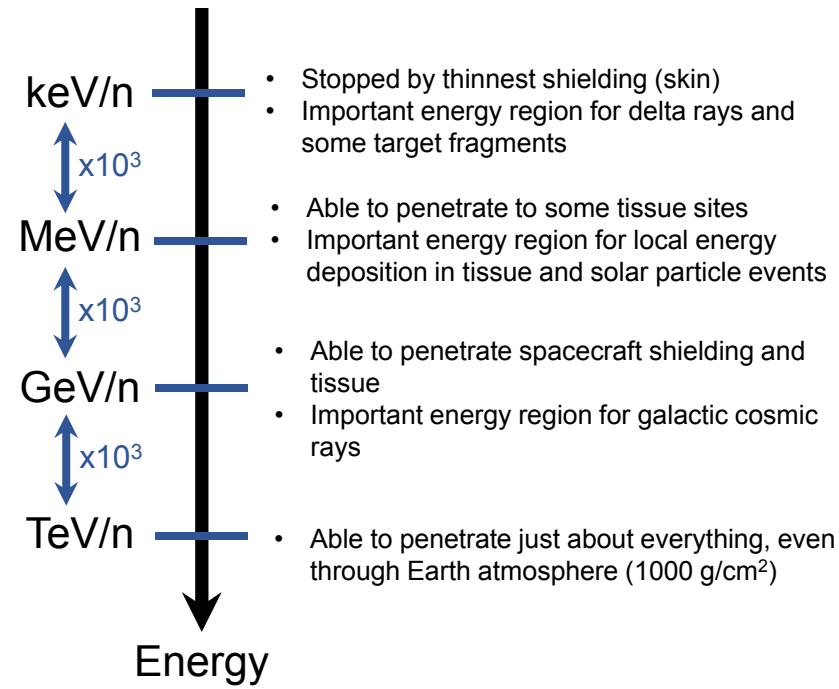
humanresearchroadmap.nasa.gov/evidence/reports/Carcinogenesis.pdf

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

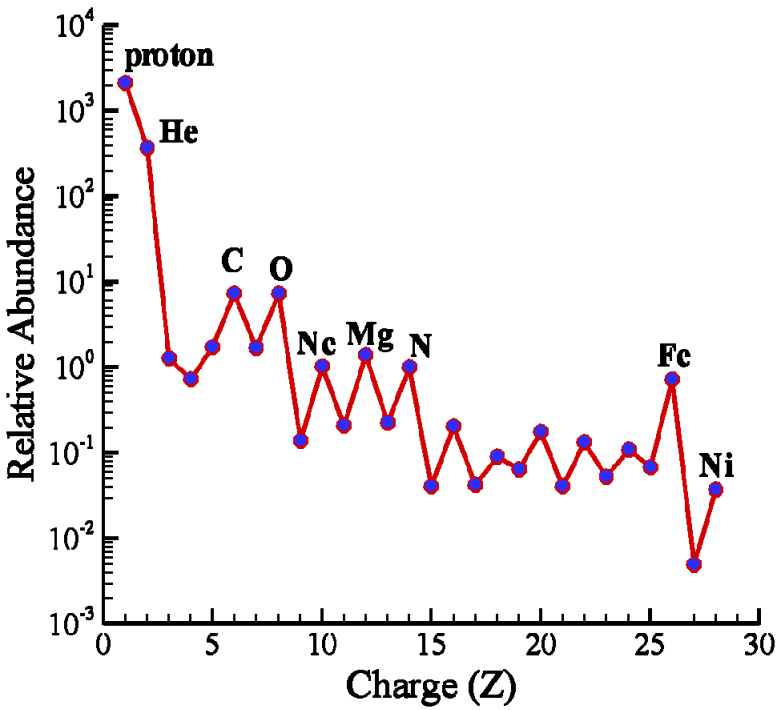




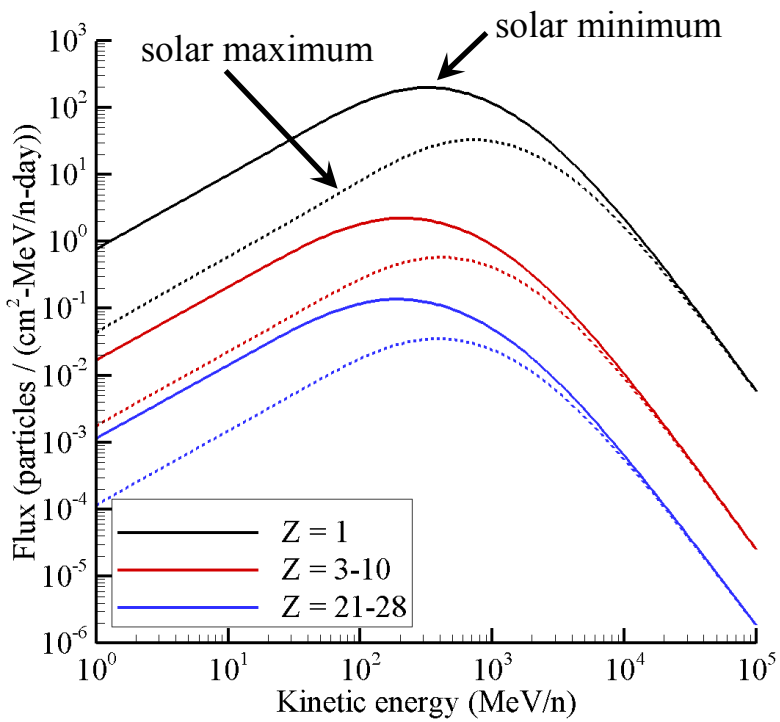
Space Radiation Environment

- 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

Relative abundance of GCR ions during solar minimum

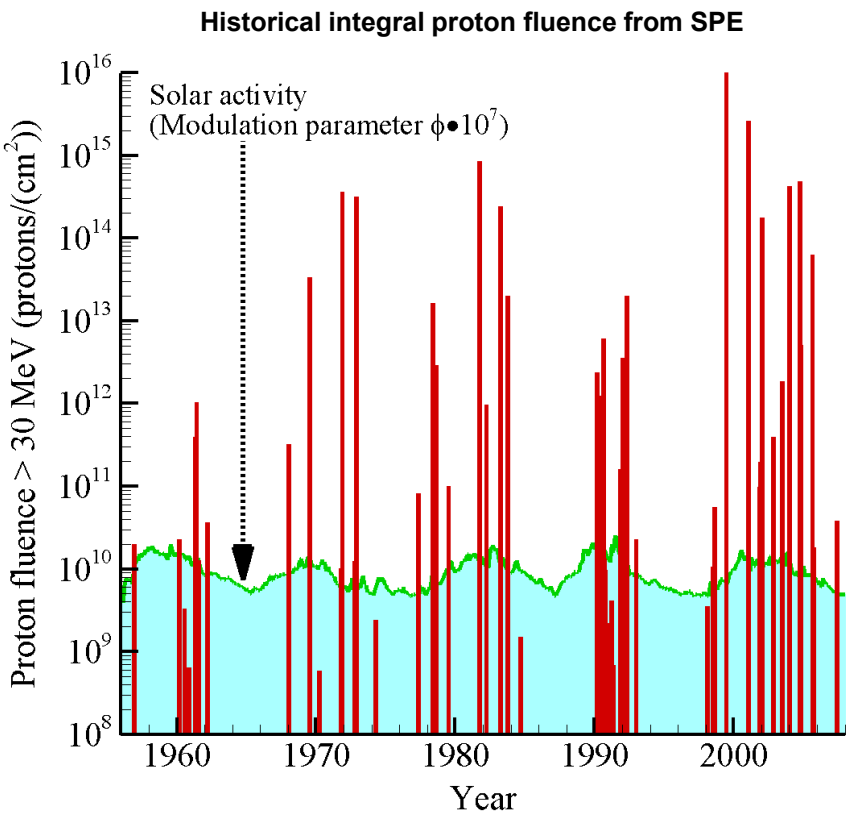


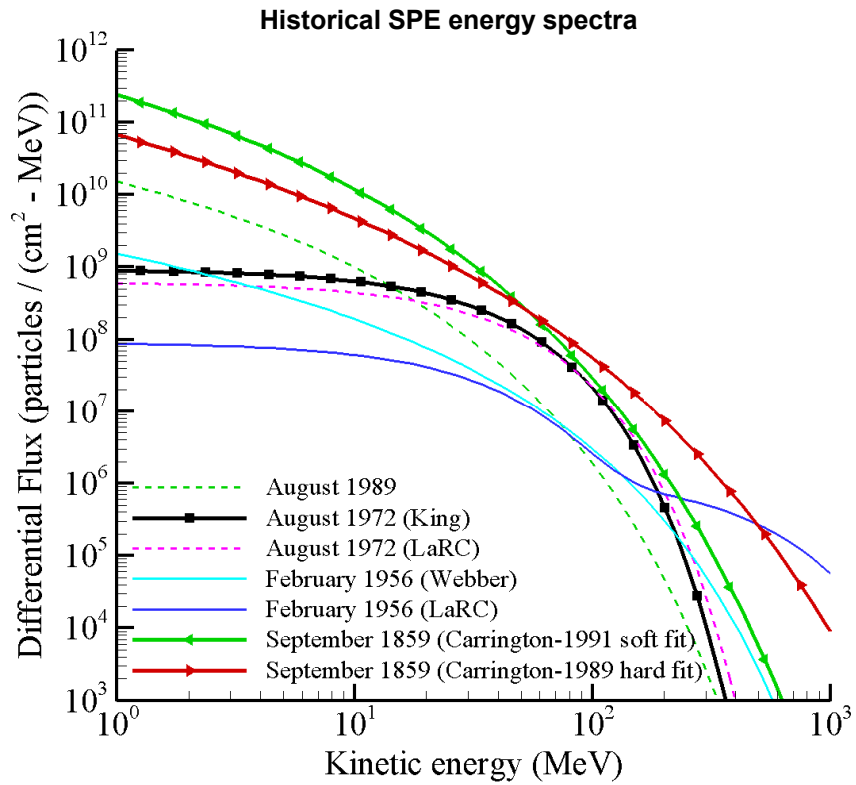
Differential energy spectrum of GCR ions



Space Radiation Environment

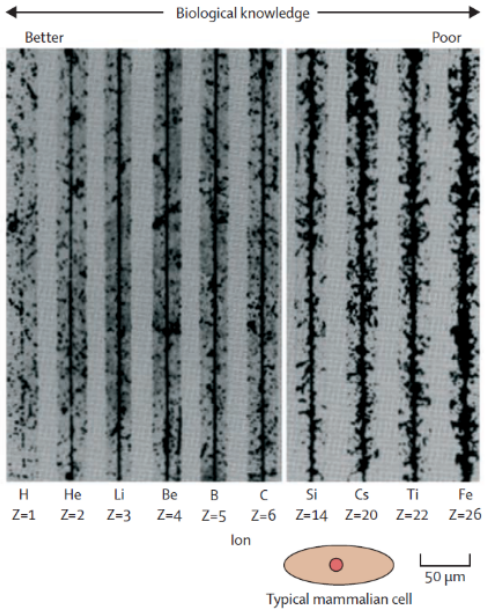
- Solar particle events (SPE) are intense bursts of protons from the Sun
  - Difficult to predict occurrence, spectral shape, or magnitude
  - More likely to occur during periods of heightened solar activity (solar max)
  - Energies up to several hundred MeV (may extend up to GeV)
  - Presents serious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





Physical Interactions

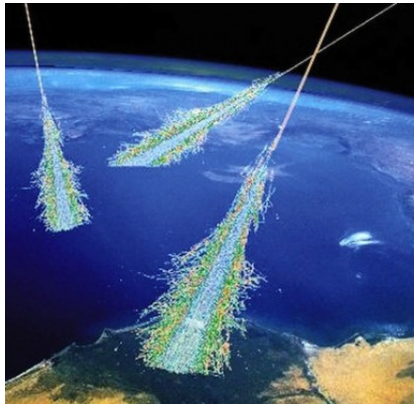
- The ambient radiation field is modified as it passes through bulk matter
  - Charged particles are slowed down
  - Secondary particle production can occur



McDonald, NASA SP 71 (1965)

- 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

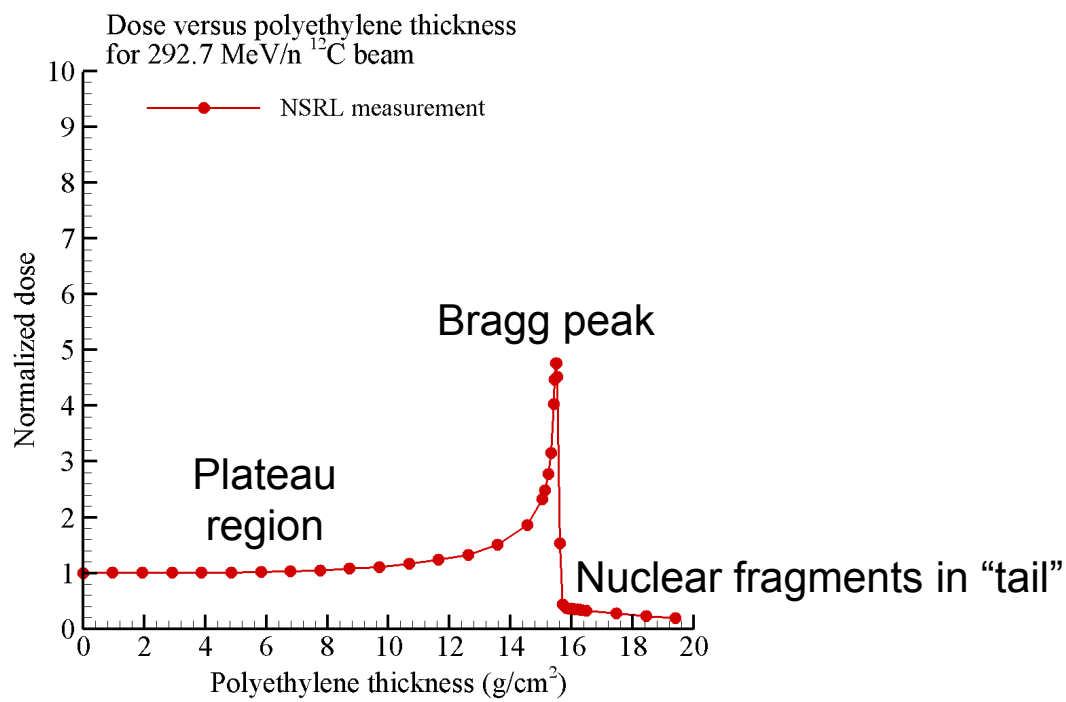


Artist depiction of cosmic ray induced atmospheric cascade. [Simon Swordy (U. Chicago), NASA]

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

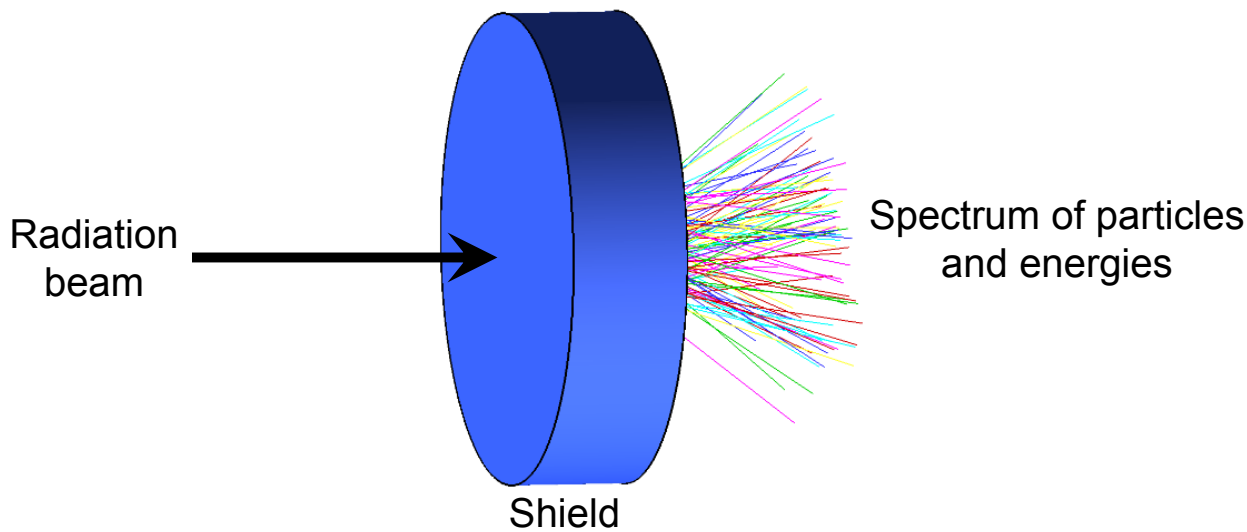
- Monte Carlo methods are typically used in clinical applications to describe beam interactions with tissue
  - Green's function methods have been developed at ODU in support of NASA applications
  - Tweed, Rockell, Walker, et al.



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)[1,2] begin investigating deterministic methods for space radiation transport applications
  - Starting point was the 3D linear Boltzmann transport equation

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

1. Wilson and Lamkin, Perturbation theory for charged-particle transport in one dimension. *Nucl. Sci. & Eng.* **57**(4): 292-299; 1975.
2. Wilson et al.,Transport methods and interactions for space radiations, NASA RP-1257, 1991.

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Flux of type *j* particles at position **x** with kinetic energy *E* moving in the direction of $\boldsymbol{\Omega}$

1. Wilson and Lamkin, Perturbation theory for charged-particle transport in one dimension. *Nucl. Sci. & Eng.* **57**(4): 292-299; 1975.
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$$\left[\underline{\boldsymbol{\Omega}\bullet\nabla} - \underline{\frac{1}{A_j}\frac{\partial}{\partial E}S_j(E)} + \sigma_j(E)\right]\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E) = \sum_k \int \sigma_{jk}(E,E',\boldsymbol{\Omega},\boldsymbol{\Omega}')\phi_k(\boldsymbol{x},\boldsymbol{\Omega}',E')d\boldsymbol{\Omega}'dE'$$

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

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

1. Wilson and Lamkin, Perturbation theory for charged-particle transport in one dimension. *Nucl. Sci. & Eng.* **57**(4): 292-299; 1975.
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Reaction cross section for type *j* particles with kinetic energy *E*

Production cross section for type k particles with direction $\boldsymbol{\Omega}'$ and energy *E*' producing type j particles with direction $\boldsymbol{\Omega}$ and energy *E*

1. Wilson and Lamkin, Perturbation theory for charged-particle transport in one dimension. *Nucl. Sci. & Eng.* **57**(4): 292-299; 1975.
2. Wilson et al.,Transport methods and interactions for space radiations, NASA RP-1257, 1991.

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: $\sigma_{jk}(E,E',\Omega,\Omega') = \tilde{\sigma}_{jk}(E,E')\delta(1-\Omega\bullet\Omega')$
  - 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

1. Wilson et al., Transport methods and interactions for space radiations, NASA RP-1257, 1991.
2. Slaba et al., Faster and more accurate transport procedures for HZETRN. *J. Comp. Phys.* **229**: 9397-9417; 2010.
3. Slaba et al., Reduced Discretization Error in HZETRN. *J. Comp. Phys.* **234**: 217-229; 2012.
4. Slaba, Faster Heavy Ion Transport for HZETRN. NASA TP 2013-217803, 2013.

Bi-directional Transport Methods

- Verification and validation for straight ahead approximation (HZETRN)
  - Extensively validated using space-flight measurements on ISS and shuttle[1,2]
  - Compared to recent data from the Mars Science Laboratory Radiation Detector (MSL/RAD)[3]
  - Verification against Monte Carlo simulations have been performed[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[5]
  - Further improvements fully coupled forward/backward transport through multiple elastic collisions[4]
  - Light ion semi-analytic solution also implemented for low energies[4]

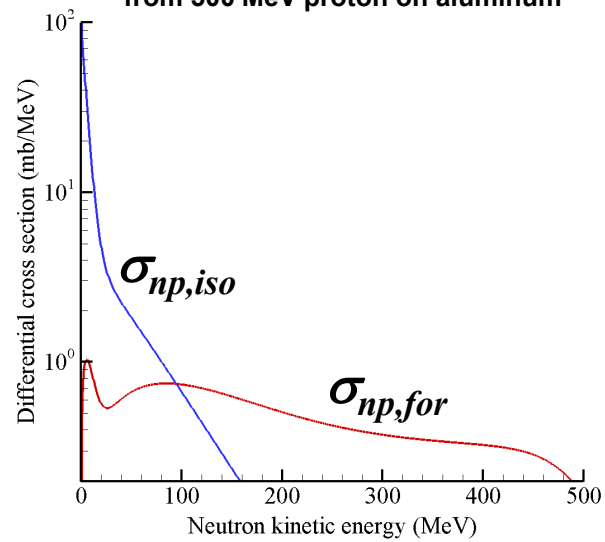
1. Wilson et al., Verification and validation: High charge and energy (HZE) transport codes and future development. NASA TP-2005-213784, 2005.
2. Slaba et al., Pion and electromagnetic contribution to dose: Comparisons of HZETRN to Monte Carlo results and ISS data. *Adv. Space Res.* **52**: 62-78; 2013.
3. Matthia et al., Particle Spectra on the Martian Surface. SWSC, accepted; 2015.
4. Slaba et al., Coupled neutron transport for HZETRN. *Radiat. Meas.* **45**: 173-182; 2010.
5. Clowdsley et al., A comparison of the multigroup and collocation methods for solving the low-energy neutron Boltzmann equation. *Can. J. Phys.* **78**: 45-56; 2000.

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]

Differential cross section for neutron production from 500 MeV proton on aluminum



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

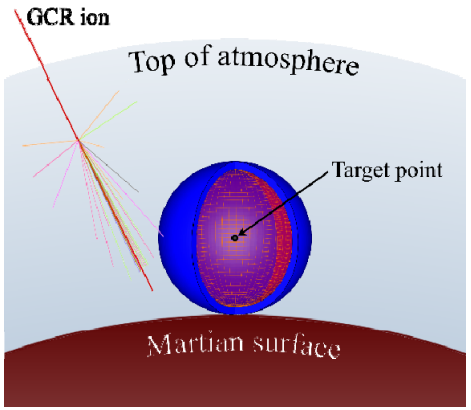
$$\left[-\frac{\partial}{\partial x}+\sigma_n(E)\right]\phi_n^{(b)}(x,E)=\int\tilde{\sigma}_{nn}^{(f)}(E,E')\phi_b(x,E')dE'+\int\tilde{\sigma}_{nn}^{(b)}(E,E')\phi_f(x,E')dE'$$

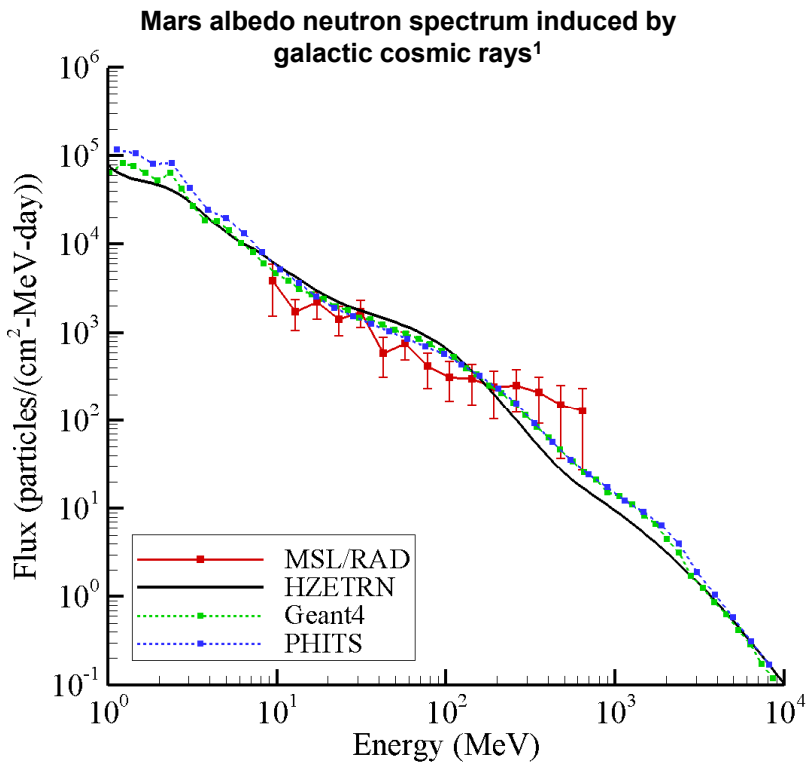
- Solution method for coupled equations[2]
  - Neumann series solution
  - Each term in series solved using collocation methods and back-substitution for matrix inversion

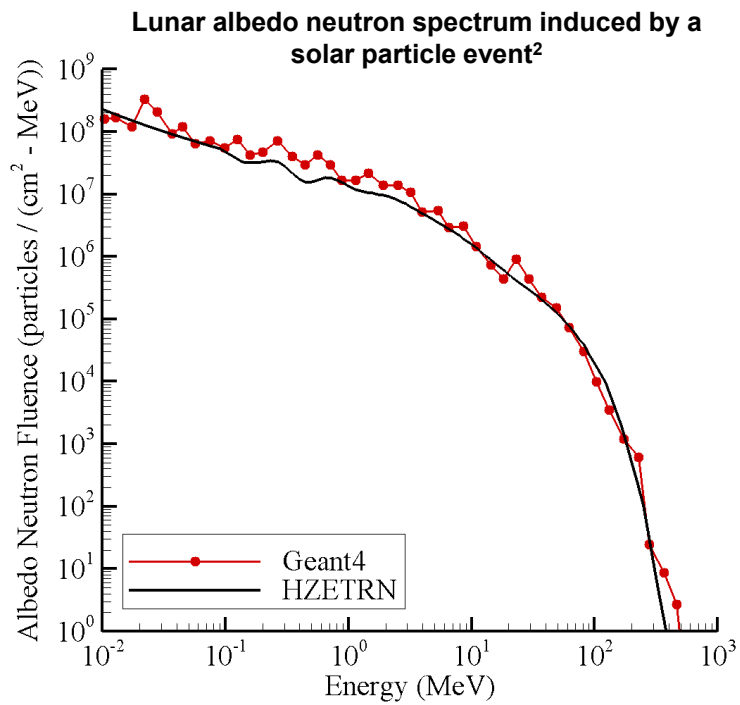
1. Clowdsley et al., A comparison of the multigroup and collocation methods for solving the low-energy neutron Boltzmann equation. *Can. J. Phys.* **78**: 45-56; 2000
2. Slaba et al., Coupled neutron transport for HZETRN. *Radiat. Meas.* **45**: 173-182; 2010.

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





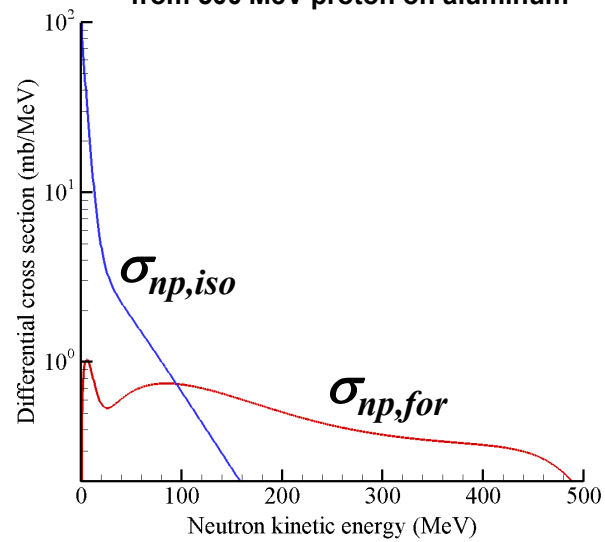


1. Matthia et al., Particle Spectra on the Martian Surface. SWSC, accepted; 2015.
2. Slaba et al., Variations in lunar neutron dose estimates. *Rad. Res.* **176**: 827-841; 2011.

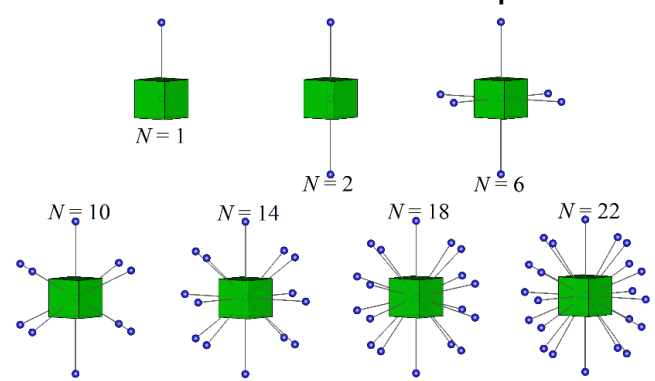
3D Transport Methods

- 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
- Isotropic 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

Differential cross section for neutron production from 500 MeV proton on aluminum



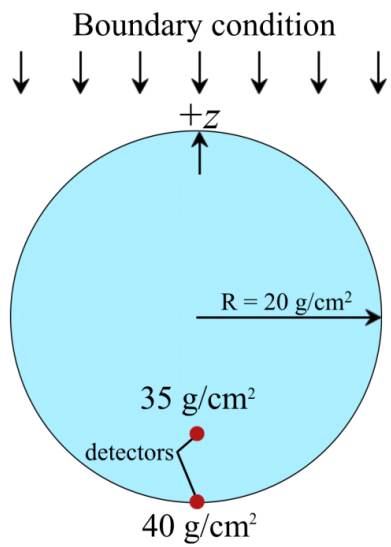
Stream distributions for 3D transport



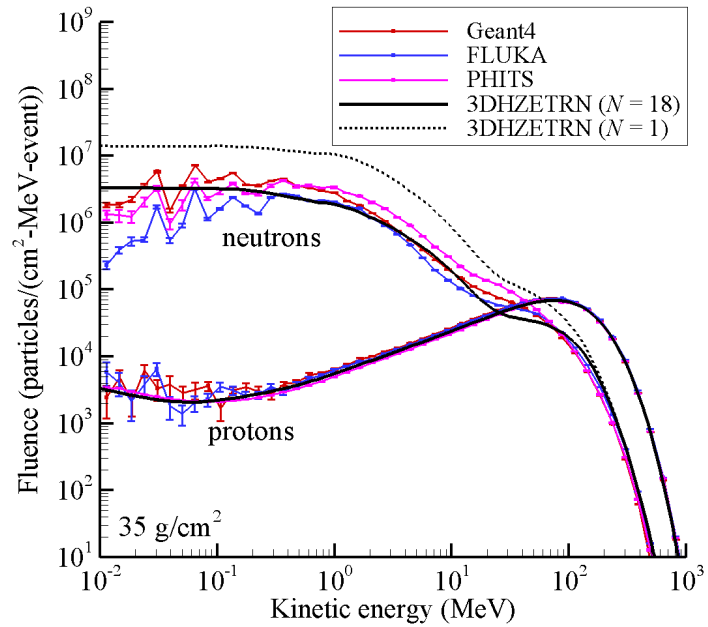
1. Wilson et al., Advances in NASA space radiation research: 3DHZETRN, *Life Sci. Space Res.* **2**: 6-22; 2014.

Verification (I)

One layer spherical geometry used for benchmark verification



Nucleon fluence induced by the 1956 Webber SPE in test geometry

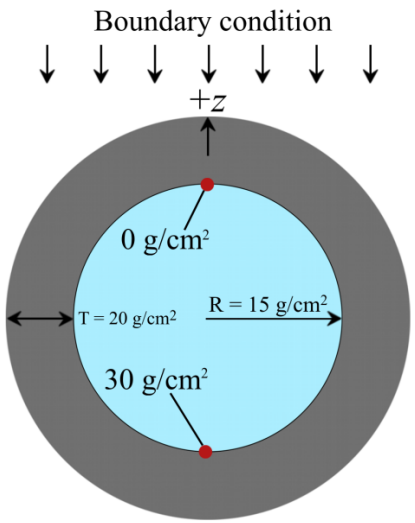


- First verification of 3D methods utilized simple spherical geometry
  - Directed (instead of isotropic) boundary conditions to emphasize 3D features
- 3DHZETRN agrees with Monte Carlo to the extent they agree with each other
  - Significant improvement over straight ahead approximation (N=1)
  - Main difference between codes is runtime: seconds for 3DHZETRN and years for Monte Carlo

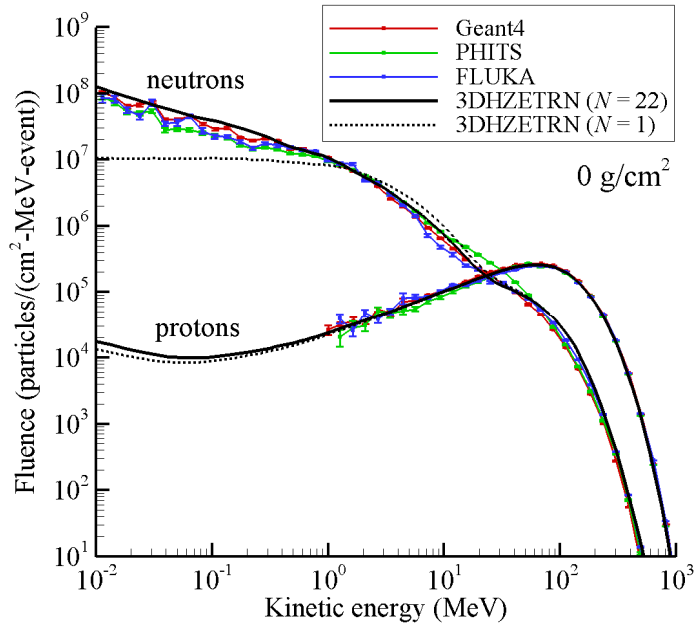
1. Wilson et al., Advances in NASA space radiation research: 3DHZETRN, *Life Sci. Space Res.* **2**: 6-22; 2014.

Verification (II)

Two layer spherical geometry used for benchmark verification



Nucleon fluence induced by the 1956 Webber SPE in test geometry

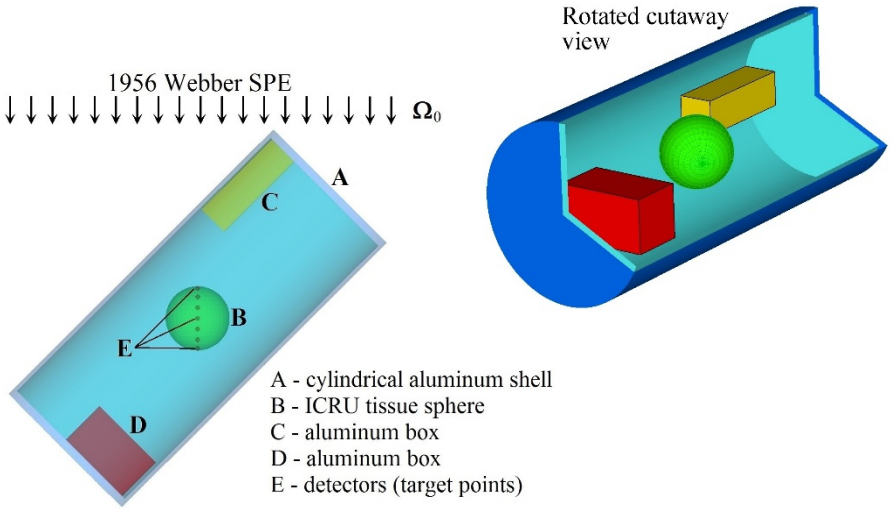


- Second verification utilized simple spherical geometry with two materials
  - Tissue sphere (astronaut proxy) embedded in spherical aluminum shell
- 3DHZETRN agrees with Monte Carlo to the extent they agree with each other
  - Significant improvement over straight ahead approximation (N=1)
  - Main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

1. Wilson et al., Advances in NASA space radiation research: 3DHZETRN, *Life Sci. Space Res.* **4**: 46-61; 2015.

Verification (III)

Combinatorial geometry used for benchmark verification



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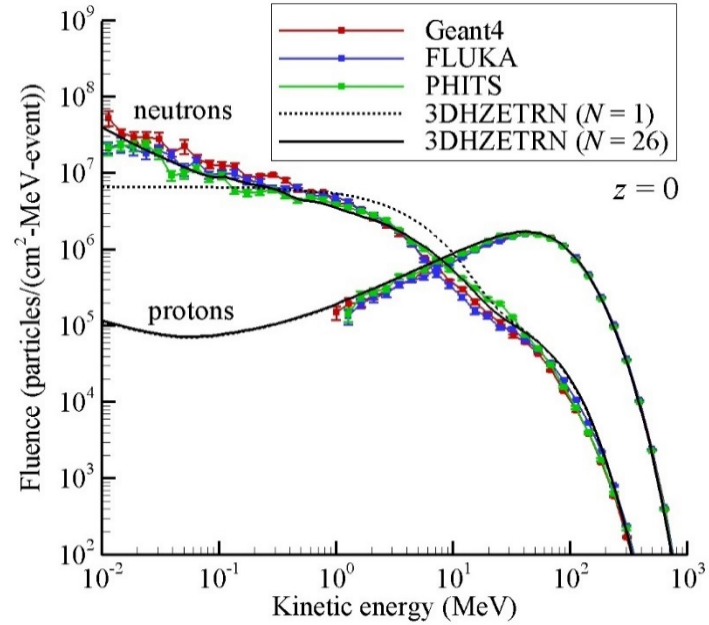


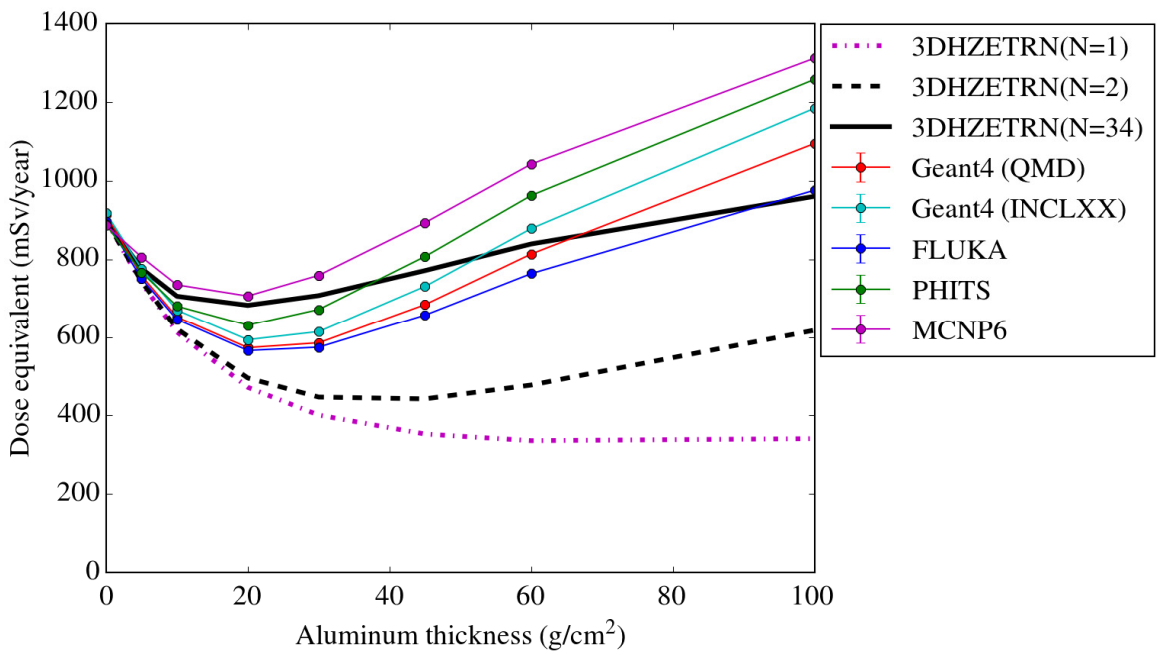
- Latest verification utilized complex combinatorial geometry
  - Tissue sphere (astronaut proxy) embedded in cylindrical aluminum shell with internal boxes
- 3DHZETRN agrees with Monte Carlo to the extent they agree with each other
  - Significant improvement over straight ahead approximation (N=1)
  - Main difference between codes is runtime: seconds for 3DHZETRN and years for Monte Carlo

1. Wilson et al., Solar proton transport within an ICRU sphere surrounded by a complex shield: combinatorial geometry. NASA TP 2015-218980, 2015.

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

Total dose equivalent versus aluminum thickness for a GCR boundary condition



Exposure Quantities

- Flux or fluence
  - Example units: particles/(cm^2-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

$$REID = \sum_{T} \int_{a_E}^{\infty} \frac{\tilde{S}(a)}{\tilde{S}(a_E)} \lambda_T^{(M)}(a, a_E, H_T) e^{-\sum_{T'} \int_{a_E}^{a} \lambda_{T'}^{(M)}(t, a_E, H_{T'}) dt} da$$

- 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 $\gg$20 Sv but protracted over time

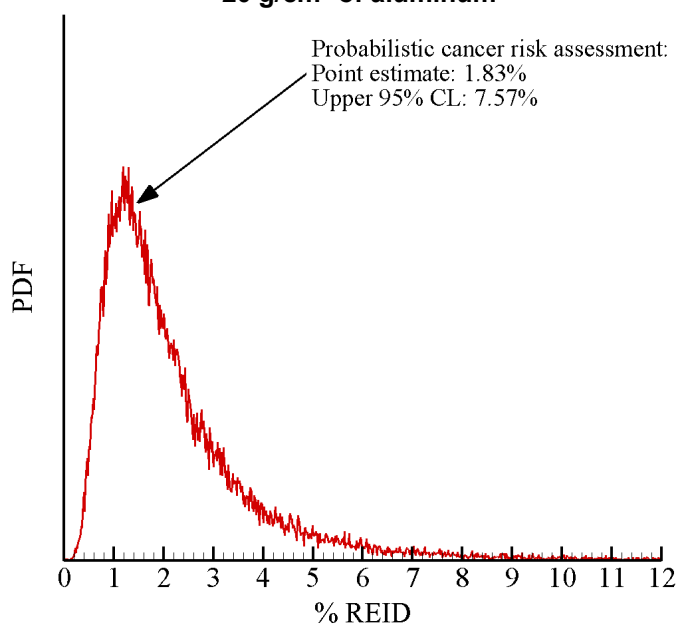
- Quality factor (large uncertainties)
  - Scales biological response from low LET gammas to response for high LET radiation
  - Derived mainly from limited animal studies with accelerator beams
  - Increased tumor lethality and other factors not accounted for in present model
  - Preliminary model for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

Risk Estimate – 1 year mission

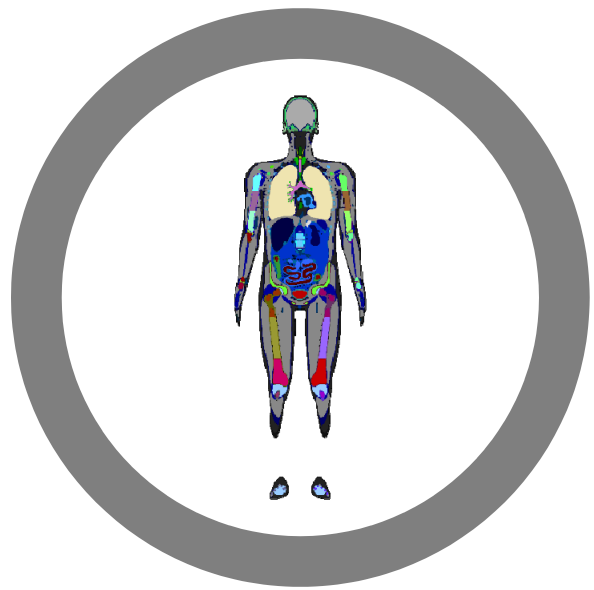
- NASA permissible exposure limits
  - Astronaut career REID does not exceed 3%
  - Protect against uncertainties in such projections at a 95% CL
  - Detriments to central nervous system and cardiovascular systems being studied

- 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/cm^2 of aluminum



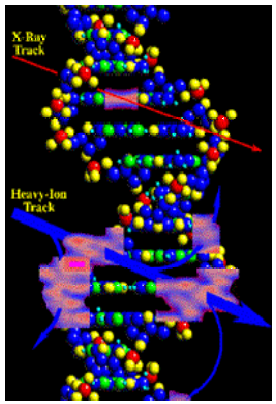
20 g/cm^2 aluminum spherical shell shielding geometry with astronaut



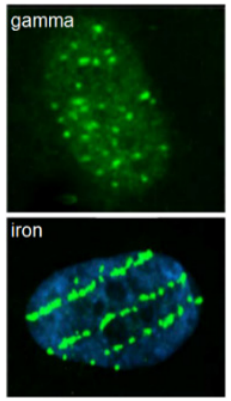
Biological Consequences and Risk

- 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/slsd/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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