Comparison of Space Radiation Calculations from Deterministic and Monte Carlo Transport Codes

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Summary
Motivation

There are many transport codes for space radiation calculations of heavy ion transport:

Deterministic transport (1-dimensional):
- HZETRN (from NASA Langley Research Center) - Fast
- UPROP (from Naval Research Lab)

Monte Carlo transport (3-dimensional):
- HETC, HETC-HEDS (from LANL/NASA/ORNL/UTK)
- FLUKA (from high energy physics)
- GEANT4 (from high energy physics)
- MCNP and MCNPX (from LANL)
- PHITS (from Japan/Sweden)
- ...

→ Are these models very different in typical space radiation calculations?

How different are 1-d deterministic results from 3-d Monte Carlo (MC) results?
Main physics in radiation transport codes

Let us look at a radiation transport equation in 1-dimension:

\[
\frac{\partial J_k(E, x)}{\partial x} = -\frac{J_k(E, x)}{\Lambda_k(E)} + \sum_j \frac{J_j(E, x)}{\Lambda_{kj}(E)} + \frac{\partial [w_k(E)J_k(E, x)]}{\partial E}
\]

Flux of particle type k

Loss of k due to its fragmentation:
\[\Lambda_k(E) = 1/(n^*\sigma_k(E))\]
total inelastic cross section of nuclear fragmentation of k

Gain of k because a heavier particle j can produce k:
\[\Lambda_{kj}(E) = 1/(n^*\sigma_{kj}(E))\]
Partial fragmentation cross section (j→k)

Ionization energy loss
\[w_k(E) = -dE/dx(E)\]

Fragmentation cross sections & energy loss are the key physics in radiation transport codes
Radiation transport codes being considered

Deterministic transport (1-dimensional):
- HZETRN (from NASA Langley Research Center)
- UPROP (from Naval Research Lab)  

Monte Carlo transport (3-dimensional):
- HETC, HETC-HEDS (from LANL/NASA/ORNL/UTK)
- FLUKA (from high energy physics)
- GEANT4 (from high energy physics)
- MCNP and MCNPX (from LANL)
- PHITS (from Japan/Sweden)

To compare the key physics in radiation transport codes, we consider the same radiation environment input, geometry & material, then compare dose-depth curves & particle spectra.
Space radiation cases being considered

3 external environments:
- Oct. 1989 Solar Particle Event (SPE),
- Jan. 2005 SPE,
- 1977 solar minimum Galactic Cosmic Rays (GCR)

2 materials: Aluminum or CH$_2$

2 geometries:
1) Slab geometry:
   a slab material
   under uni-directional irradiation

2) Spherical geometry:
   a spherical shell under isotropic irradiation,
   shell thickness 10g/cm$^2$
HZETRN & Monte Carlo show reasonable agreement in proton spectra, difference in neutrons, especially at low energies; UPROP gives a lower proton spectrum (Note: UPROP does not treat neutrons)

FLUKA, Geant4 & HZETRN are consistent in dose, some difference in dose equivalent; UPROP dose is lower behind shielding

2005 version of HZETRN includes improved neutron transport, especially at low energies (<100 MeV)

Neutron transport in HZETRN is still evolving with time

Proton transport remains ~same

OLTARIS: https://oltaris.larc.nasa.gov

HZETRN 2005 reference:
Heinbockel et al., NASA-TP-2009-215560
Results for slab geometry: GCR

Geant4 & HZETRN are consistent in dose; UPROP dose is lower behind shielding.

HZETRN & Monte Carlo show rough agreement in proton spectra, difference in neutrons, especially at low energies; UPROP proton spectrum is much lower.
Results for slab geometry: GCR

HZETRN, UPROP & Geant4 show reasonable agreements in Oxygen & Iron spectra,
→ fragmentation cross sections are similar in these models (for O & Fe at least)
Agrees with earlier findings based 1-dimensional transport:

Lin, Baalla & Townsend, Radiation Measurements 44 (2009)

“Variation of space radiation exposure inside spherical and hemispherical geometries”

• lowest radiation exposure is at the inside wall;
• highest exposure is at the center of the spherical shell;
• exposure decreases by a large factor in SPE environments

Results for spherical geometry

Good agreement for the SPE environment
Summary

We have compared typical space radiation calculations from two 1-dimensional deterministic codes (HZETRN, UROP) & two 3-dimensional Monte Carlo codes (FLUKA, Geant4)

Monte Carlo codes (FLUKA and Geant4) results are mostly consistent, HZETRN results are close to Monte Carlo results, except for neutrons

UPROP results are often quite different from the other 3 codes, suggesting the need of improvements (e.g. by treating neutrons)

Radiation exposure at different locations inside a spherical shell: 4 models give consistent results, earlier result of Lin, Baalla & Townsend is confirmed

To identify the exact physics causing the differences in the model results is very useful but will require more efforts