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

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Motivation

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

Deterministic transport (1-dimensional):

HZETRN (from NASA Langley Research Center)
UPROP (from Naval Research Lab)

Fast

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)
…

slower, but better treats 3-d particle transport

→ 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

Ionization energy loss
$w_k(E) = -dE/dx(E)$

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)

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) → *1995 version used here*
UPROP (from Naval Research Lab)

Monte Carlo transport (3-dimensional) :

HETC, HETC-HEDS (from LANL/NASA/ORNL/UTK)
FLUKA (from high energy physics) → *very limited results*
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

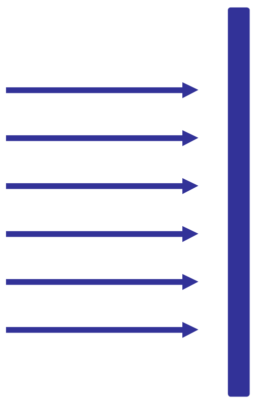
3 external environments:

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

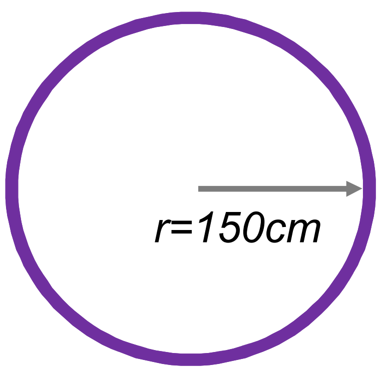
2 materials: Aluminum or CH_2

2 geometries:

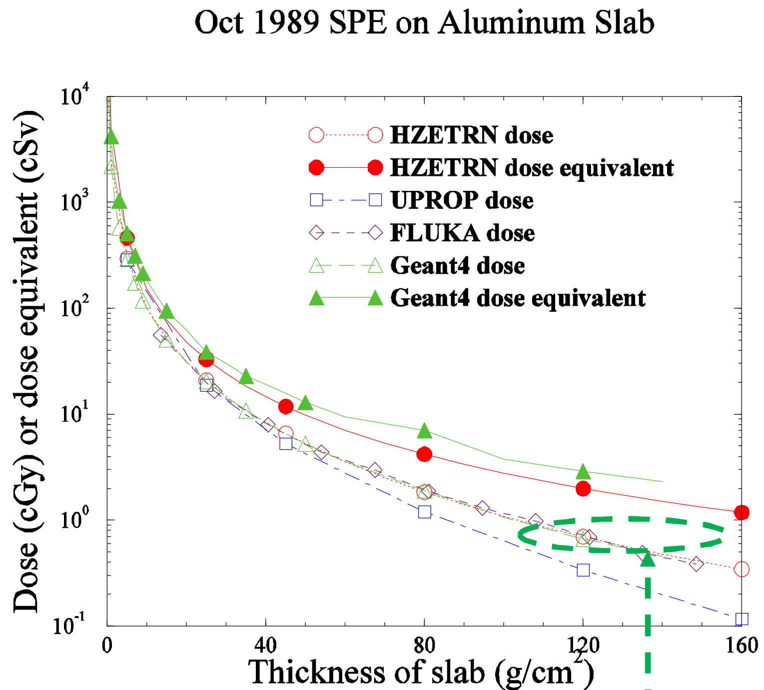
1) Slab geometry:
a slab material
under uni-directional irradiation

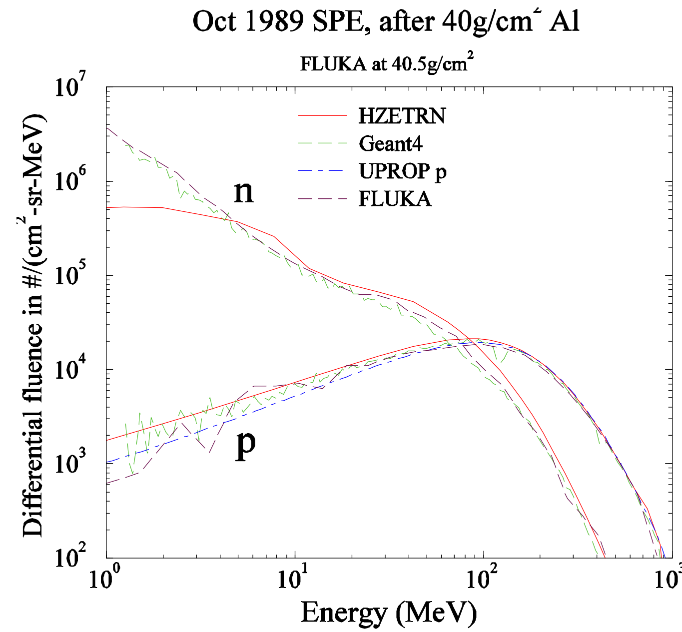


2) Spherical geometry:
a spherical shell under isotropic irradiation,
shell thickness $10 g/cm^2$

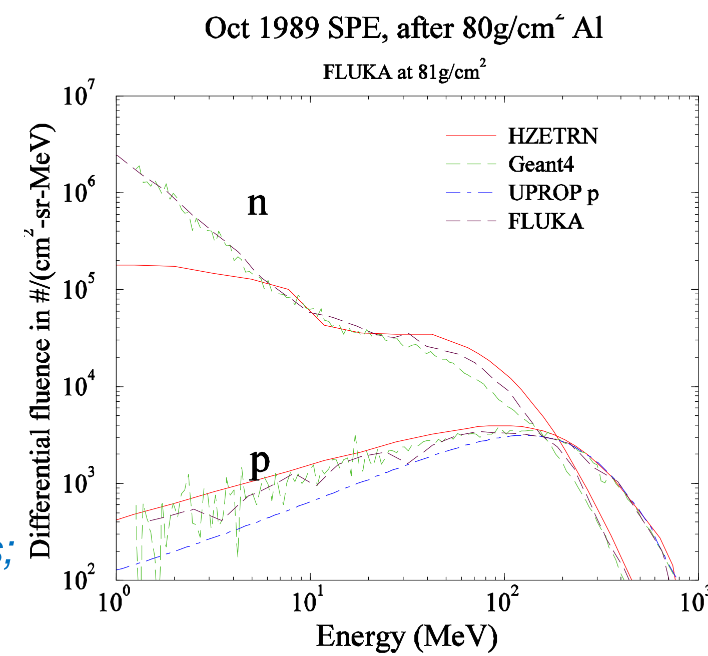


Results for slab geometry: SPE





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



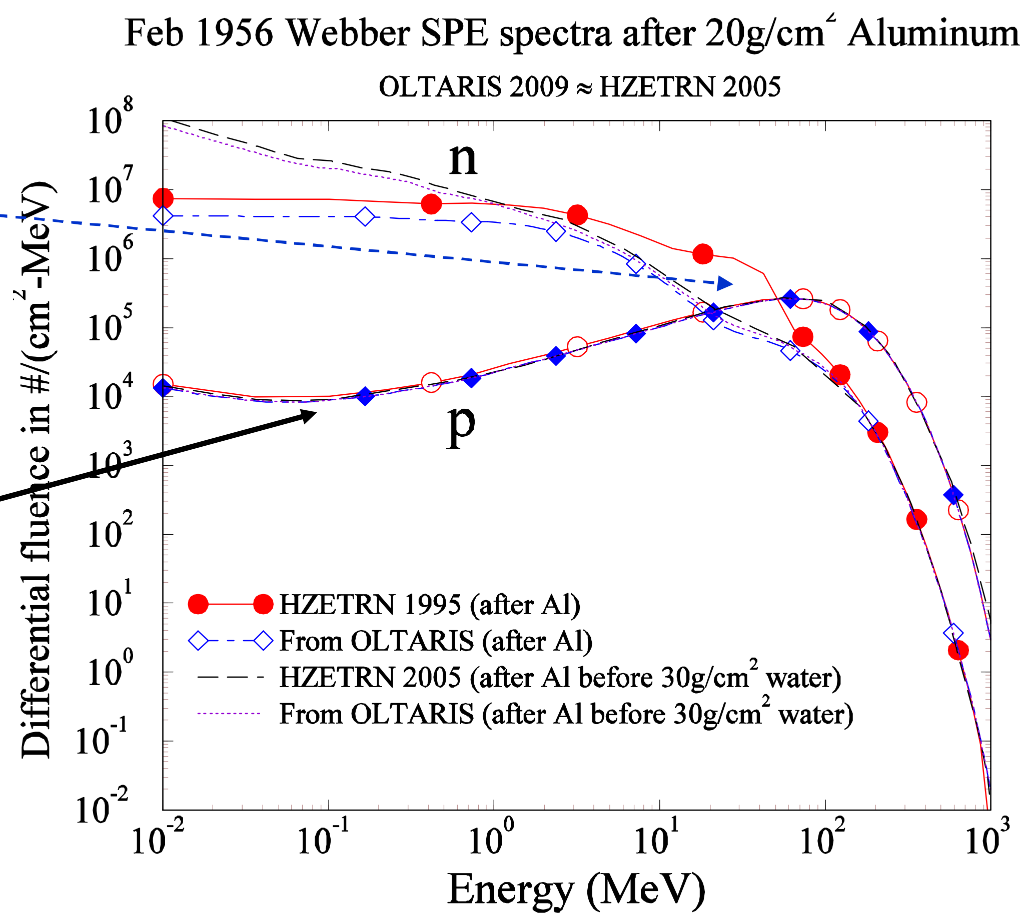
HZETRN & Monte Carlo show
reasonable agreement in proton spectra,
difference in neutrons, especially at low energies;
UPROP gives a lower proton spectrum
(Note: UPROP does not treat neutrons)

Results for SPE: new(2005) & old(1995) versions of HZETRN

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

Neutron transport in HZETRN is still evolving with time

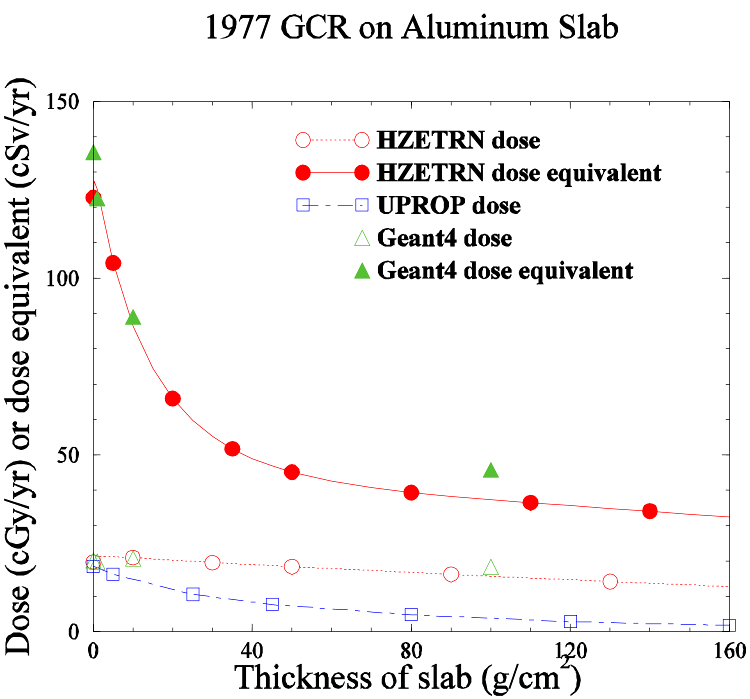
Proton transport remains ~same

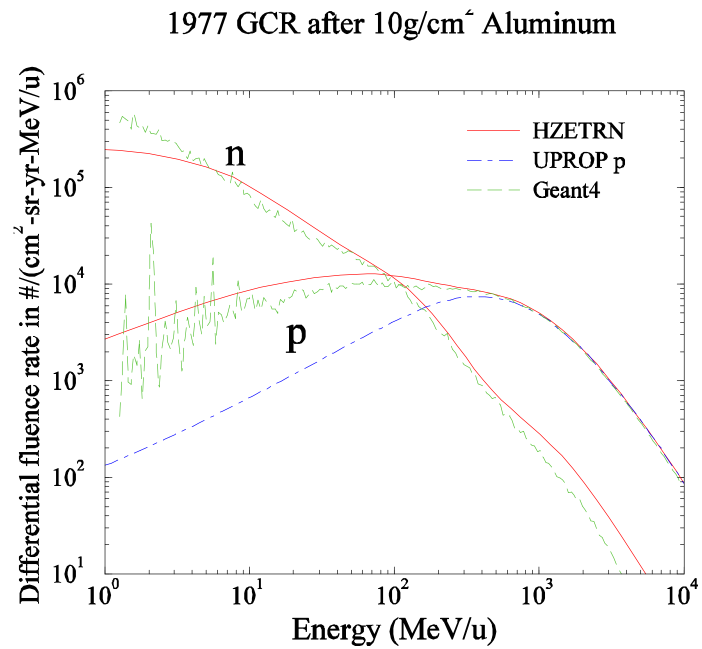


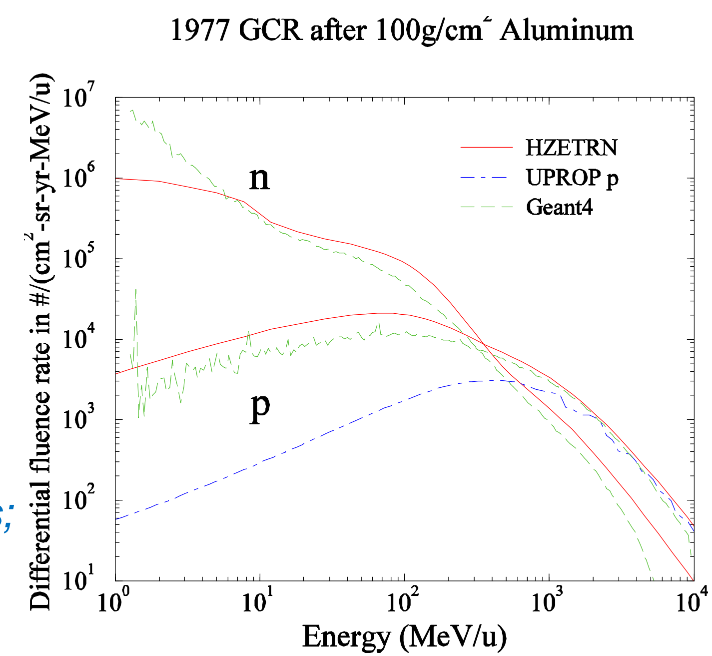
OLTARIS: https://oltaris.larc.nasa.gov

HZETRN 2005 reference:
Heinbockel et al., NASA-TP-2009-215560

Results for slab geometry: GCR



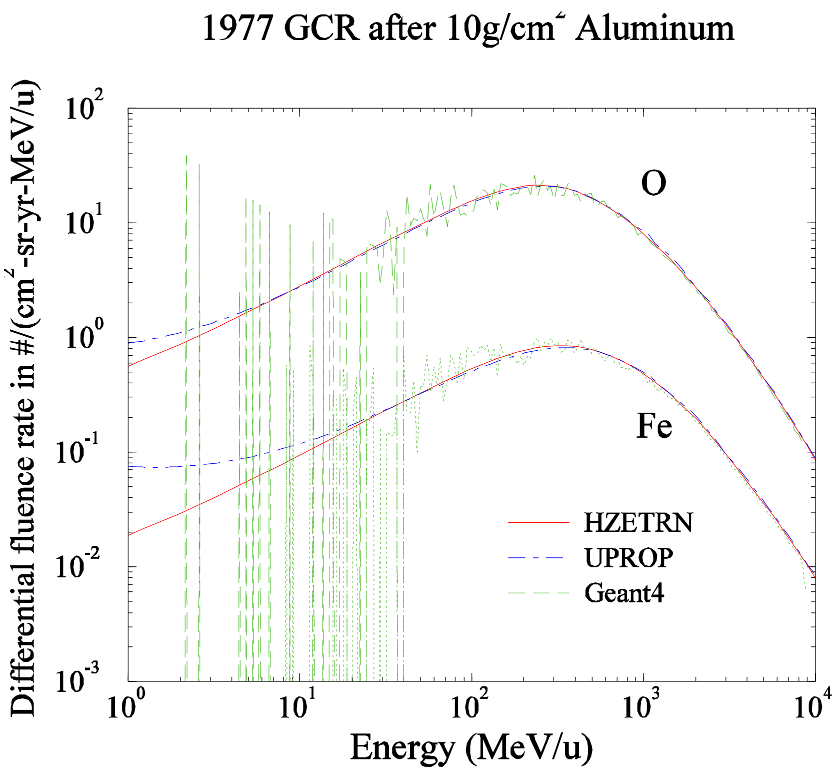


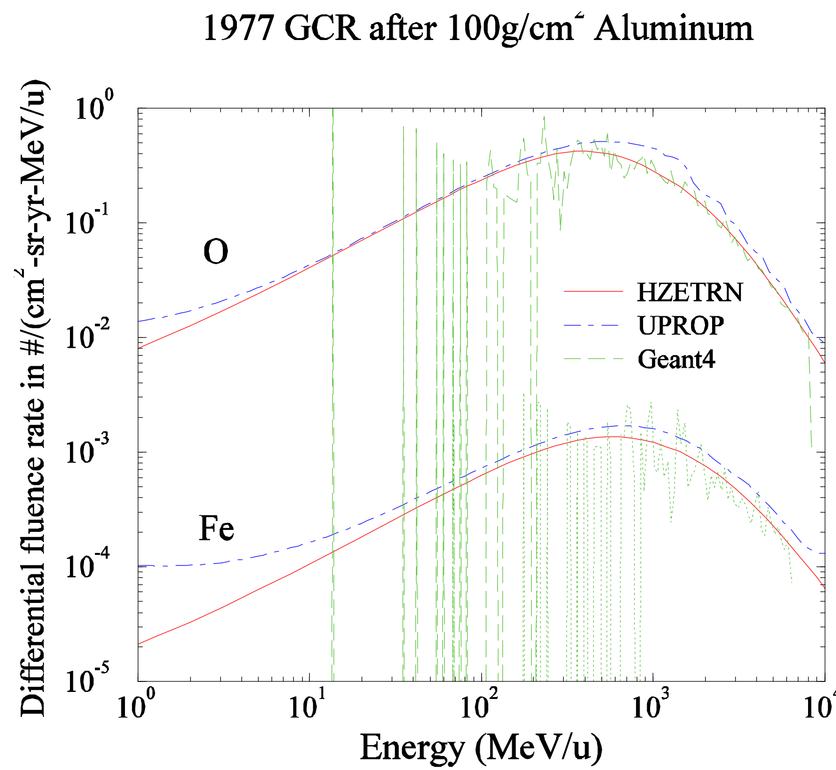


Geant4 & HZETRN are consistent in dose;
UPROP dose is lower behind shielding

HZETRN & Monte Carlo show
rough agreement in proton spectra,
difference in neutrons, especially at low energies;
UPROP proton spectrum is much lower

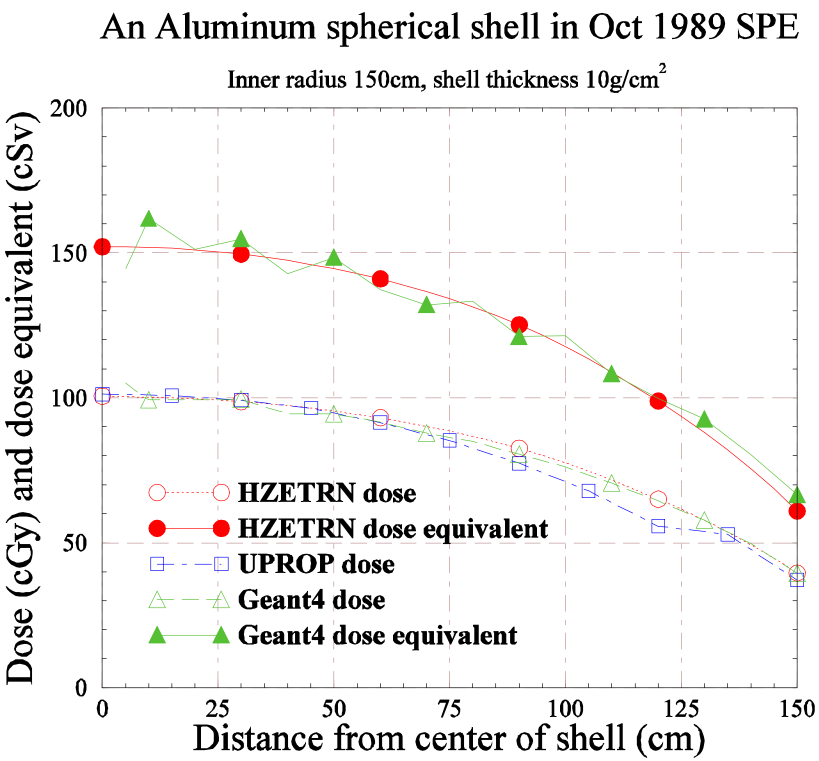
Results for slab geometry: GCR

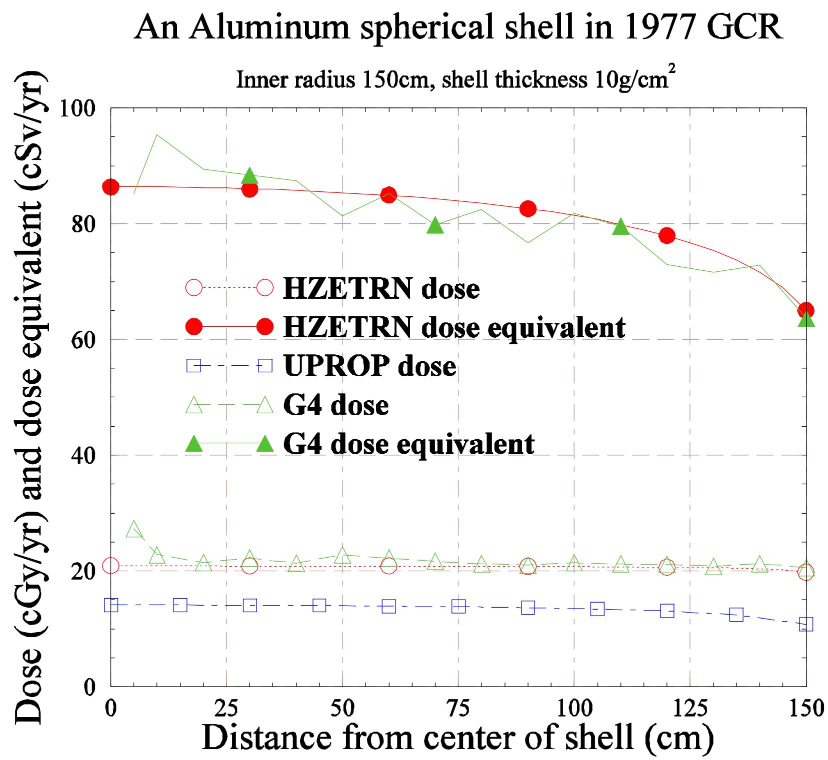




HZETRN, UPROP & Geant4
show reasonable agreements in Oxygen & Iron spectra,
→ fragmentation cross sections are similar in these models (for O & Fe at least)

Results for spherical geometry





Good agreement for the SPE environment

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

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