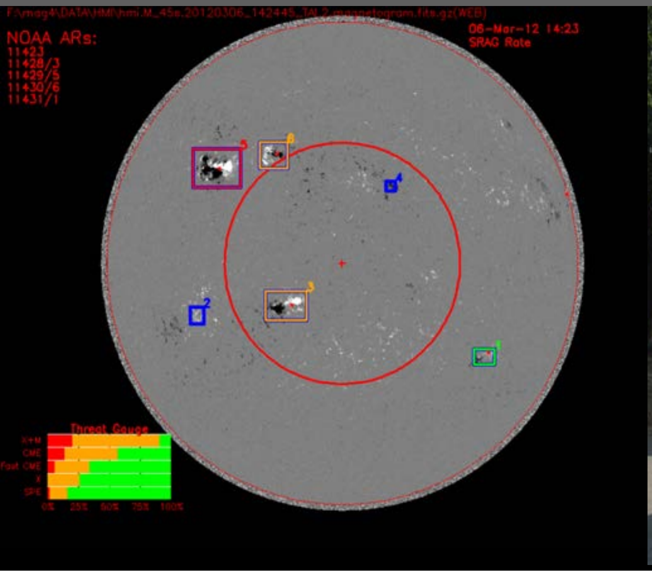
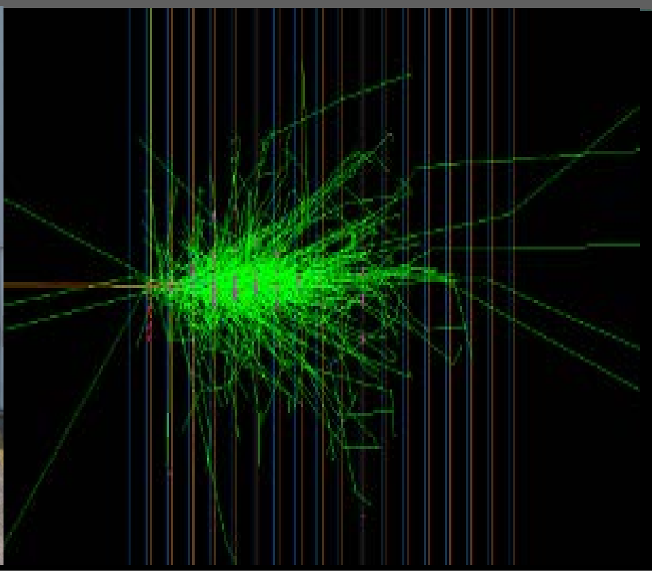
National Aeronautics and Space Administration

SCIENCE & TECHNOLOGY OFFICE





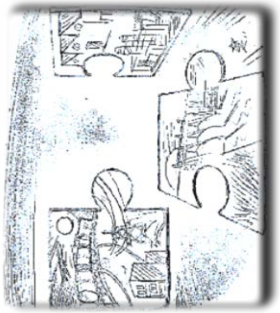
Modeling the radiation quality factor as a linear 'time'-dependent Ornstein-Uhlenbeck process

Nasser Barghouty

Astrophysics Office, NASA-MSFC

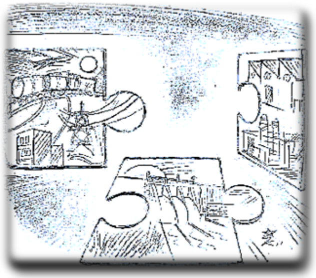
AMS Sectional Meeting, march 28, 2015, Huntsville, AL

The Main Points



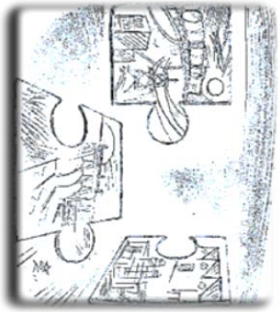
- ✓ **The drive**
  Capture the uncertainties in the Q factor for more robust exposure and risk estimates

- ✓ **A brief introduction to space radiation**
  The sources; the expected exposure; the risk; mitigation strategies



- ✓ **Modeling the Q factor**
  Namely Monte Carlo

- ✓ **The Q factor as a linear stochastic process**
  'time'-dependent Ornstein-Uhlenbeck



- ✓ **Benefits**
  Bracketing the risk?

Space Radiation: The Drive & The Challenges

The Drive

A NASA strategic radiation protection guideline is the:

"*Demonstration of shielding concepts providing radiation protection focusing on light-weight multi-functional structure-capable materials that can provide GCR/SPE protection while providing other functionalities such as thermal insulation, structural integrity, and/or MMOD protection*."

The Challenges

Effective shielding against the combined effects of GCRs and SEPs can be mass prohibitive

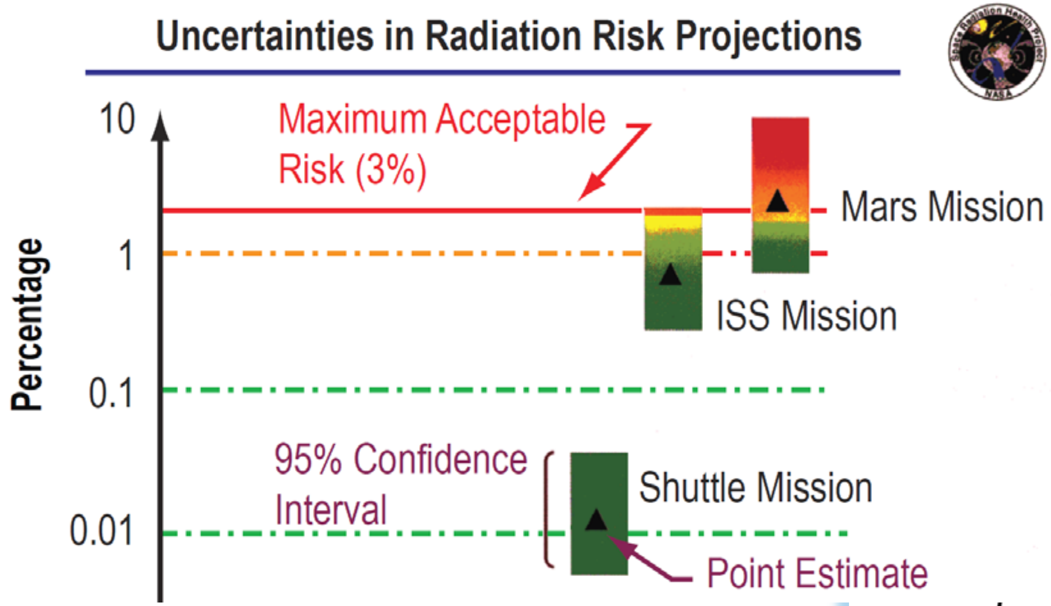
Shielding effectiveness of new, potential shielding materials (or combinations thereof) is not well characterized

Little data to guide dose and risk assessment models

Known, <u>large uncertainties and variabilities</u> in radiobiological effects

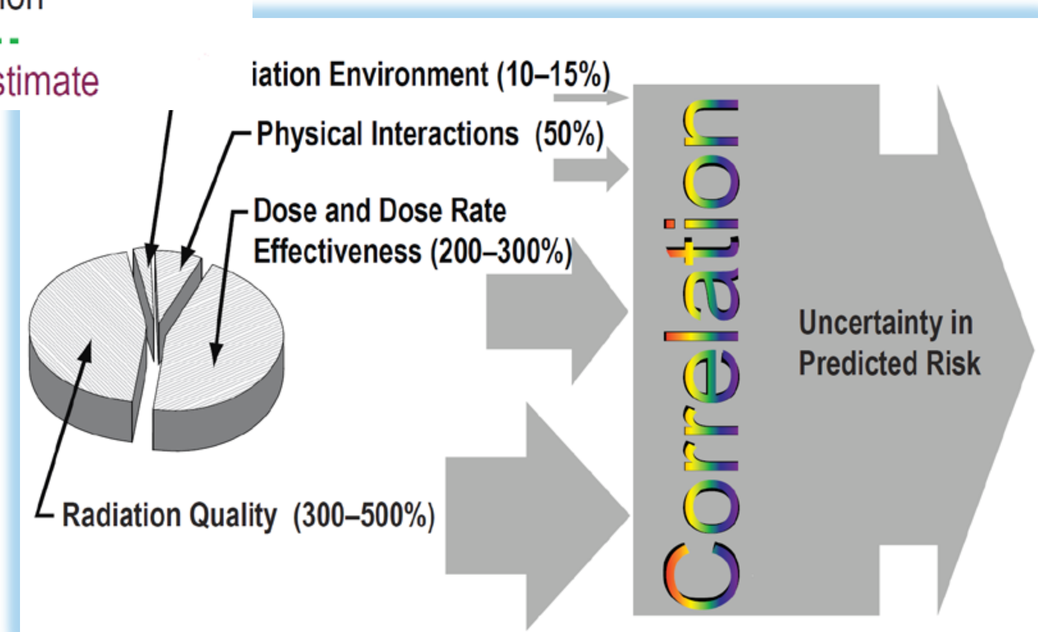
Other uncertainties and variabilities? (e.g., in generalization and scale-up of shielding or protection solutions)

Space Radiation: The Drive & The Challenges



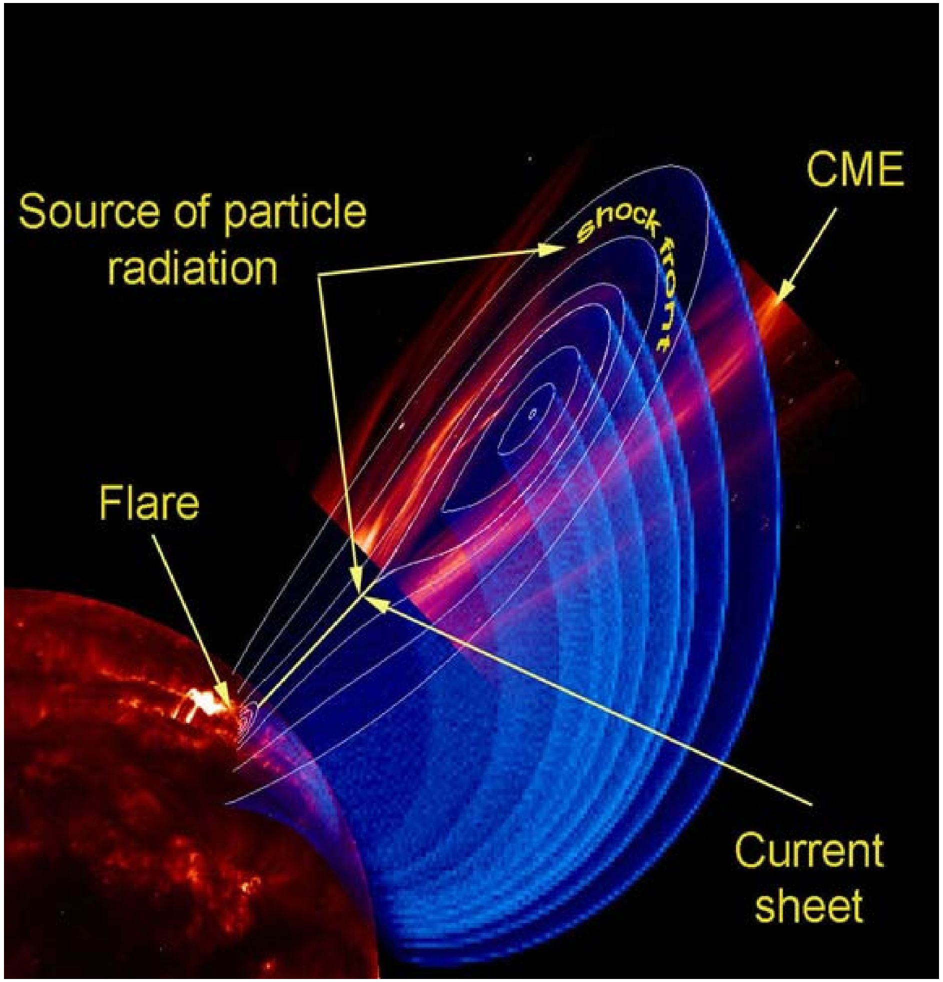
Radiobiological uncertainties dominate!

These large uncertainties can frustrate -even defeat- any mitigation solution



Space Radiation: Natural Sources

Two main sources of ionizing radiation:



Space Radiation: Uncertainties in radiobiological effects

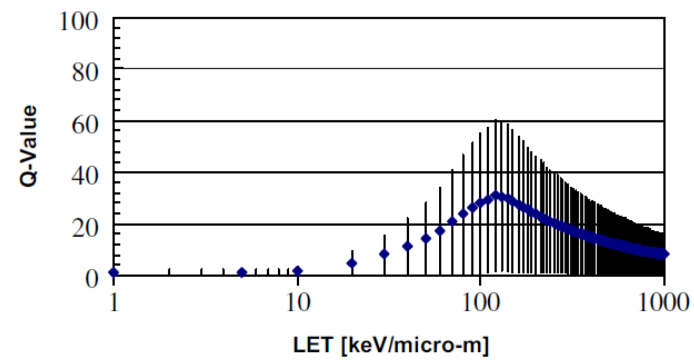
Large uncertainties -and variabilities- in the radiation quality factor is seen as a main hindrance toward reliable dose and risk estimates

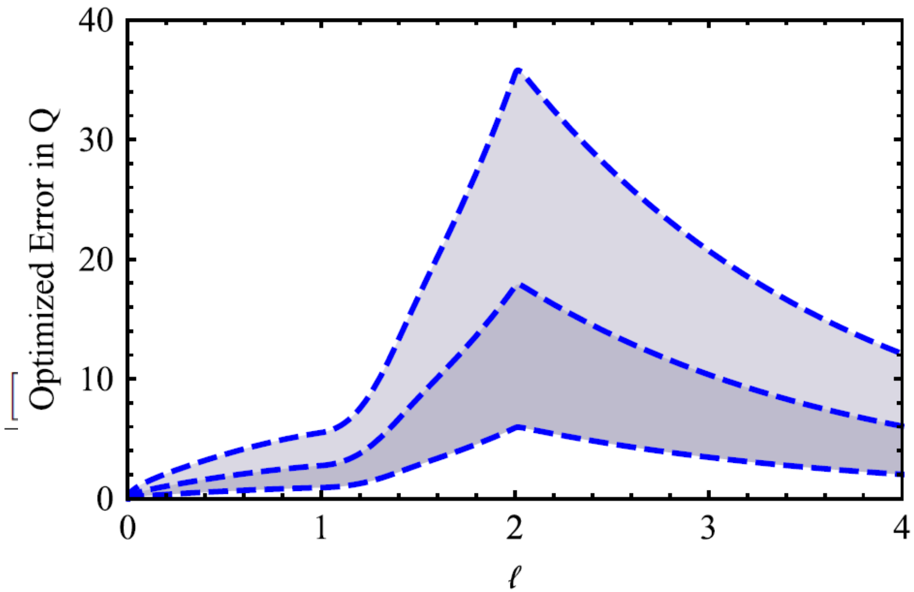
These can be captured mathematically if we model the quality factor as an Ornstein-Uhlenbeck process,

$$dQ = C(\ell)Q\,d\ell + \sqrt{D(\ell)}\,dW$$

with a corresponding PDF of the form,

$$f_Q(Q,\ell;Q_0,0) = \frac{1}{\sqrt{4\pi q_1(\ell)}} \exp\left\{ - \right.$$





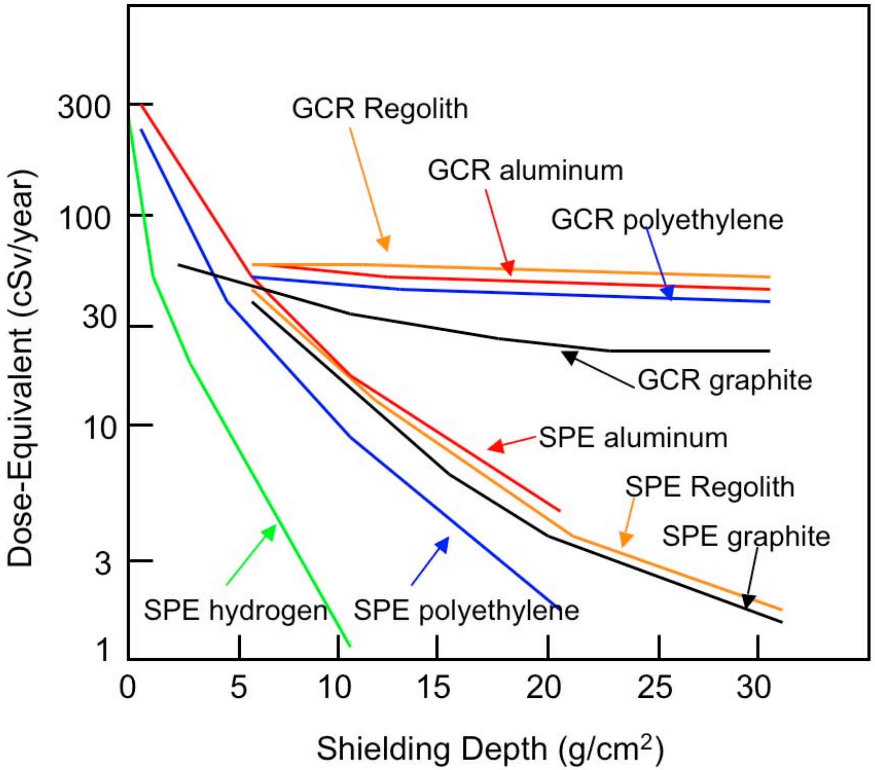
Space Radiation: Shielding effectiveness (how certain?)

Materials vary in their ability to shield against GCR nuclei

Polymeric based materials tend to be most effective - but their structural and safety properties remain poor or poorly known

Aluminum, like all metals, is **a poor GCR shield**

Regolith is not that much better either!



Space Radiation: Regolith as a shield material

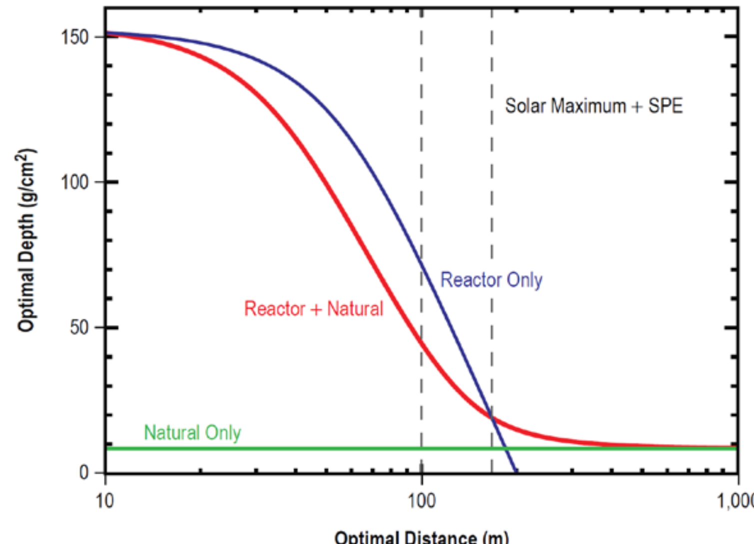
TABLE I: 1999 NCRP-recommended dose limits by organ and exposure duration.

Limit (cSv)	Bone Morrow	Eye	Skin
30-day Exposure	25	100	150
Annual	50	200	300
Career	50-300	400	600

TABLE II: Expected doses on the lunar surface with and without shielding (no nuclear power source assumed).

Duration (days)	GCR (cSv)	SEP (cSv)	Mission (cSv)
10	0.3/0.8	7.5/20.5	7.8/21.3
30	1.0/2.5	7.5/20.5	8.5/23.0
180	6.0/15.0	7.5/20.5	13.5/35.5
360	12.0/30.0	7.5/20.5	19.5/50.5

In-Space expected levels and limits



Cosmic 8%
Terrestrial 8%
3%

Use of regolith as a shield material in the presence of a small nuclear power source

Distribution of terrestrial exposure of few cSv/yr

Space Radiation at Marshall

- Monitoring & Detection

  protons- TaSEPS

  neutrons- ANS

- Forecasting

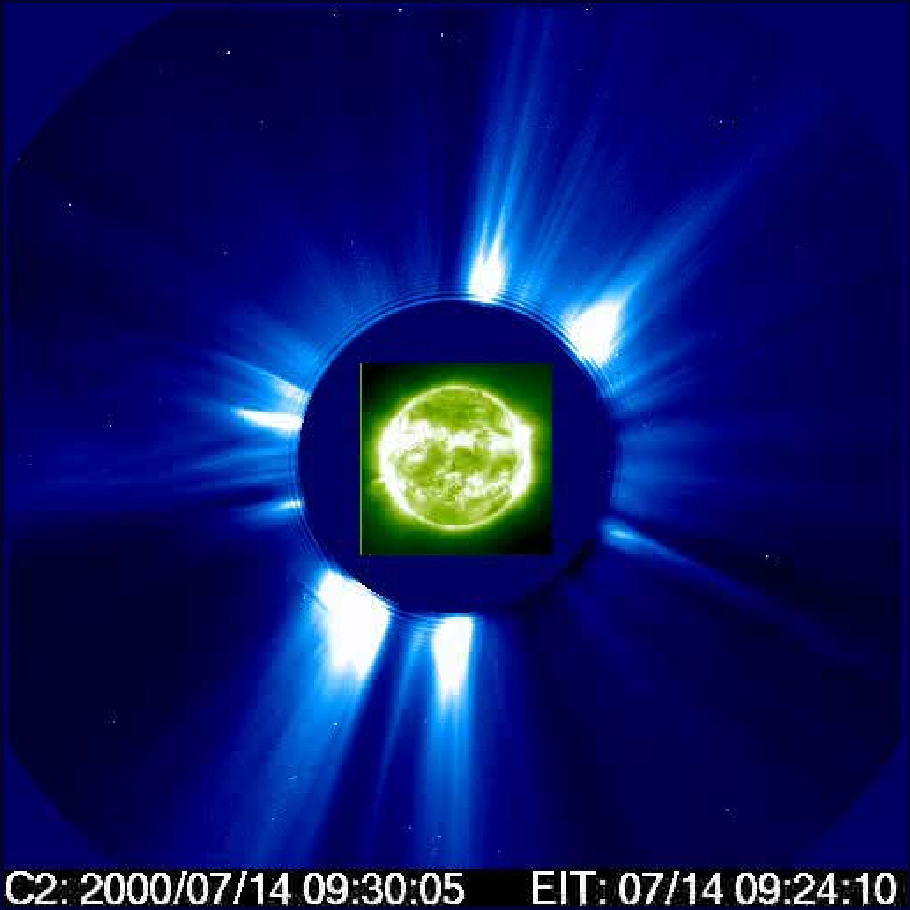
  Mag4

- Modeling & Simulation

  Geant4-based

- Radiation-Smart Structures

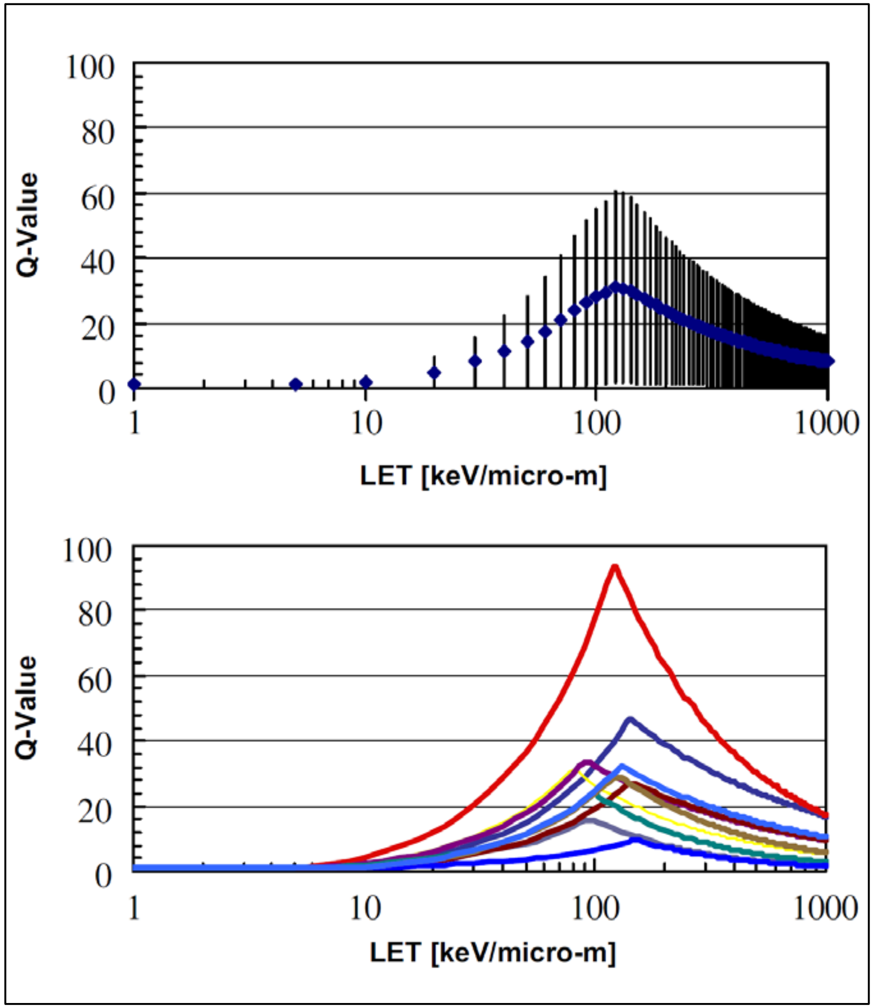
  Geant4-informed



Bastille Day (2000 July 14) Flare, Coronal Mass Ejection and Solar Energetic Particle Event

Space Radiation: Monitoring & Detection

$$Q(L) = \begin{cases} 1 & L_0 > L; \\ aL - b & L_m > L \geq L_0; \\ cL^{-p} & L \geq L_m. \end{cases}$$



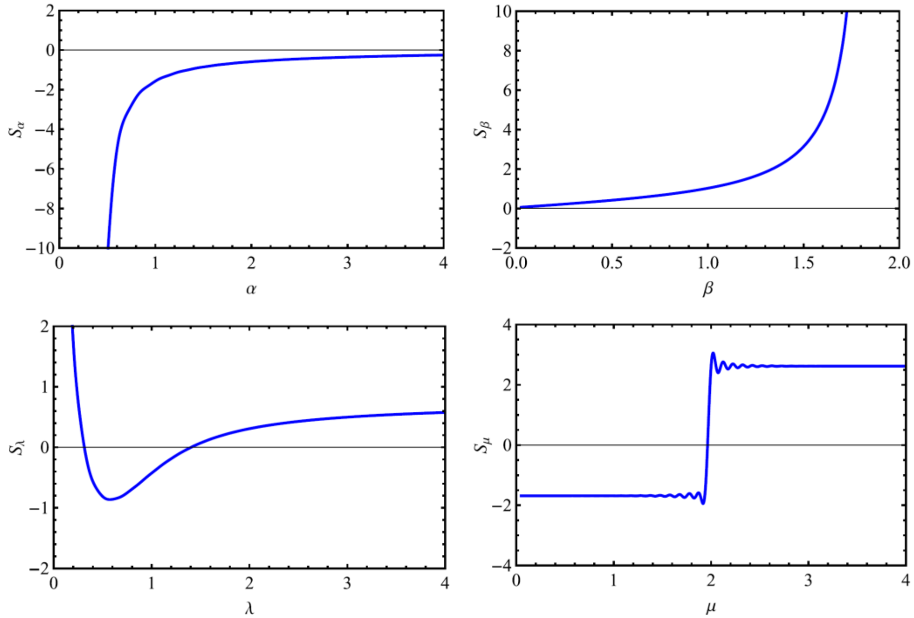
$$dQ = C(\ell)Q\,d\ell + \sqrt{D(\ell)}\,dW$$

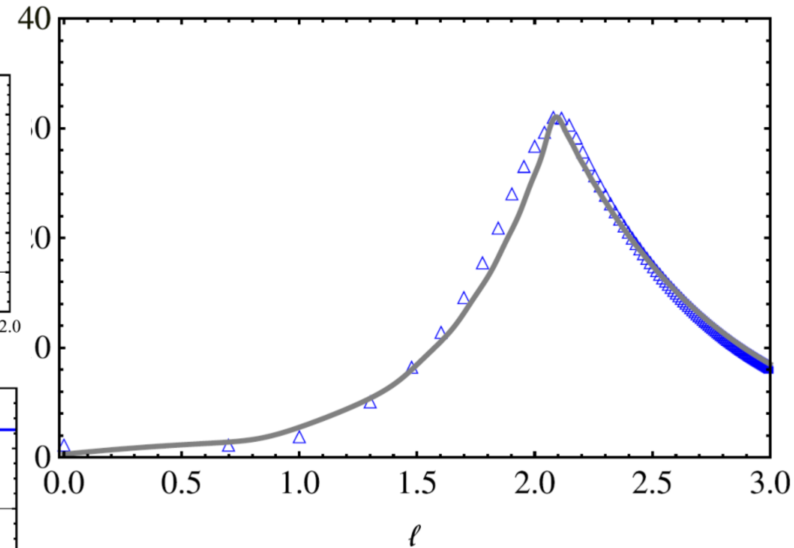
$$C(\ell) = \frac{1}{\langle Q\rangle}\frac{d\langle Q\rangle}{d\ell} \qquad D(\ell) \approx \frac{1}{2}(\langle Q\rangle)^2$$

$$\frac{\partial f_Q(Q,\ell)}{\partial \ell} = -\frac{\partial}{\partial Q}\left[C(\ell)Qf_Q(Q,\ell)\right] + \frac{1}{2}D(\ell)\frac{\partial^2}{\partial Q^2}\left[f_Q(Q,\ell)\right]$$

$$f_Q(Q,\ell;Q_0,0) = \frac{1}{\sqrt{4\pi q_1(\ell)}}\exp\left\{-\frac{[Q\exp(q_2(\ell)) - Q_0]^2}{4q_1(\ell)} + q_2(\ell)\right\}$$

Space Radiation: Monitoring & Detection





Space Radiation: Monitoring & Detection

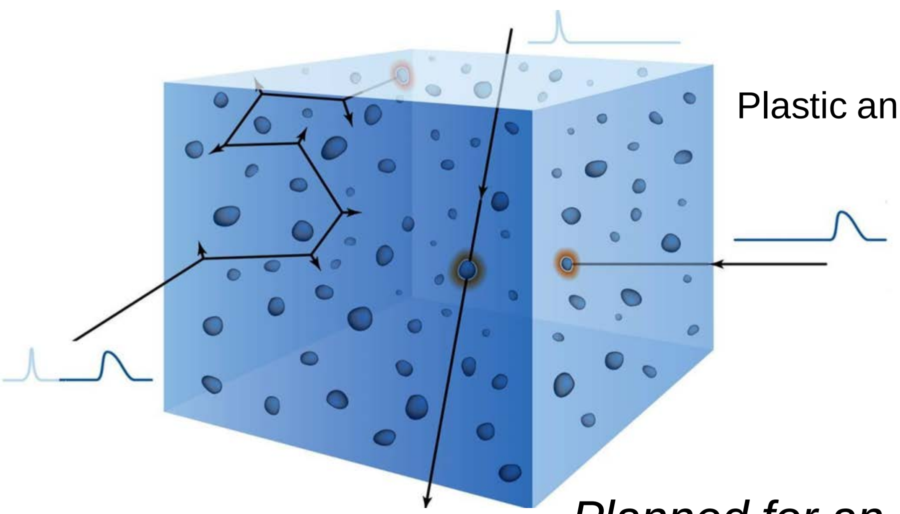
- Marshall scientists and engineers develop state-of-the-art charged particle and neutral particle detectors suitable for the harsh environments of space:

-Advanced Neutron Spectrometer (ANS): *is a new instrument technique being developed to meet NASA's requirements to monitor the radiation exposure due to <u>secondary neutrons</u> for future crewed missions. New instrument designs are needed to achieve the measurement performance requirements that fit within the resource limits of exploration missions beyond Earth's protective magnetic field*

$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He$
Q = 4.78

$n + Gd \rightarrow Gd^{*} + \gamma$
Q = [0,2]

$n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He$
Q = 2.73 (93%)
or 2.25 (7%)



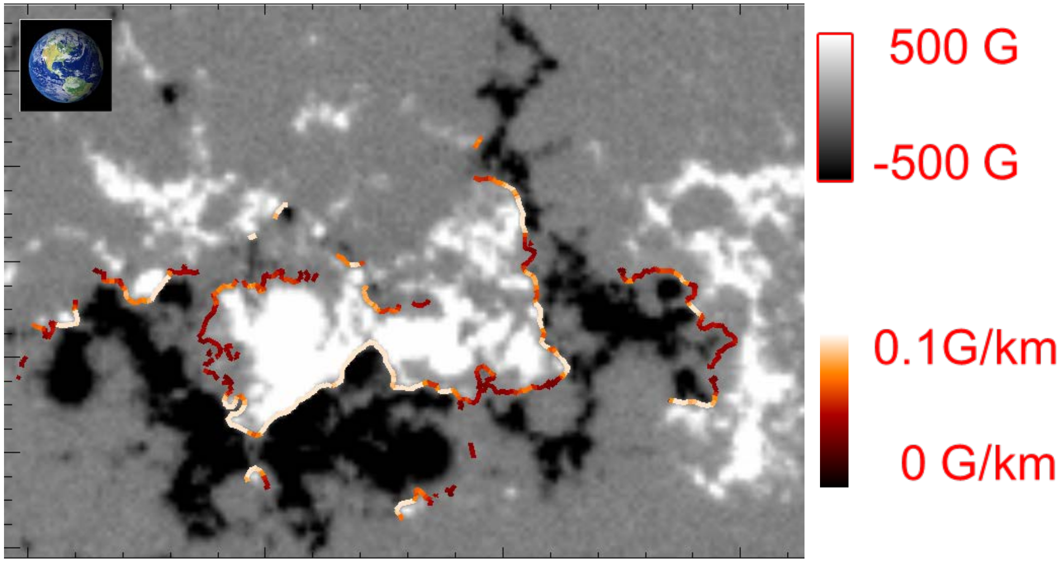
Plastic and Li-Gd-B scintillator

Planned for an ISS flight demonstration

Space Radiation: Magnetic-based Forecasting (Mag4)

- Marshall scientists and engineers developed an automated prediction system that downloads and analyzes magnetograms from the HMI (Helioseismic and Magnetic Imager) instrument on NASA SDO (Solar Dynamics Observatory), and then automatically converts the rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events

[Present cadence of new forecasts: **96 min**; Vector magnetogram actual cadence: **12 min**]



A magnetogram of an active region on the Sun

When the transverse gradient of the vertical (or line-of-sight) magnetic field is large, there is more free-energy stored in the magnetic field

For each Active Region: The integral of the gradient along the neutral line is the free-energy proxy

Mag4: A Comparison of Safe and Not Safe Days

June 26, 2013

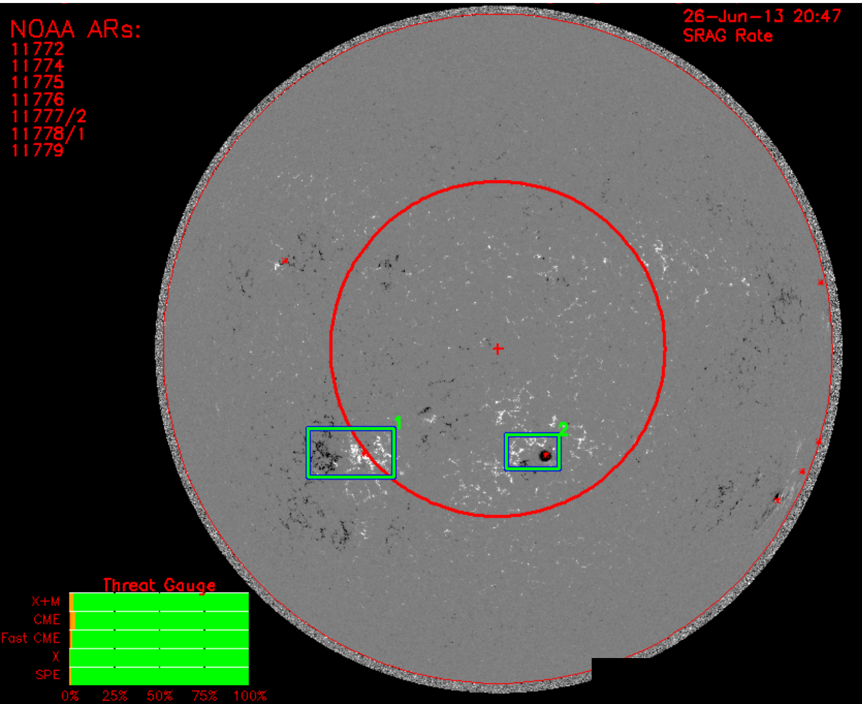
C1, C1.5 flares

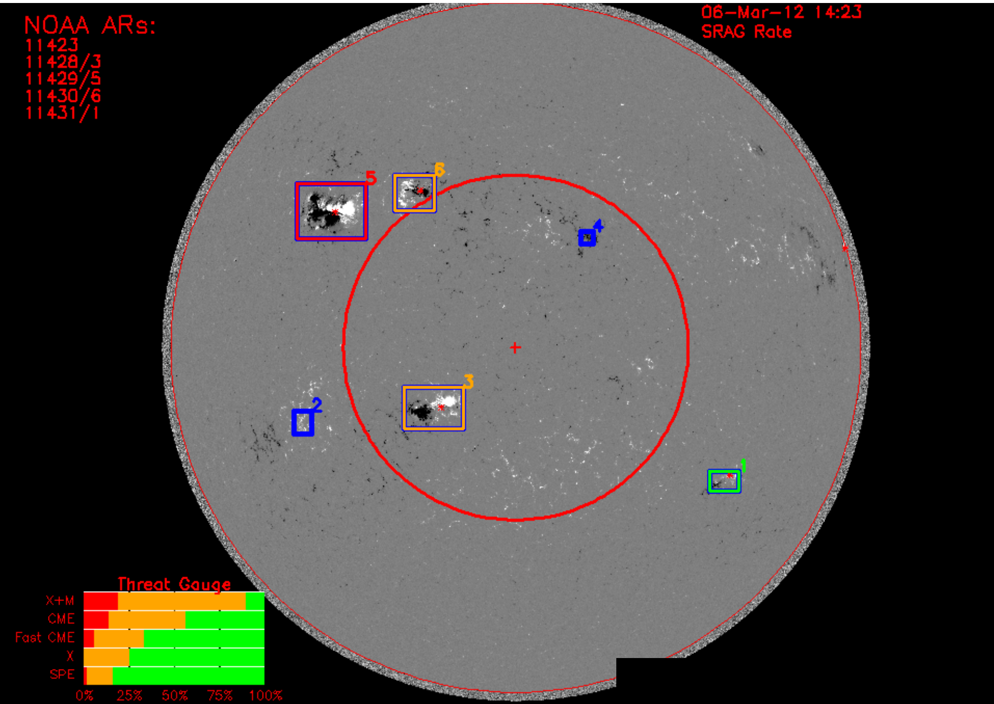
March 7, 2012

X5.4, X1.3, C1.6

CME 2684, 1825 km/sec,

Solar Energetic Proton Event reaches 6530 ‘particle flux unit’ >10 MeV





Space Radiation: Modeling & Simulation

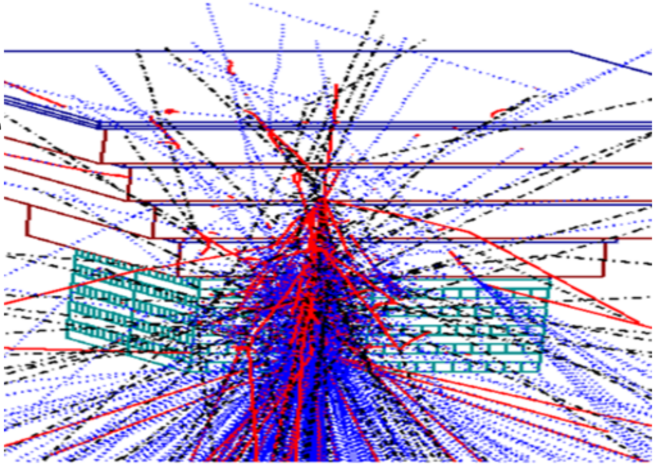
- Marshall scientists and engineers use Geant4 for the design, analysis, and development of

  particle detector systems

  exposures at accelerators and in-situ

  dose estimates

  shielding solutions

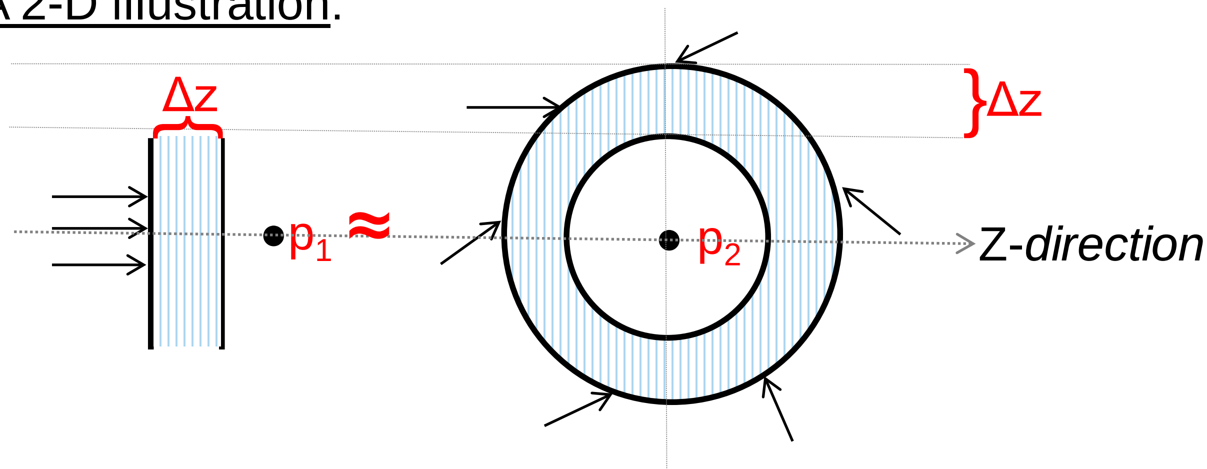


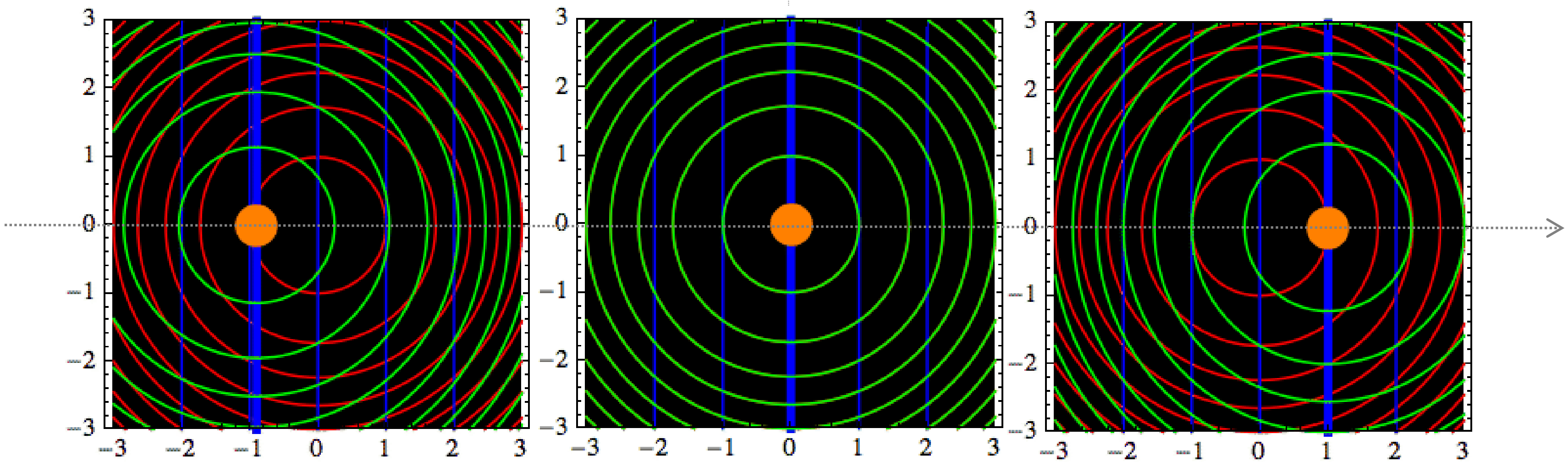
- Marshall scientists and engineers collaborate with experimental and theoretical and computational groups at Oak Ridge National Laboratory, Berkeley's Lawrence National Laboratory, Brookhaven National Laboratory, Indiana University's Cyclotron Facility, Japan's HIMAC facility, and others for basic and applied nuclear modeling, simulation, and exposure and shielding studies

Space Radiation: Modeling & Simulation

Complex geometry and material composition -in the presence of known physical uncertainties- are expected to produce sizable errors in any radiation protection solution.

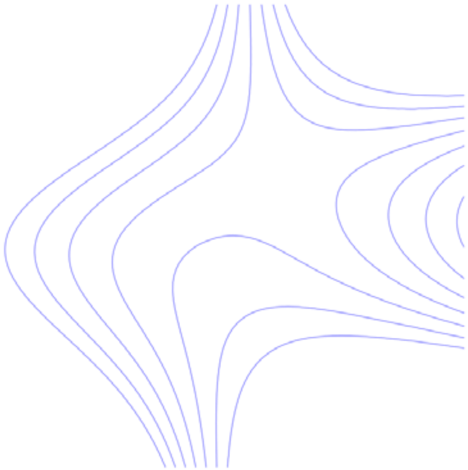
A 2-D illustration:

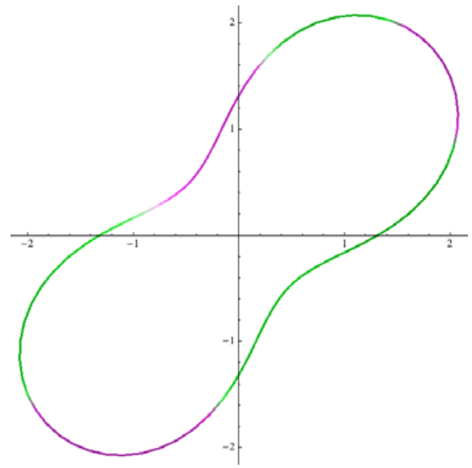


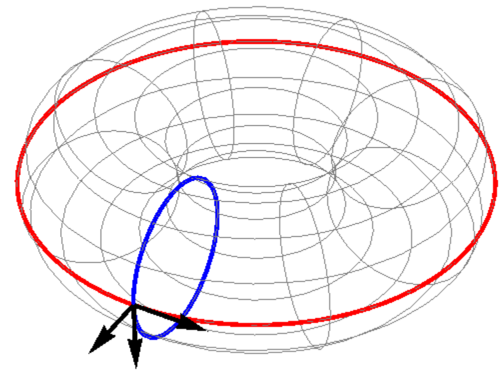


Space Radiation: Modeling & Simulation

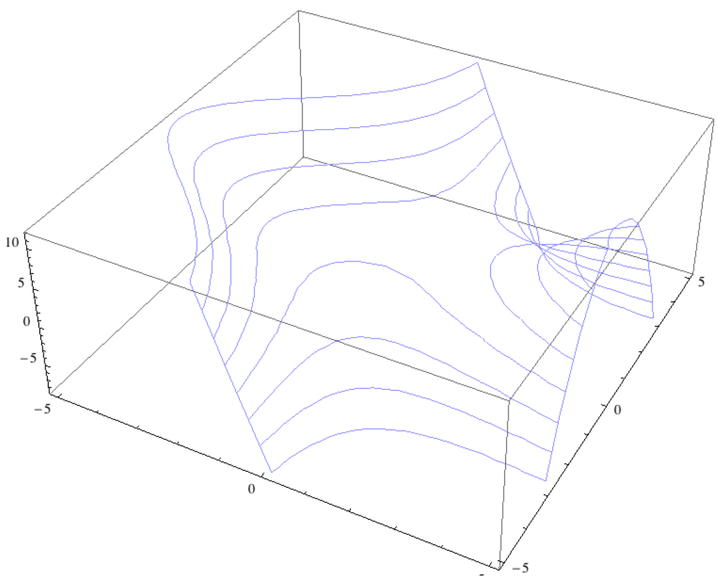
A 3-D illustration:

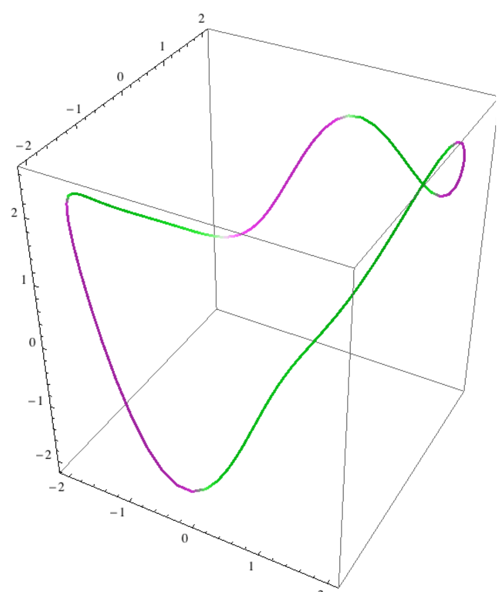


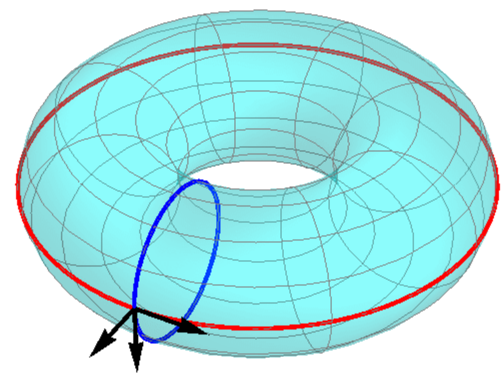




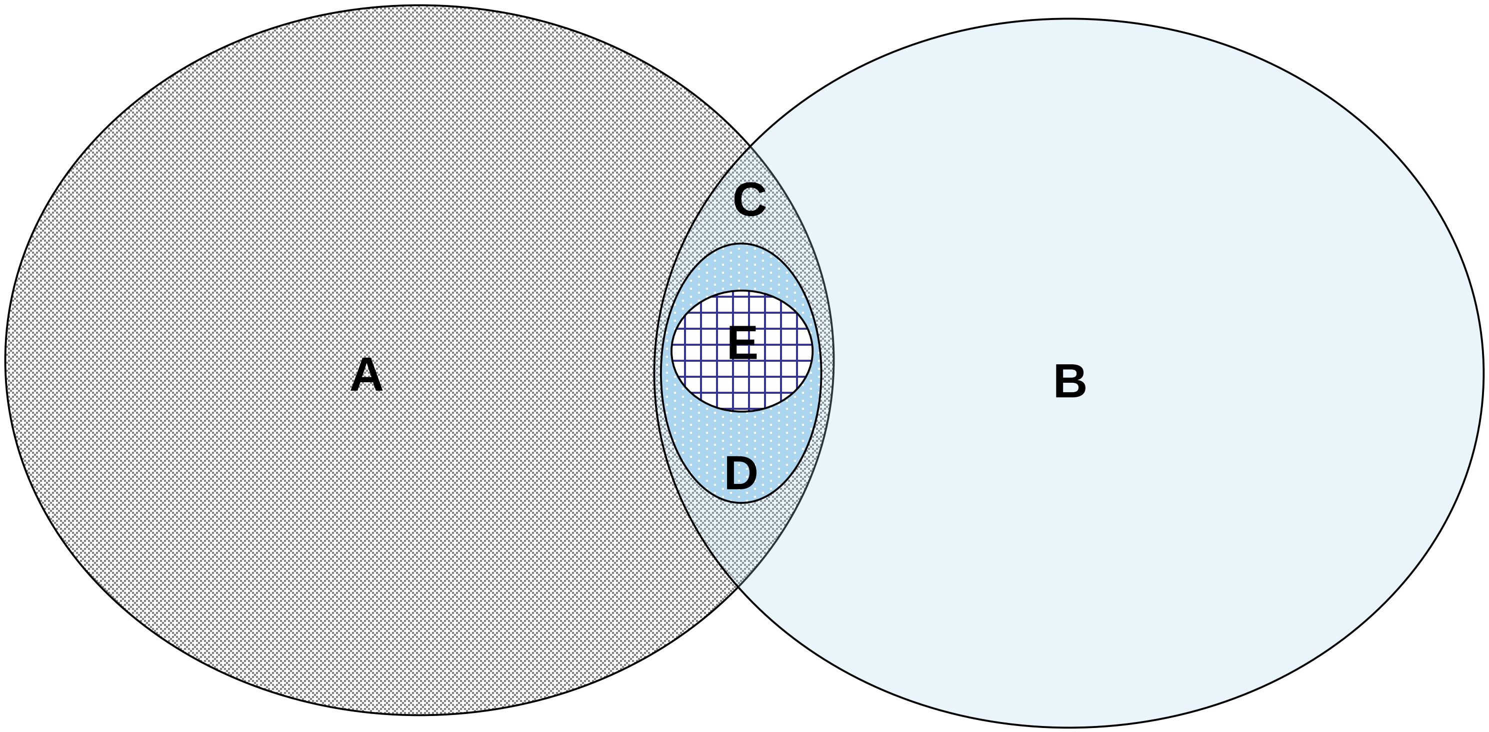
Unlikely?







Radiation-Smart Structures and Designs?



A: Adaptive Structures
B: Sensory Structures
C: Controlled Structures
D: Active Structures
E: Intelligent Structures