National Aeronautics and Space Administration

Space Radiation Environment

Comparison and Validation of GCR Models

Briefing to
NAC HEO/SMD Joint Committee
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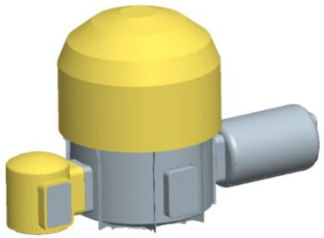
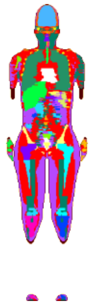
NASA Human Research Program

Outline

- Exposure analysis overview
- Galactic cosmic ray environment and models
- Radiation transport through shielding
- Projecting exposures for mission analysis and vehicle design
- Summary

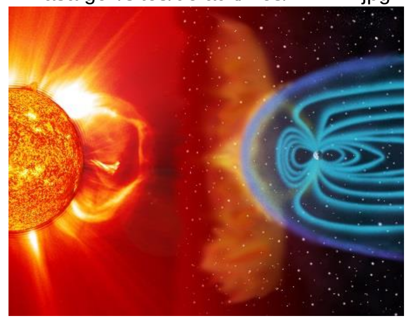
Exposure Analysis Overview



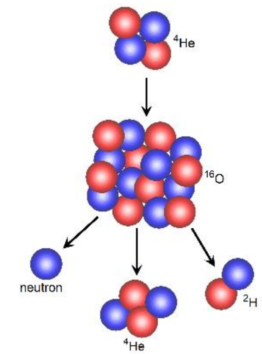


Shielding models

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

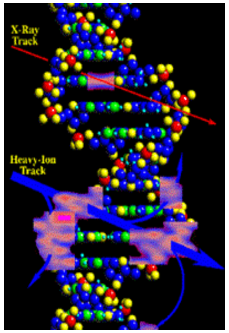


Environment models



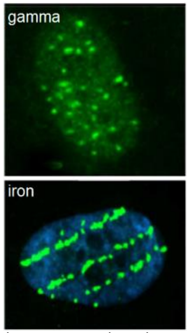
Physics models

Radiation transport models



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

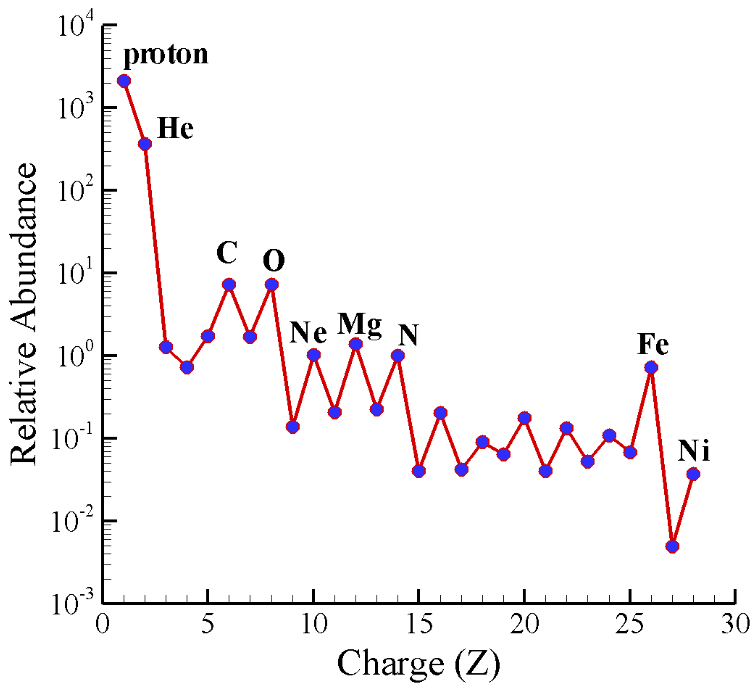
Exposure & Biological response



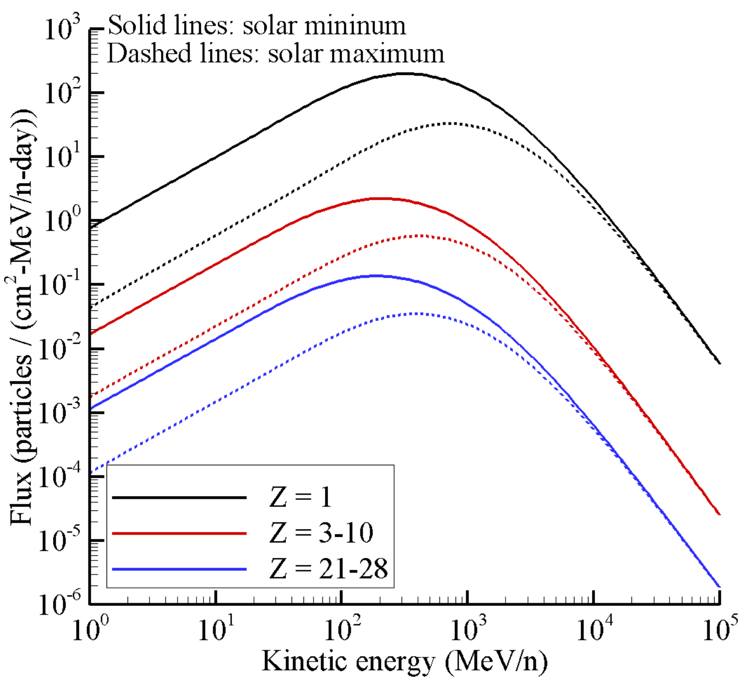
humanresearchroadmap.nasa.gov/evidence/reports/Carcinogenesis.pdf

Galactic Cosmic Ray Environment

- The galactic cosmic ray (GCR) environment is omnipresent in space and fluctuates between solar minimum and solar maximum on an approximate 11 year cycle
  - Exposures differ by approximately 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 elements in the 1977 solar minimum GCR environment, normalized to neon



GCR flux at solar minimum and solar maximum

Galactic Cosmic Ray Model Description

- The Badhwar O'Neill (BON) galactic cosmic ray model[(1)] is used at NASA as input into radiation transport codes for
  - vehicle design, mission analysis, astronaut risk analysis
  - other models used as well (discussed in later slides)
- The BON model has had several revisions[(2-5)]; all of them are based on the same fundamental framework
  - Model equations are solved to describe particle transport through solar system
  - Solar activity is described by a single parameter (Φ) related to observed sunspot numbers

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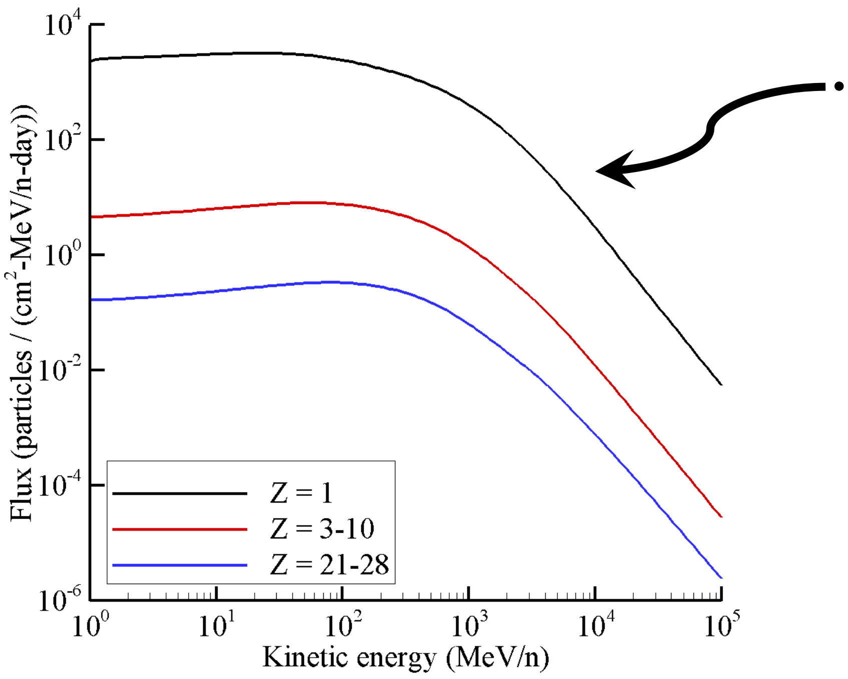

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  - Referred to as the local interstellar spectrum (LIS)
  - Nearly constant over time

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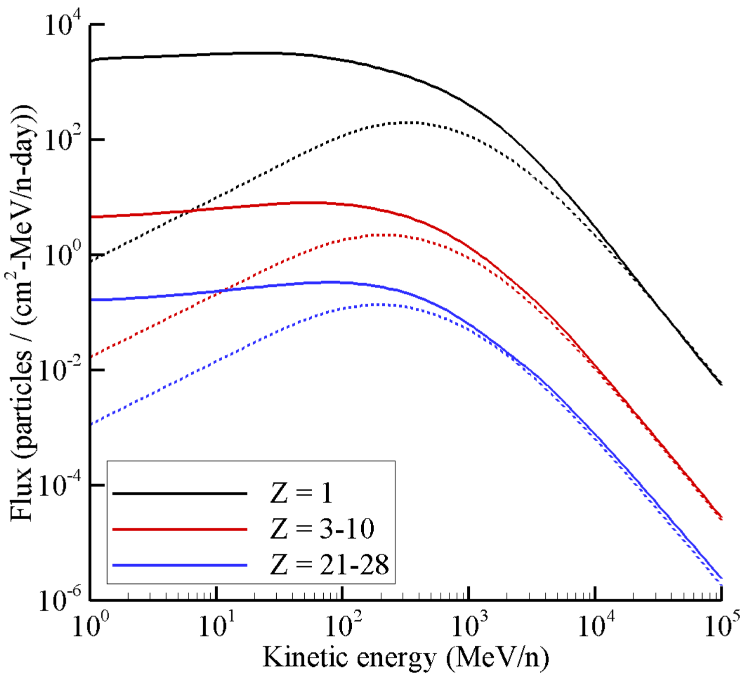

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  - Dashed lines show model spectra near Earth during solar minimum (Φ = 475)

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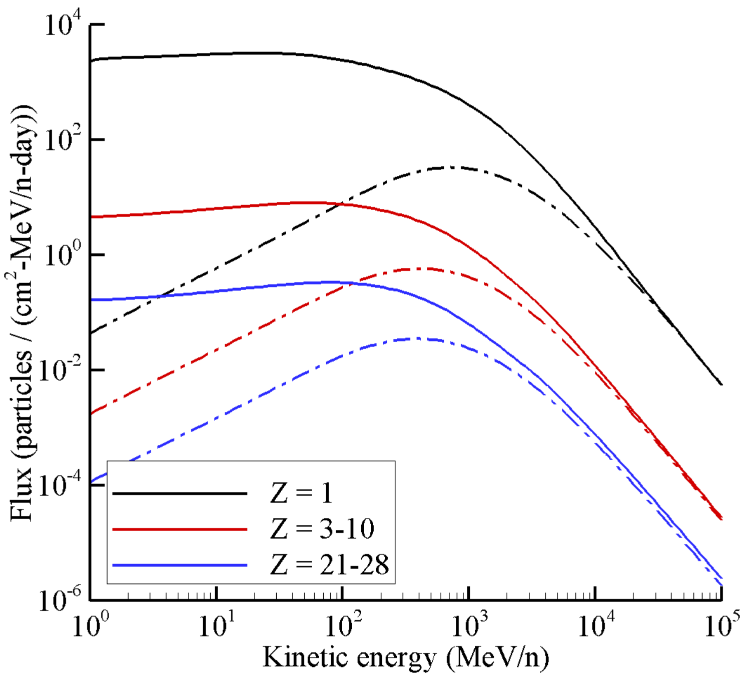

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  - Nearly constant over time
- GCR spectrum is attenuated near Earth and affected by solar activity level
  - Dashed lines show model spectra near Earth during solar minimum (Φ = 475)
- GCR spectrum is more heavily attenuated during solar maximum
  - Dashed lines show model spectra near Earth during solar minimum (Φ = 1100)

Galactic Cosmic Ray Model Development

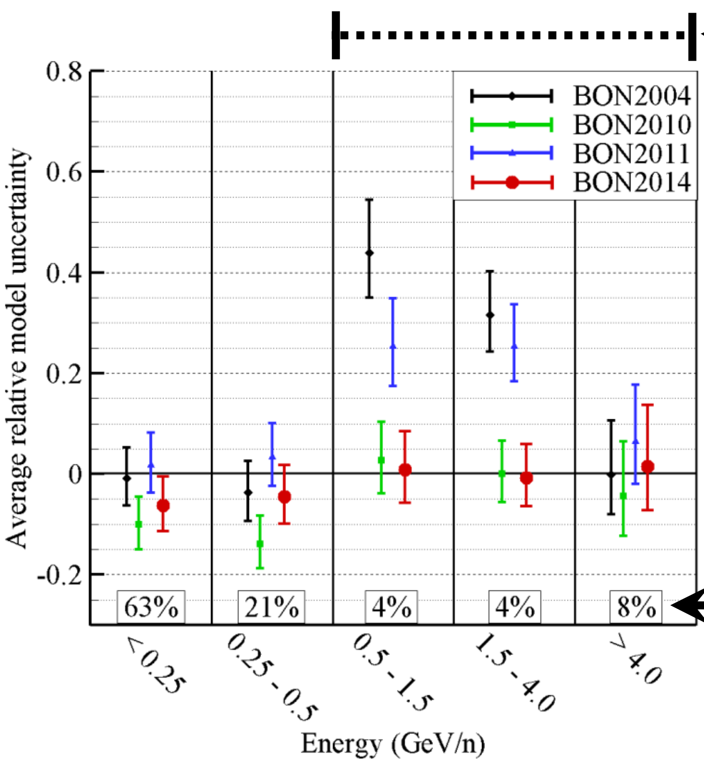
- GCR models are developed and validated by using measurements supported by Science Mission Directorate and others over the past 40 years
  - Short duration, high energy, balloon and satellite measurements
  - Low energy, continuous measurements from ACE/CRIS (most of the available measurements)
  - Current gap in measurement database for continuous, high energy measurements[6,7]
  - Collaboration with AMS-II will begin to fill this important gap

Name	Flight	Time	Ions (Z)	Energy (GeV/n)	Data pts.
ACE/CRIS	Satellite	1998-present	5-28	0.05 – 0.5	8288
AMS	STS-91	1998	1, 2	0.1 – 200	58
ATIC-2	Balloon	2002	1, 2, 6, 8, 10,…,14, 26	4.6 – 10^3	55
BESS	Balloon	1997-2000, 2002	1, 2	0.2 – 22	300
CAPRICE	Balloon	1994, 1998	1, 2	0.15 – 350	93
CREAM-II	Balloon	2005	6-8, 10, 12, 14, 26	18 – 10^3	42
HEAO-3	Satellite	1979	4-28	0.62 – 35	331
IMAX	Balloon	1992	1, 2	0.18 – 208	56
IMP-8	Satellite	1974	6, 8, 10, 12, 14	0.05 – 1	53
LEAP	Balloon	1987	1, 2	0.18 – 80	41
MASS	Balloon	1991	1, 2	1.6 – 100	41
PAMELA	Satellite	2006-2009	1, 2	0.08 – 10^3	472
TRACER	Balloon	2003	8, 10, 12,…,20, 26	0.8 – 10^3	55
Lezniak	Balloon	1974	4-14, 16, 20, 26	0.35 – 52	131
Minagawa	Balloon	1975	26, 28	1.3 – 10	16
Muller	STS-51	1985	6, 8, 10, 12, 14	50 – 10^3	16
Simon	Balloon	1976	5-8	2.5 – 10^3	46

82% of available data

Galactic Cosmic Ray Model Development

- Recent work has significantly reduced model uncertainties by taking a more rigorous approach to model calibration and validation – resulted in BON2014[1]
  - Determined measurements (energies) most important for exposure quantities behind shielding[6]
  - Model parameters calibrated using optimization methods with an emphasis on higher energies[1,7]
  - Comprehensive validation metrics applied to quantify model uncertainty[1,7]
  - Previous efforts focused more heavily on lower energy ACE/CRIS measurements

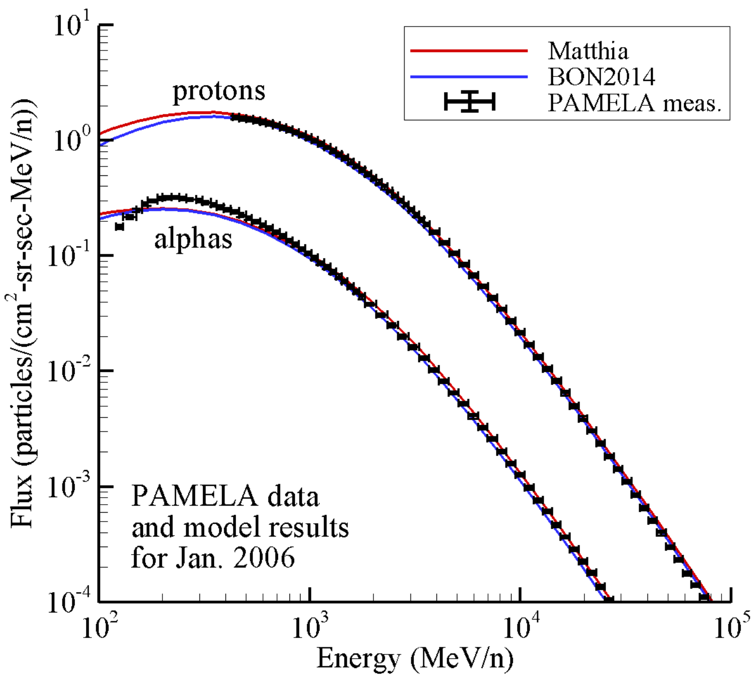


- Significant need for continuous, time-resolved (e.g. monthly) high energy measurements to further reduce model uncertainties[7]
  - <u>AMS-II collaboration will begin to fill this important gap</u>
- Energy region *above* 0.5 GeV/n accounts for 95% of exposure[6]
- Most of the measurements have been taken *below* 0.5 GeV/n[7]

Fraction of available measurements in each energy bin

International Models and Comparisons

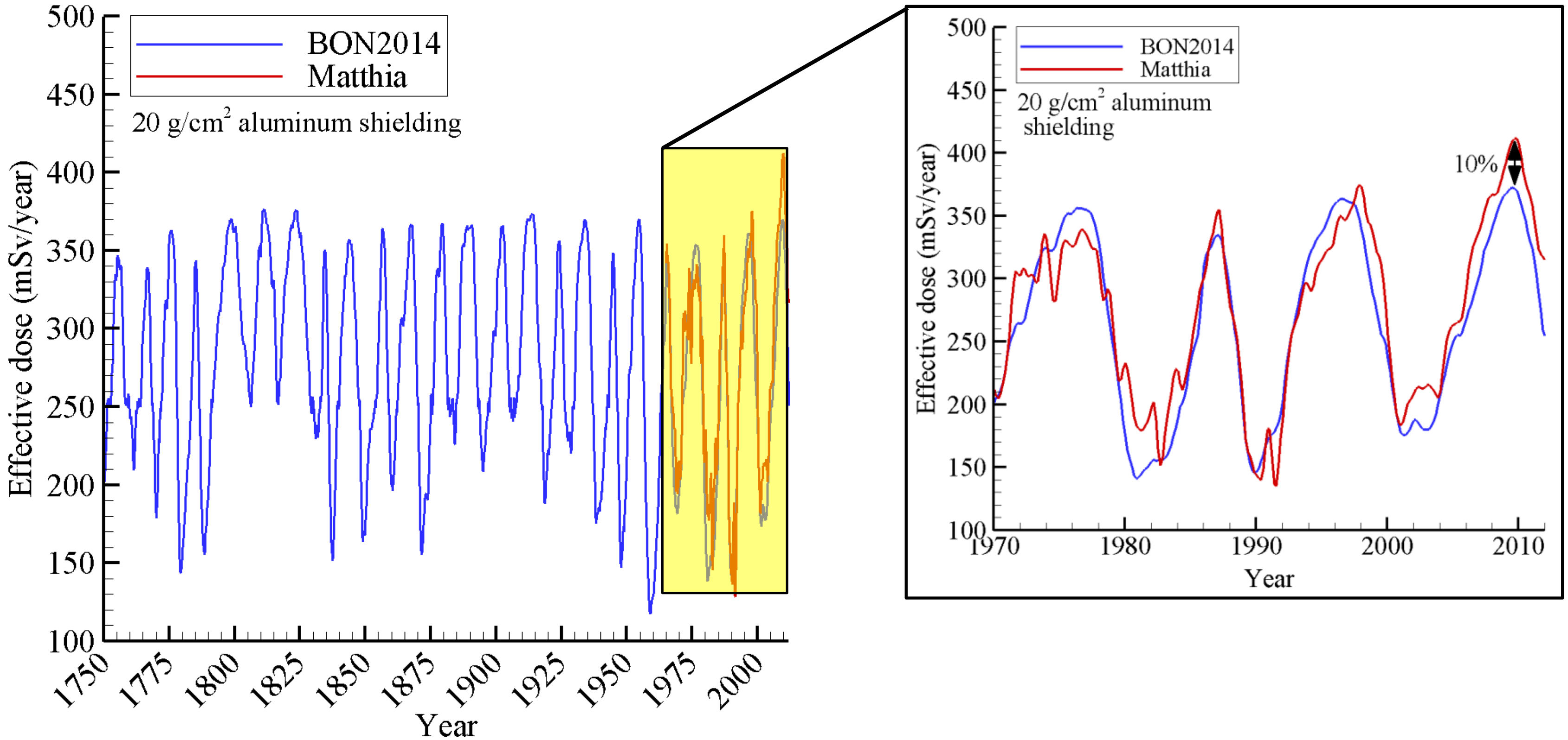
- GCR models tend to agree reasonably well at highest energies where effects of solar modulation are less pronounced
  - Most important for exposure quantities behind shielding[6]
- Continuous, time-resolved (e.g. monthly) measurements at high energies needed to further reduce uncertainties
  - Most important gap is high energy proton and alpha data
  - AMS-II collaboration will begin to fill gap



- Nymmik (MSU) has developed a semi-empirical model[8,9]
  - Used by Russian Space Agency and others (DLR, ESA)
  - Official update has not been provided recently
- Matthia et al. (DLR) recently developed a simplified form of Nymmik's model[10]
  - Shown to be reasonably accurate[7,10]

International Model Comparisons

- Human exposure quantities behind shielding are in good agreement if updated galactic ray models are used
  - Effective dose computed as weighted sum of tissue exposures in detailed human model
  - BON2014 and Matthia are within 10% of each other, on average, over past 40 years
  - Models tend to agree well at higher energies where impacts of solar activity are reduced

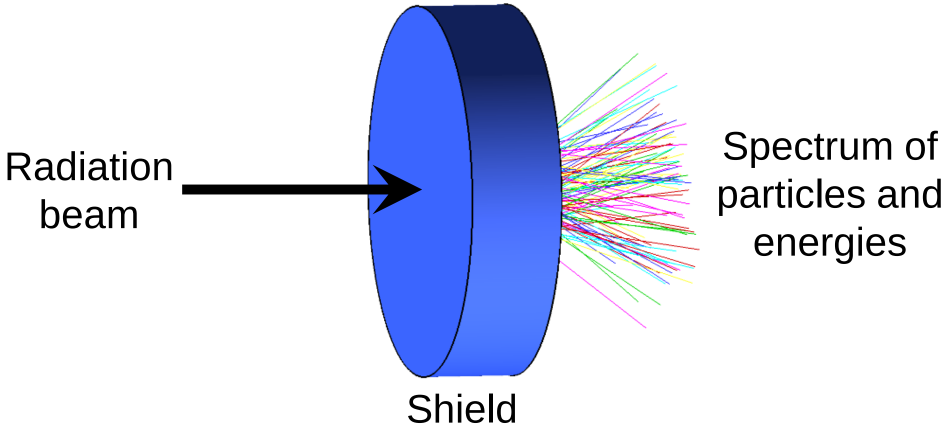


Radiation Transport

- Radiation is modified as it passes through shielding and tissue
  - Modifications due to atomic and nuclear interactions

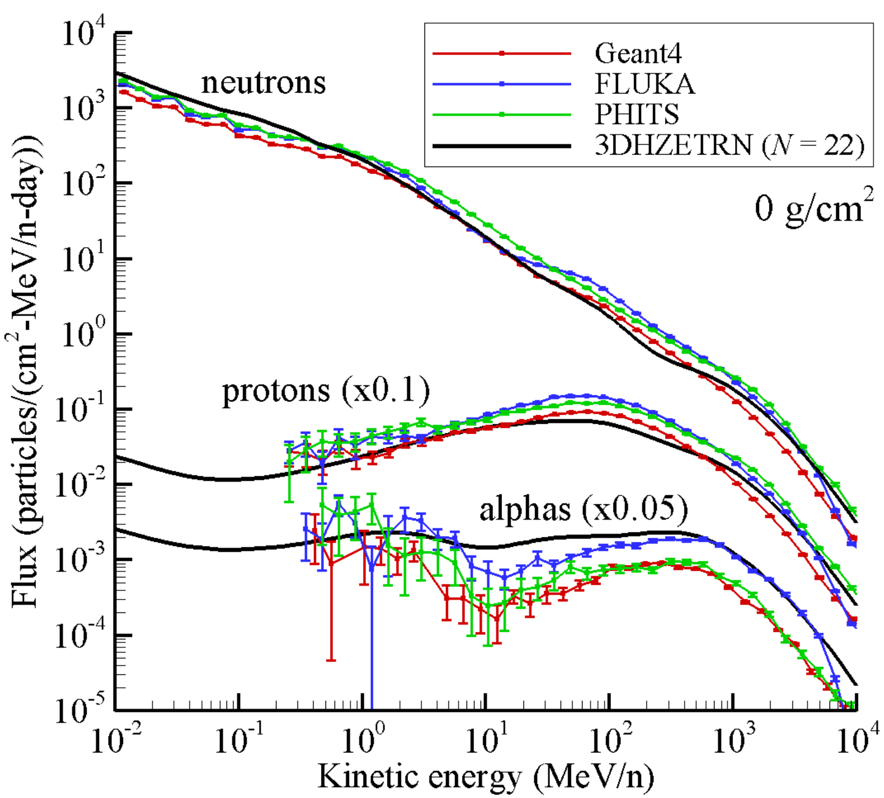
- Radiation transport codes are used to describe these processes
  - Galactic cosmic ray model provides the boundary condition
  - Atomic and nuclear interaction parameters are generated by separate models
  - Shielding model for realistic vehicles is also required (and has some uncertainty)

- NASA's radiation transport code is HZETRN[11-15]
  - Highly efficient compared to Monte Carlo methods (seconds vs. days or longer)
  - Efficiency needed to support vehicle design, engineering, and optimization activities
  - Extensive verification against Monte Carlo and validation against space flight measurements

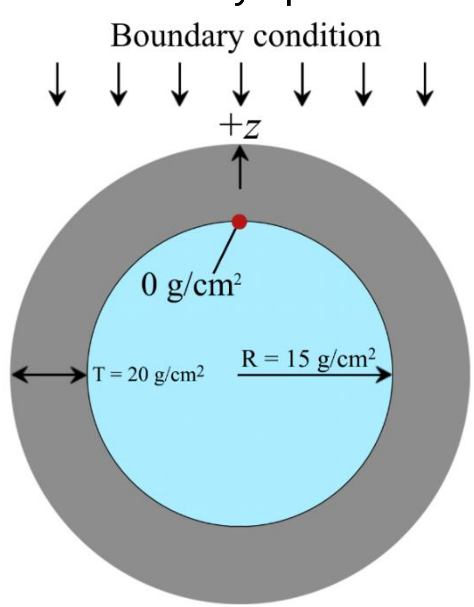


Transport Code Comparisons

- Comparisons against state-of-the-art Monte Carlo codes shown below(16)
  - HZETRN agrees with Monte Carlo to the extent they agree with each other(13,15-17)
  - Differences in nuclear interaction models still present and highlights need for further model development and experimental measurements(15,16,18-20)



^{56}Fe solar minimum galactic cosmic ray spectrum



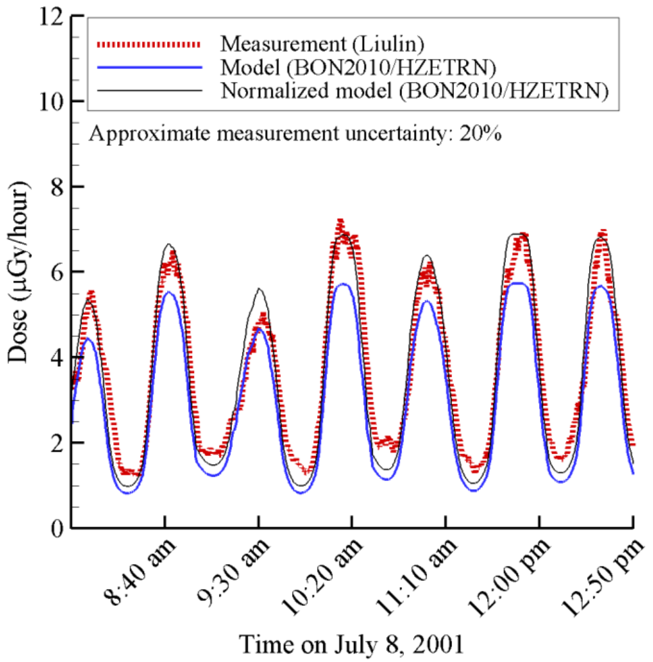
Tissue sphere with radius 15 g/cm^2 surrounded by 20 g/cm^2 of aluminum

Integrated Model Validation - ISS

- For astronaut risk assessment, end-to-end model results are normalized to area dosimeters on the International Space Station (ISS)
  - Cancer risk models require more detailed information than area dosimeters provide
  - Normalization procedures ensure cancer risk estimates are consistent with available dosimetry
  - Normalized end-to-end model uncertainty is within 15%

- Direct model evaluation (without normalization) is used in validation and uncertainty quantification efforts
  - Direct model evaluation needs to be accurate when dosimetry is unavailable (e.g. projections)
  - Integrated model uncertainties for a recent ISS analysis(21) ranged from 10% - 50% and includes uncertainties associated with
    - GCR and geomagnetic field models
    - Nuclear physics and transport codes
    - Shielding mass distribution of the ISS
    - Dosimeter response

- Efficiency of NASA's transport code has allowed detailed validation studies to be performed using minute-by-minute active dosimetry(21)
  - Allows rigorous statistical analyses to be performed
  - Helped identify deficiencies in geometry models, geomagnetic field models, and high energy nuclear physics



Integrated Model Validation – MSL/RAD

- Comparisons between Mars Science Laboratory/Radiation Assessment Detector (MSL/RAD) and NASA models are ongoing
  - Cruise dose measurements and models show reasonable agreement[22]
  - Surface dose measurements and models show reasonable agreement[23]

- Comparisons between NASA models and MSL/RAD surface measurements of particle fluxes have been made[24]
  - Provides a more rigorous test of models than just dose / dose eq. comparisons
  - Surface flux measurements show good agreement for some ions and reveals poor agreement for others
  - Highlights the need for continued model development and additional measurements

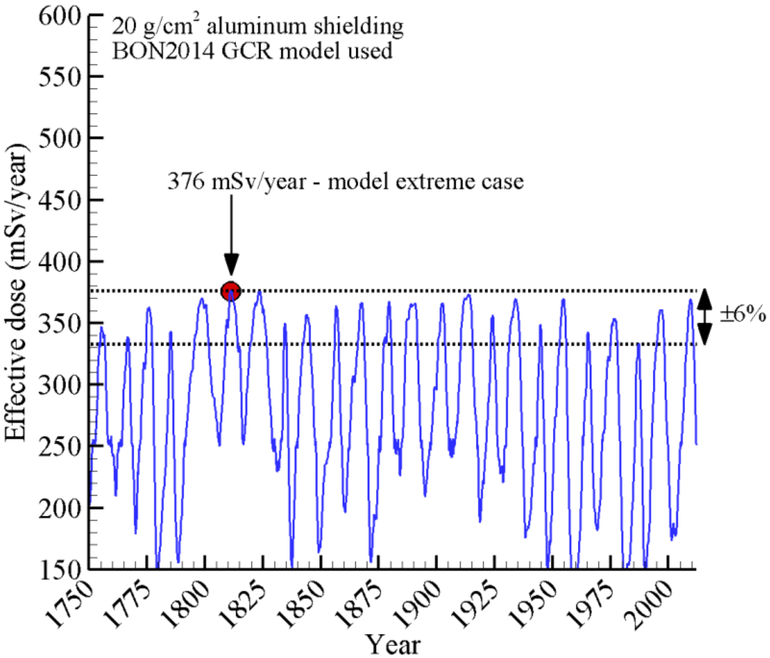
MSL/RAD cruise exposure rates compared to BON2011/HZETRN model[22]

	Dose (μGy/day)	Dose Eq. (μSv/day)	Avg. Q
BON2011/HZETRN	0.445	1.80	4.05
MSL/RAD	0.481$\pm$0.08	1.84$\pm$0.33	3.82$\pm$0.25

Mission Planning and Shield Design

- Past studies utilized static, representative environments for design analysis
  - e.g. 1977 solar minimum used as a “design case”
  - Solar modulation parameter, Φ = 1100 MV, used as a representative solar maximum

- Current studies can now utilize a more robust probabilistic approach, allowing estimates to be provided within a certain confidence level
  - Solar activity predictions are notoriously unreliable(25-27)
  - Analysis not tied to specific solar activity or time period

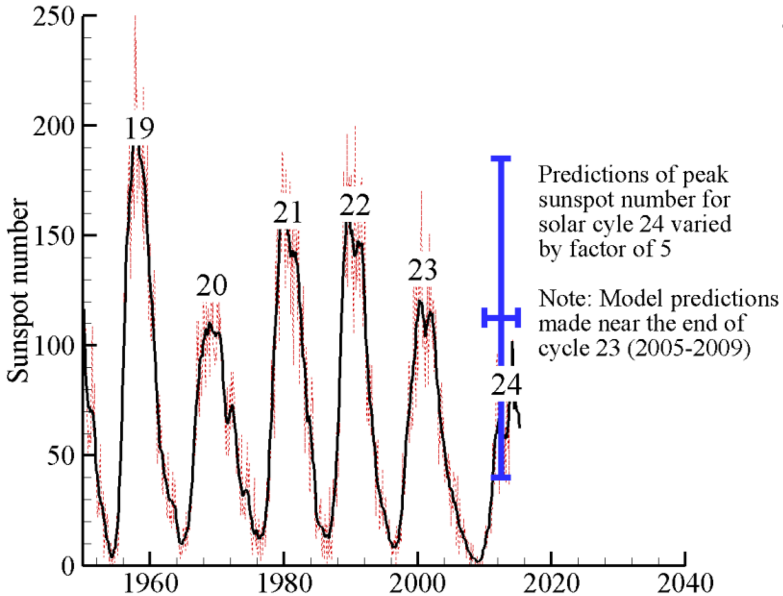


- Plot at left considers variation in effective dose due to past solar activity as represented by BON2014
  - For this shield configuration, effective dose values at solar minimum vary by ±6% over the past 265 years

- The data shown in the plot can be further analyzed to quantify probability of exceeding a given exposure value
  - e.g. 2.5% probability of exceeding 369 mSv/year for this shielding configuration
  - This type of analysis does not account for dramatic changes in future solar activity and other uncertainties (e.g. radiobiology)

Projecting Solar Activity

- Limiting case galactic cosmic ray environment would occur in the absence of solar activity and solar magnetic field
  - Same as the environment outside the solar system, which is nearly constant over time
  - In this environment, human exposures are ~2x larger than deepest solar minimum seen over past 265 years (unlikely to occur)
  - Historical analyses[25,26,28] indicates solar magnetic field will not completely disappear during grand solar minimum (Dalton grand minimum occurred ~1800-1830)

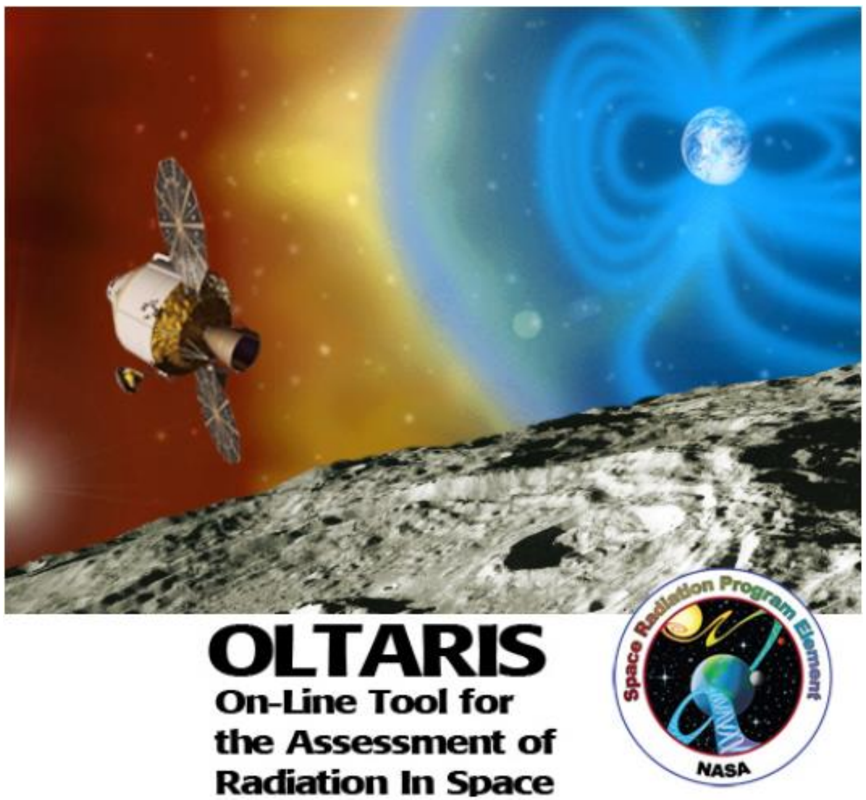


See reference (27) for discussion of predictions for solar cycle 24

- Model predictions of future solar activity (even near term) are uncertain
  - Predictions (made near end of cycle 23) of peak activity for cycle 24 varied by factor of 5 [27]
  - Longer term solar activity (beyond a solar cycle) may be intrinsically unpredictable[25,26]
  - Probability of grand solar minimum in next 30 years estimated to be <10%[29]
  - Maybe equally likely to see a strong solar maximum in next 30 years[29]
  - For future mission planning, uncertainties in solar activity predictions and possible schedule slips make it difficult to plan for a specific solar level (e.g. plan mission for solar max)

Design Tools

- The models used at NASA to support mission planning and vehicle design have been integrated into a web-based framework
  - OLTARIS: https://oltaris.nasa.gov



- BON and Matthia galactic cosmic ray models
- Solar particle events (SPE)
  - Fits to historically significant events (i.e.1972, 1989) are available and can be scaled
  - User-defined spectra are supported through commonly used fitting functions with few parameters
- Environmental models can be evaluated in low Earth orbit, deep space, or on planetary surface
- Environmental models are integrated with physics/transport models, detailed human phantom models and various geometry options

Summary

- Radiation analysis tools used for ISS operations, mission planning, and vehicle design in deep space and planetary surfaces are rigorously developed and validated
  - Measurements from SMD and others used directly for model development and validation
  - International models are compared or utilized where possible or appropriate
  - Model development and validation efforts are ongoing

- Based on recent (~30 years) solar activity and available measurements
  - Uncertainty assessment of BON2014 galactic cosmic ray model is $\pm$20%
  - <u>Normalized</u> end-to-end model uncertainties are within 15%
  - End-to-end uncertainties if normalization is not used range from 10%-50%
  - Additional measurements needed to further reduce uncertainties (e.g. AMS-II)

- Mission planning and vehicle design is moving towards more robust probabilistic approaches
  - Allows exposure estimates to be provided within a specified probability
  - Allows various sources of uncertainty (solar activity, shielding, radiobiology) to be rigorously accounted for in the analyses

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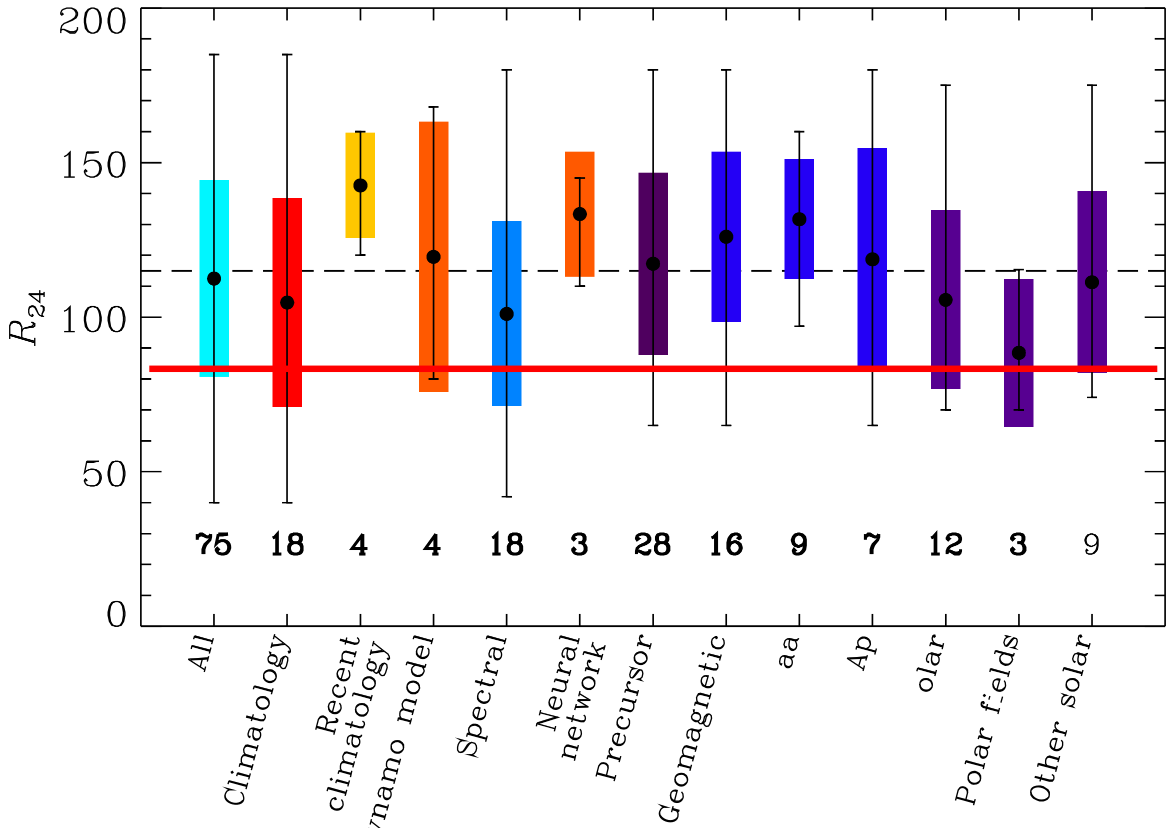
Backup – Solar Activity Predictions

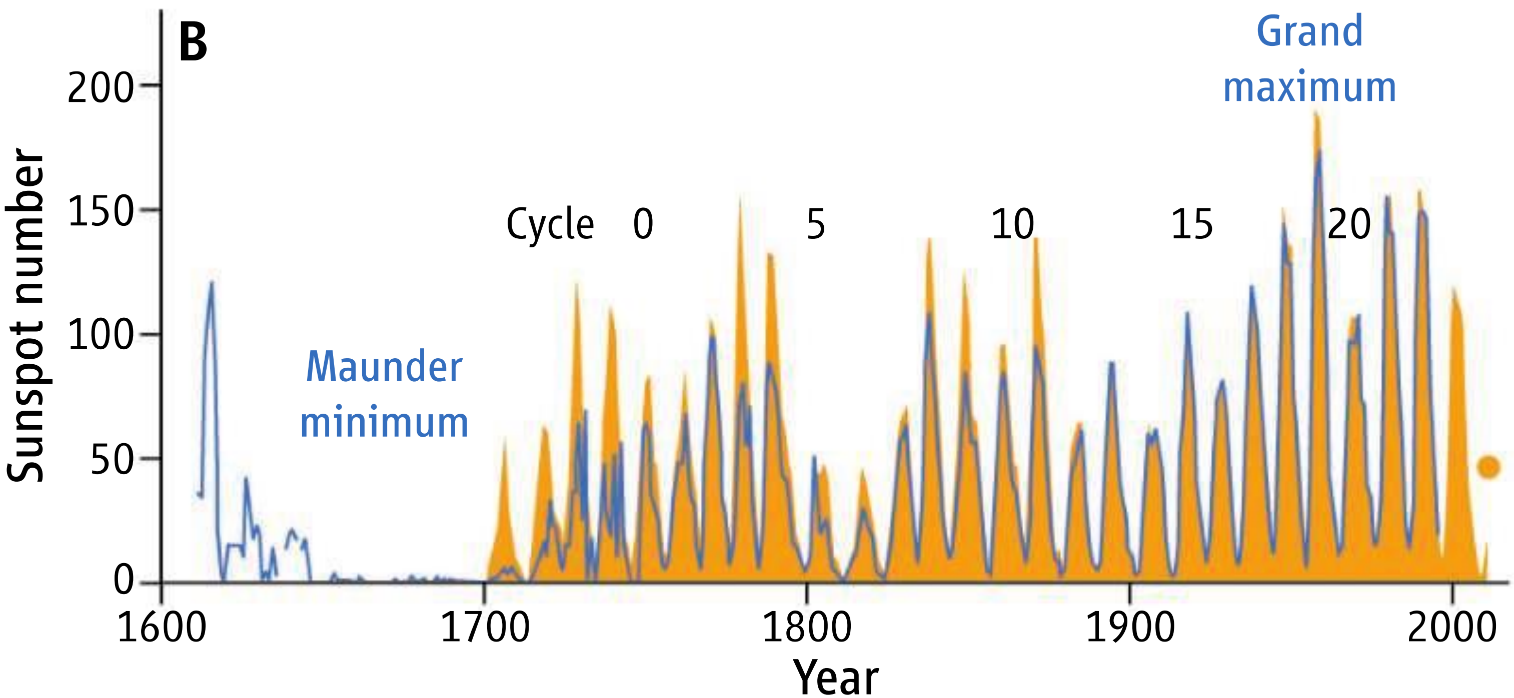
- Maximum SSN predictions of various types of models for cycle 24.
- The observed maximum (so far) is 82 (horizontal red line).



From ref (27): Pesnell, W.D. (NASA Goddard Space Flight Center)
Solar Physics **281**: 507, 2012.

Backup – Deep Solar Minimum

- Sunspot numbers in Maunder minimum and near ~1810 were zero



From ref (28): Solanki, S., Krivova, N., *Science* **334**: 916-917, 2011.
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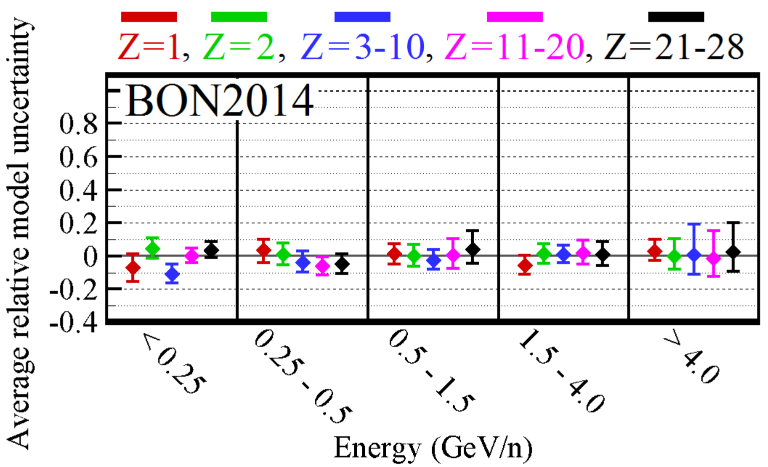
Backup – BON Model Assumptions

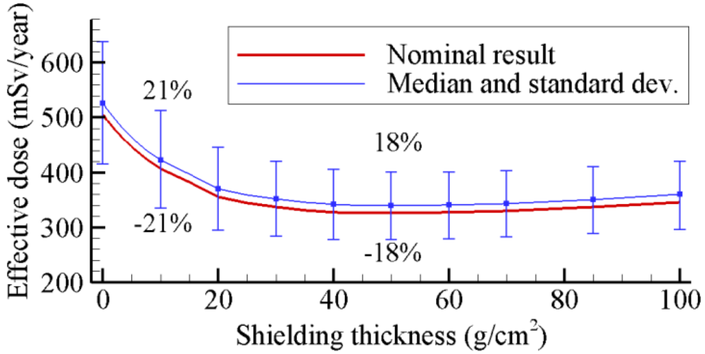
- The BON GCR model is a semi-empirical model, calibrated to measurements taken near Earth
  - Numerical solutions to the Fokker-Planck equation are obtained to describe GCR modulation through the heliosphere
  - GCR spectrum outside the solar system, referred to as the local interstellar spectrum (LIS), is the boundary condition for the model and is described with 3 free parameters for each ion
  - Solutions to the Fokker-Planck differential equation are obtained under the assumption of a quasi-steady state and radially symmetric interplanetary medium
  - Solar wind speed is assumed to be constant at ~400 km/s
  - Solar activity is related to sunspot number using a linear fitting function and Nymmik's empirical time-delay [8,9]

- Free parameters describing the LIS are calibrated by comparing model results near Earth to available measurements
  - Recent efforts have taken a more rigorous and comprehensive approach to calibration and validation, resulting in the BON2014 model
  - Model uncertainties above 0.5 GeV/n (500 MeV/n) are within measurement error (error bars on plot)
  - Model uncertainties below 0.5 GeV/n are slightly larger but mostly within measurement uncertainty
  - Model uncertainties below 500 MeV/n have a small impact on exposure quantities behind shielding [6]



Backup – BON Model Uncertainty

- Model uncertainties are rigorously quantified using interval-based uncertainty metrics
  - Measurement uncertainty (ranges up to 50% for some data) is included in the analysis
  - Uncertainty distributions are obtained for specific ions and energy groups
  - Uncertainty propagation methods were developed[30] to quantify how errors in the GCR model impact effective dose behind shielding
- AMS-II data will provide a unique opportunity to perform independent validation of the available GCR models
  - Data was not available when models were calibrated
  - Data will be used to improve parameter calibration after independent validation is performed



Female effective dose versus aluminum shielding thickness during solar minimum. Error bars represent BON2014 GCR model uncertainty at 1 standard deviation (68% CL)

- GCR model uncertainties can be propagated into effective dose behind shielding
  - This connects environmental model uncertainty directly to exposure quantities of interest behind shielding

Backup – Transport Codes

- Particle transport through materials is described either with Monte Carlo or deterministic methods
  - Monte Carlo: Use random number generators to sample the physical interaction models and track each particle individually as it passes through matter (Geant4, FLUKA, PHITS, MCNP6)
  - Deterministic: Solve the relevant Boltzmann transport equation using analytic and numerical methods

- NASA's radiation transport code, HZETRN[11-15], is deterministic
  - Highly efficient compared to Monte Carlo methods (seconds vs. days or longer)
  - Efficiency needed to support vehicle design, engineering, and optimization activities
  - Extensive verification against Monte Carlo and validation against space flight measurements

- HZETRN is based on a converging sequence of physical approximations
  - Early versions of the code were based on the straight ahead approximation [11]
  - Straight ahead approximation has been shown to be accurate for HZE particles [11,31]
  - Recent code developments have included 3D corrections for neutrons and light ions while maintaining overall code efficiency [15,16]

- Validation and uncertainty quantification efforts for transport codes and associated nuclear physics models are ongoing
  - HZETRN agrees with Monte Carlo codes to the extent they agree with each other in most cases [13,15-19]
  - Development, validation and uncertainty quantification of nuclear physics models is ongoing
  - Space flight validation efforts (Shuttle, ISS and MSL/RAD) and uncertainty quantification for integrated model-set has been described elsewhere [21-23,31]

Backup – Human Phantoms

- For computing effective dose and astronaut risk, detailed models of the human body are needed to describe body self-shielding for radiosensitive tissues
  - The stylized CAM/CAF phantoms developed in the 1970s to match 50^{th} percentile US Air Force personnel have been used extensively in space radiation analyses and tools [32,33]
  - State-of-the-art phantoms, developed to match ICRP anatomical reference values, are also available and have been coupled to HZETRN using various methods [34,35]
  - Variation in exposure quantities caused by differing human phantoms is generally small if state-of-the-art phantoms are used [ref]

- Plot below shows effective dose (FAX phantom) and point dose equivalent (no phantom) behind shielding
  - Additional tissue shielding provided by body attenuates exposure and variation associated with solar activity