E M M R E M

Earth-Moon-Mars Radiation Environment Model

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The Space Radiation Environment

Solar particle events (SPE) (generally associated with Coronal Mass Ejections from the Sun):

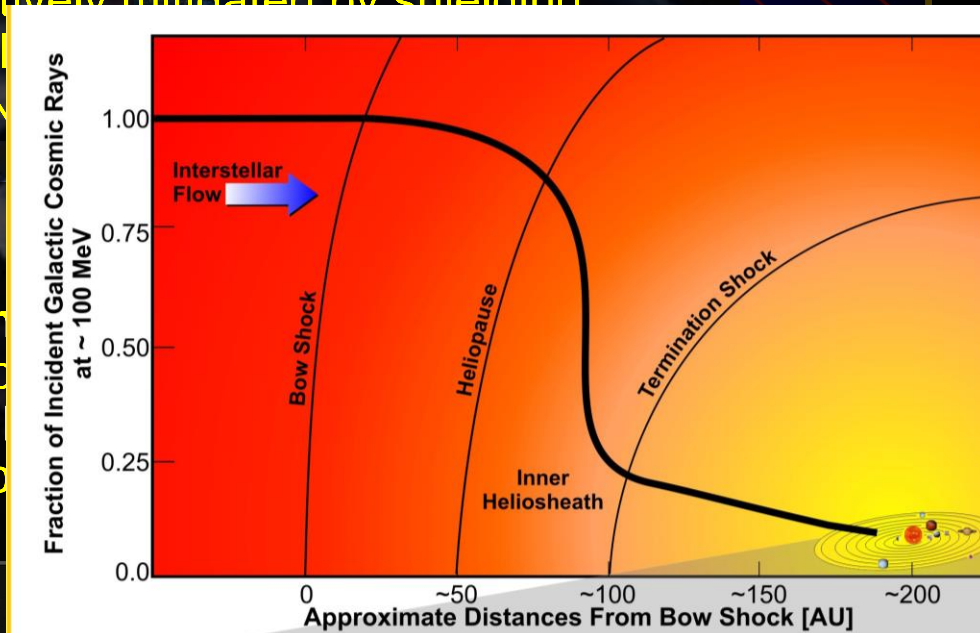
medium to high energy protons
largest doses occur during maximum solar activity
not currently predictable
MAIN PROBLEM: develop realistic forecasting and warning strategies

Trapped Radiation:

medium energy protons and electrons
effectively mitigated by shielding
mainl
MAIN

Galactic Cosmic Rays (GCR)

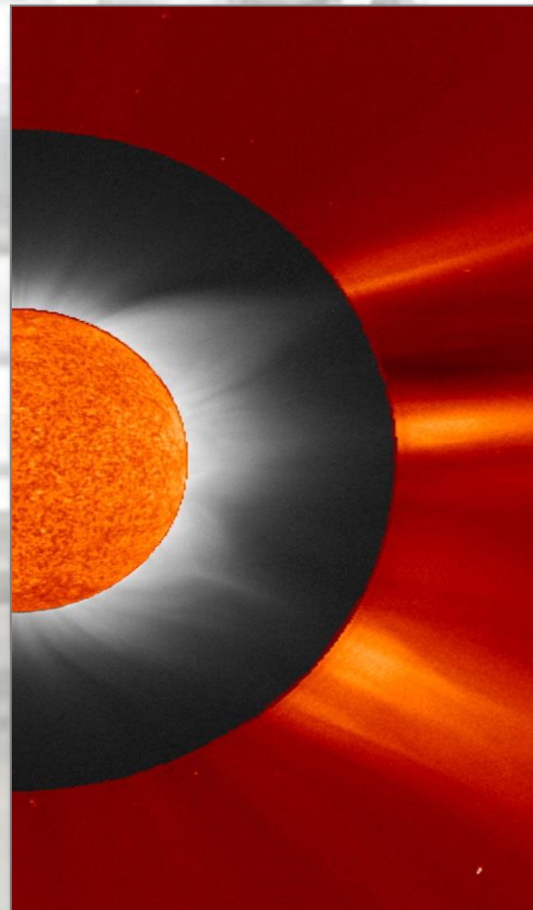
high energy protons
highly charged, energetic atomic n
not effectively shielded (break up into
abundances and energies quite well
MAIN PROBLEM: biological effects p
significant long-term space radiation



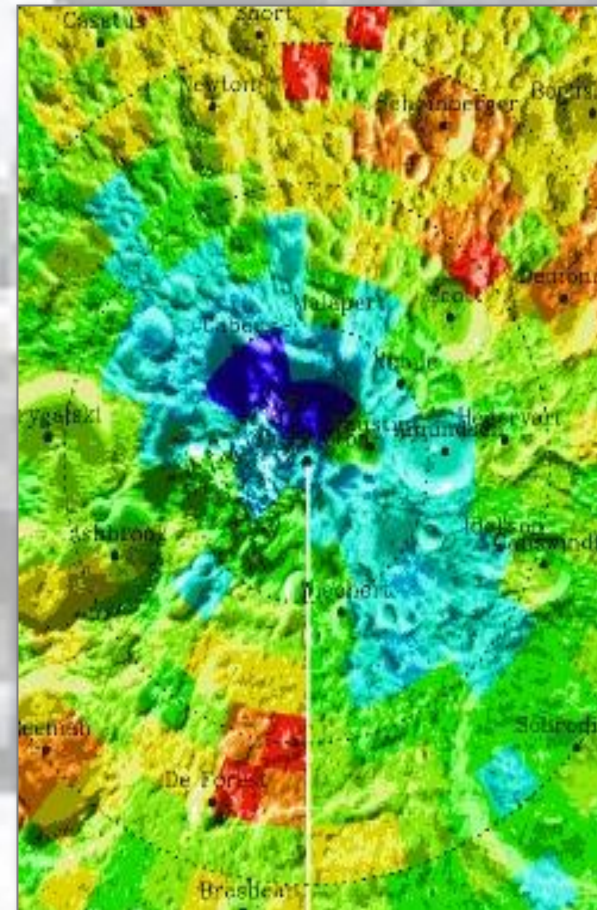
Space Weather, Safeguarding the Journey

EMMREM

Interaction of dust and plasma on the surface of the Moon and in the exosphere



Space weather impacts on robotic and human productivity



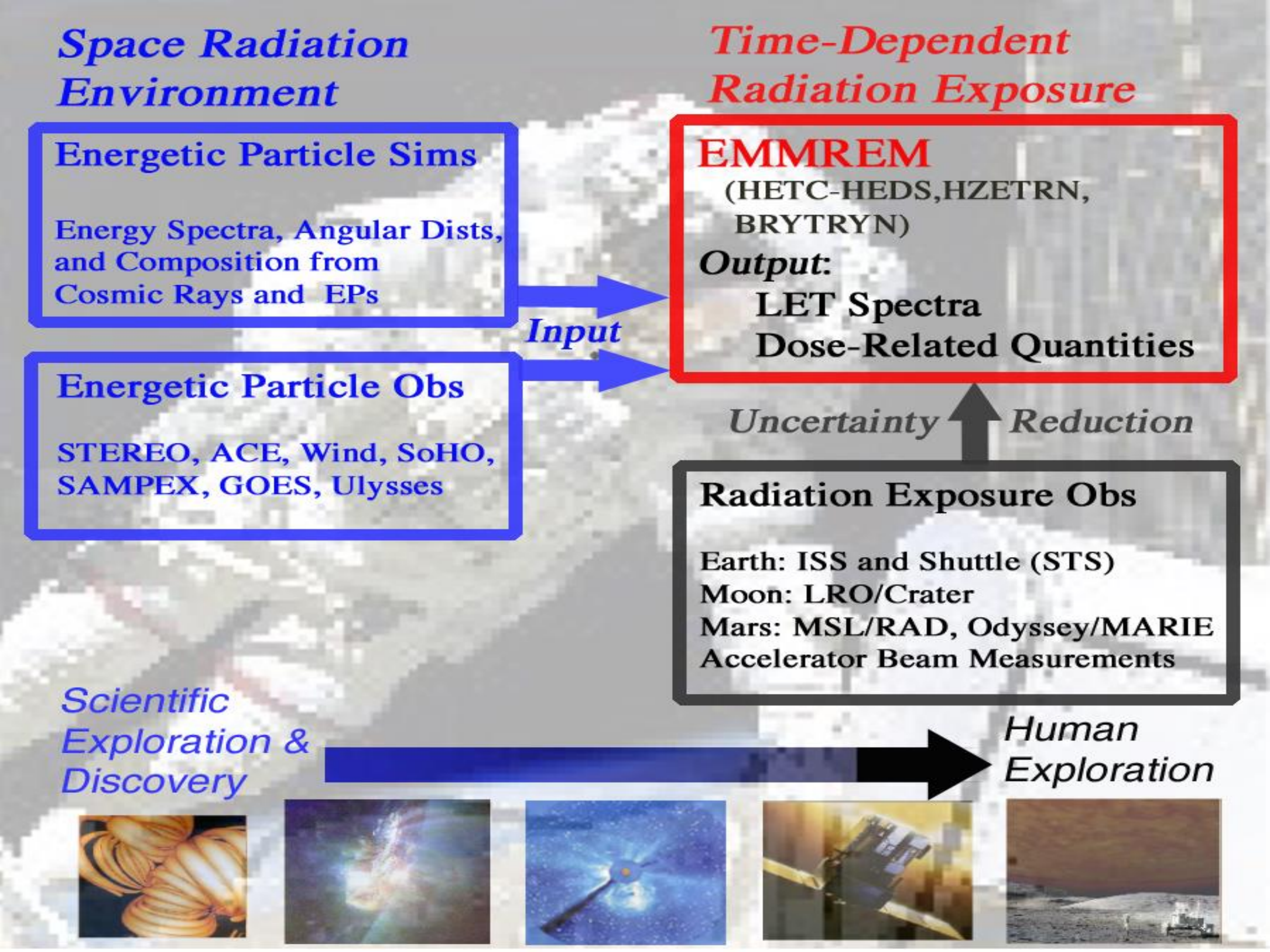
Radiation bombardment on the lunar surface and subsurface

The EMMREM Objective

Central objective of EMMREM is to develop and validate a numerical module for completely characterizing time-dependent radiation exposure in the Earth- Moon-Mars and Interplanetary space environments

Predict near-real-time radiation exposure anywhere on the surface of Mars, and in interplanetary space between Earth and Mars

Connect observations and theory in solar and heliospheric physics with radiation biology



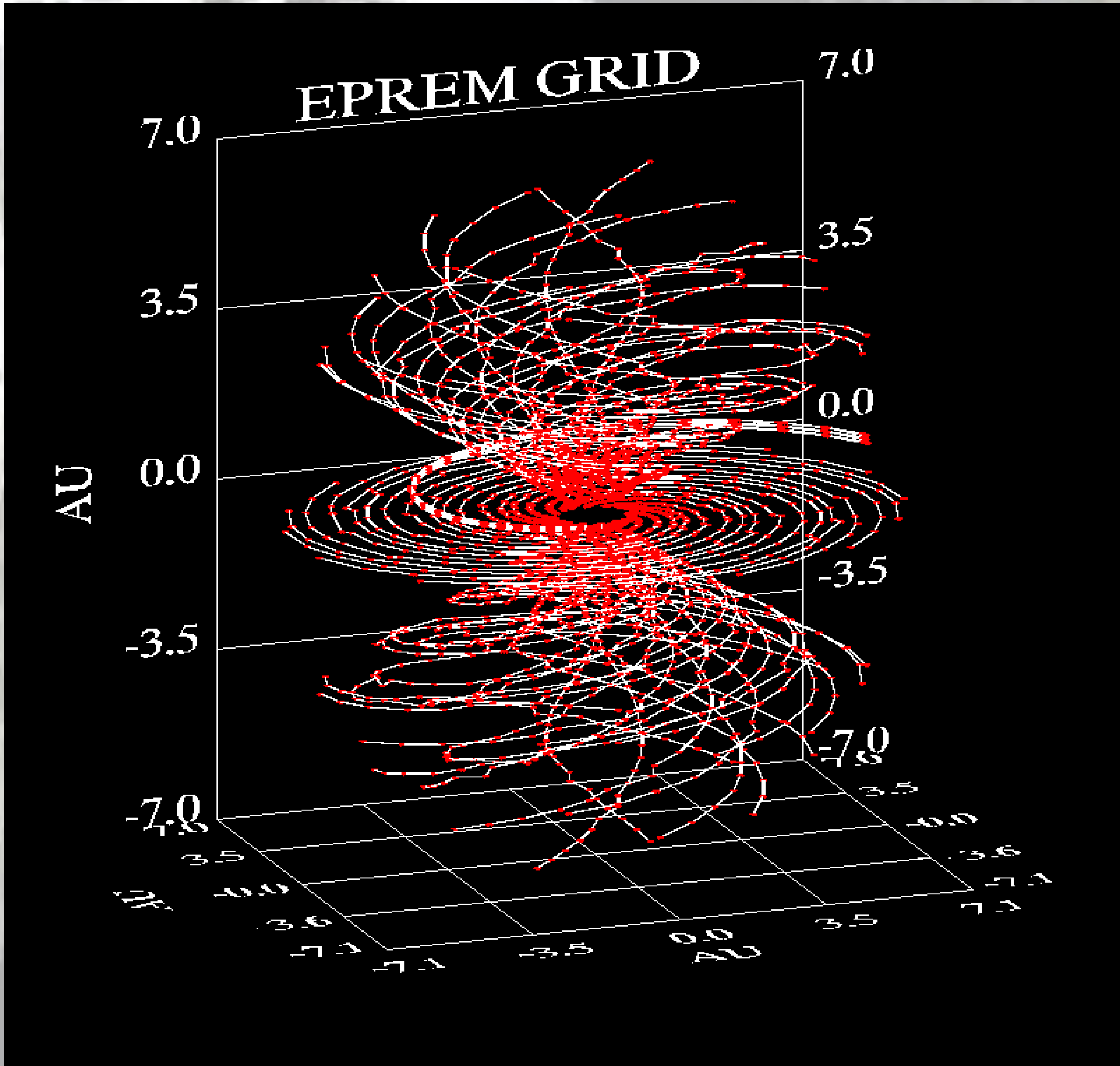
Space Radiation Environment
Time-Dependent Radiation Exposure
Energetic Particle Sims
Energy Spectra, Angular Dists, and Composition from Cosmic Rays and EPs
EMMREM
(HETC-HEDS,HZETRN, BRYTRYN)
Output:
LET Spectra
Dose-Related Quantities
Input
Energetic Particle Obs
STEREO, ACE, Wind, SoHO, SAMPEX, GOES, Ulysses
Uncertainty
Reduction
Radiation Exposure Obs
Earth: ISS and Shuttle (STS)
Moon: LRO/Crater
Mars: MSL/RAD, Odyssey/MARIE
Accelerator Beam Measurements
Scientific Exploration & Discovery
Human Exploration

EMMREM: Primary Transport

The Energetic Particle Radiation Environment Model (EPREM) is a physical 3D kinetic model for the transport of energetic particles.

- Capable of simulating the transport of protons, electrons, and heavier ions.

- Currently run on an event-by-event basis (boundary conditions from ACE & GOES)



Energetic Particle Transport and Acceleration

- Solves for particle transport along field lines in the Lagrangian grid (Kota, 2007)

$$\left(1-\frac{(\vec{u}\cdot e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\cdot\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial \mu}+$$

$$\left[-\frac{\mu e_b}{v}\cdot\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial \mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial \mu}\right)+S$$

- Model also includes perpendicular diffusion and gradient and curvature drift

EMMREM: Secondary Transport

- ***Radiation transport – Input is time series from EPREM.***

  - BRYNTRN (BaRYoN TraNsport) code for light ions, primarily for SEP calculations;

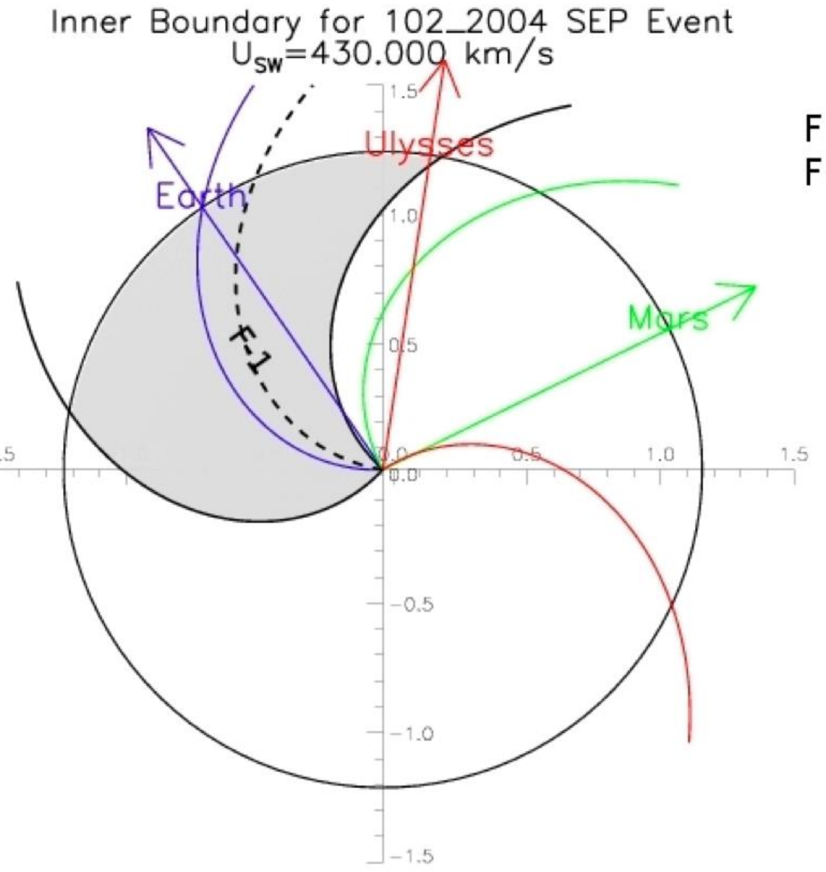
  - HZETRN code for high Z primary and secondary ions transport – for SEP and GCR calculations; Look-up tables for Mars atmosphere.

  - HETC-HEDS (High-Energy Transport Code – Human Exploration and Development of Space) Monte Carlo code; Look-up tables for Earth atmosphere

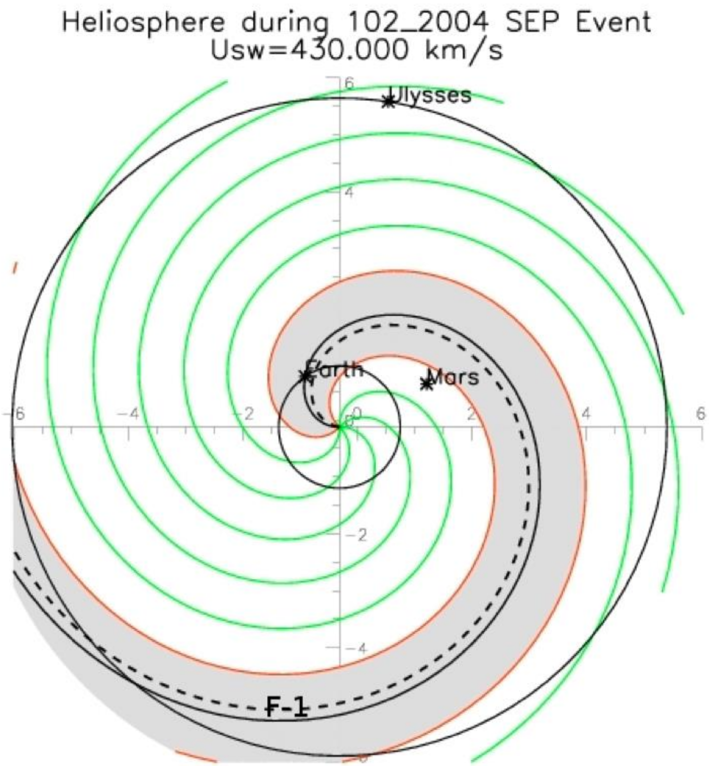
- ***Scenarios***
  - ***Earth***
  - ***Moon***
  - ***Mars***
  - ***Interplanetary***

Completed EMMREM framework will be capable of performing radiation calculations that account for time-dependent positions, spacecraft and human geometry, spacesuit shielding, atmospheres and surface habitats.

Heliosphere conditions for April 2004 SEP event

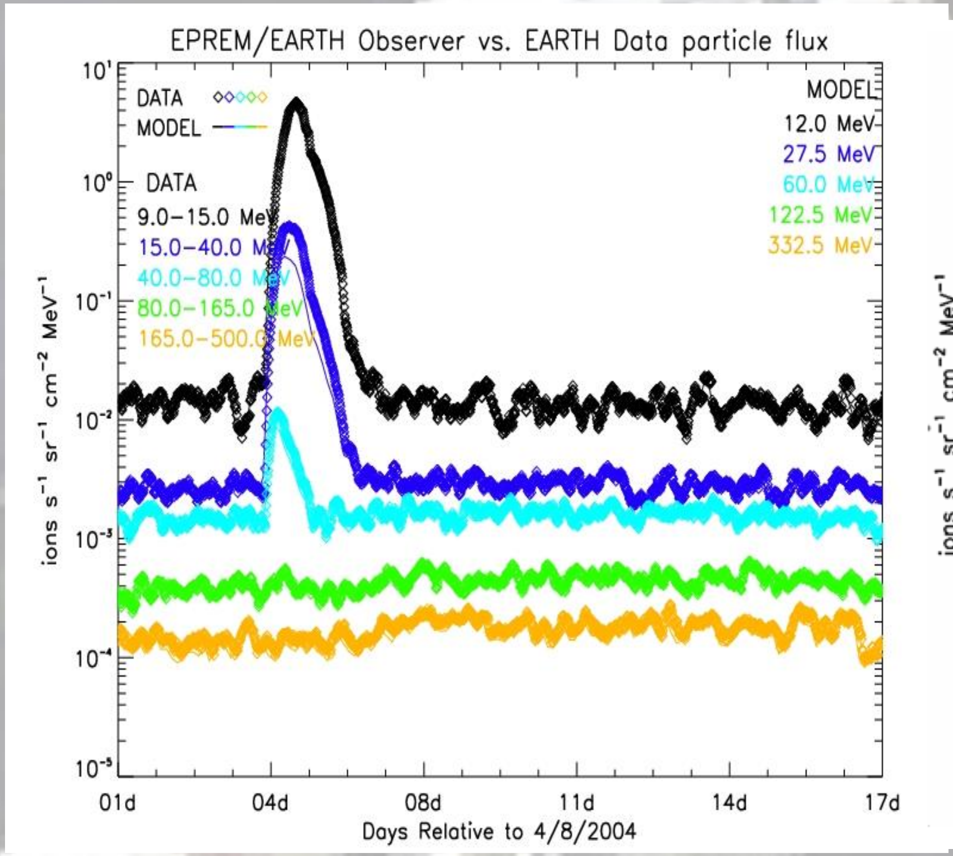


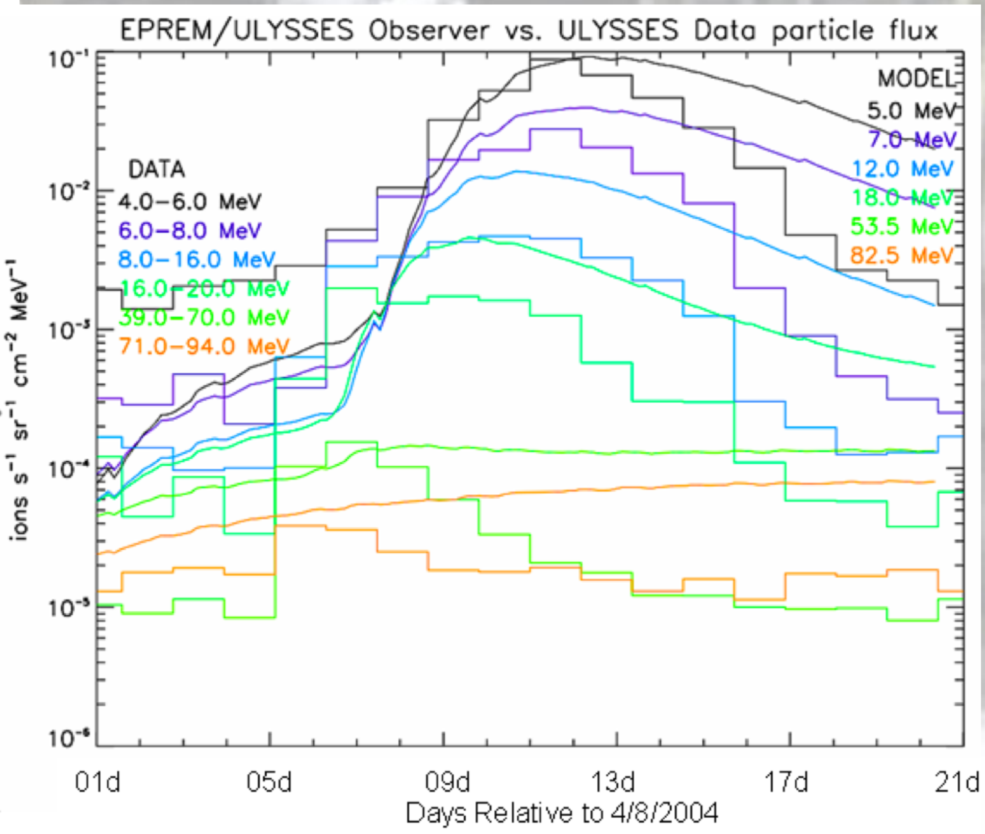
Flare/X-Ray Class
F-1 / C9



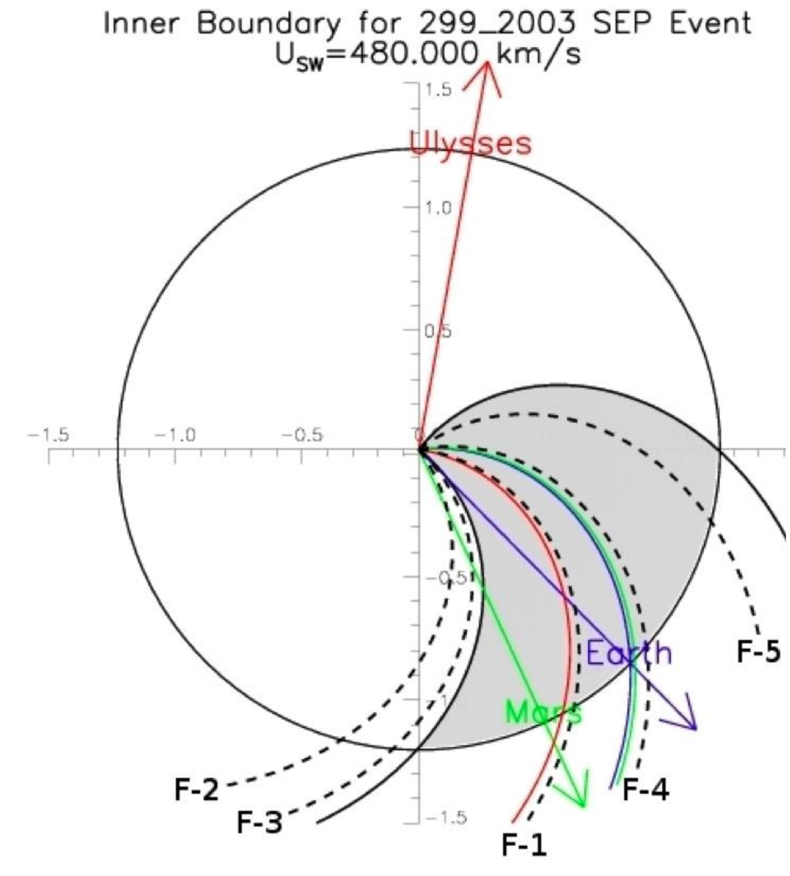
Flare/X-Ray Class
F-1 / C9

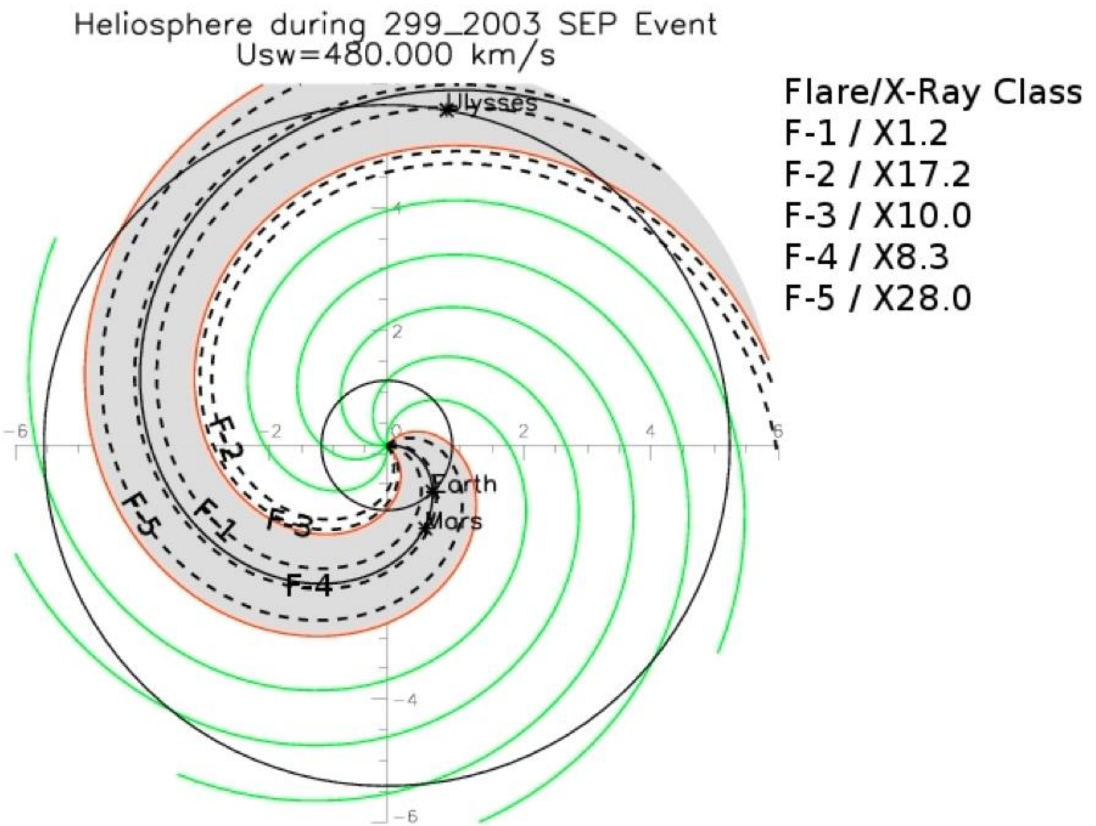
Earth and Ulysses fluxes: April 2004



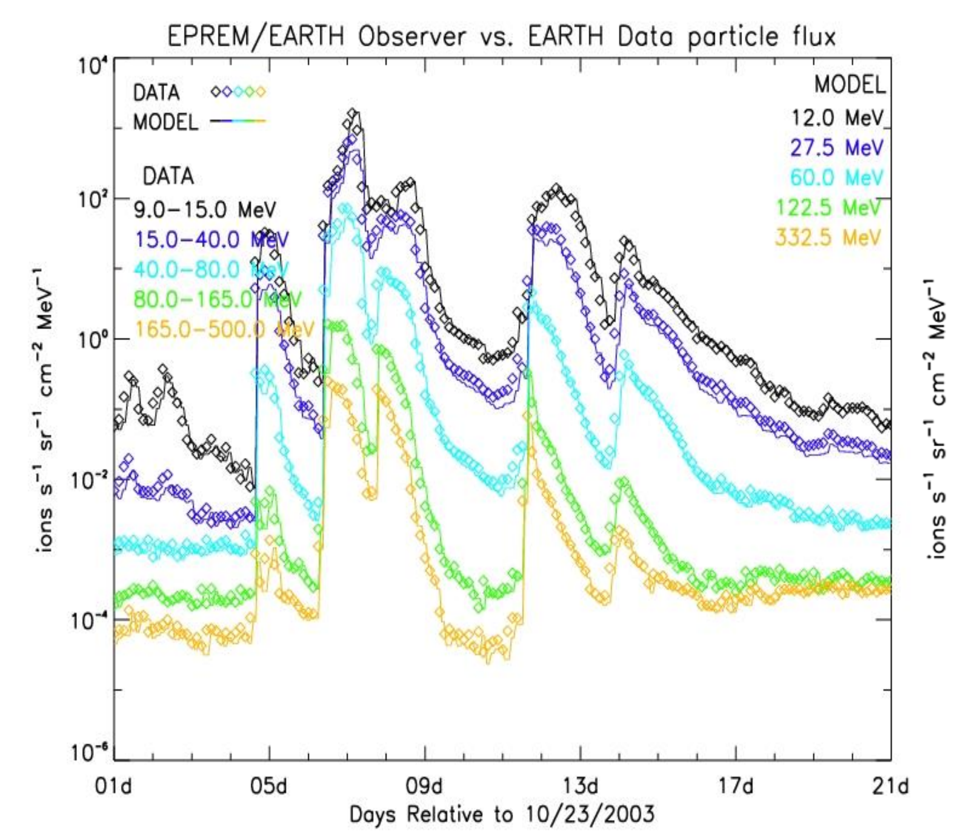


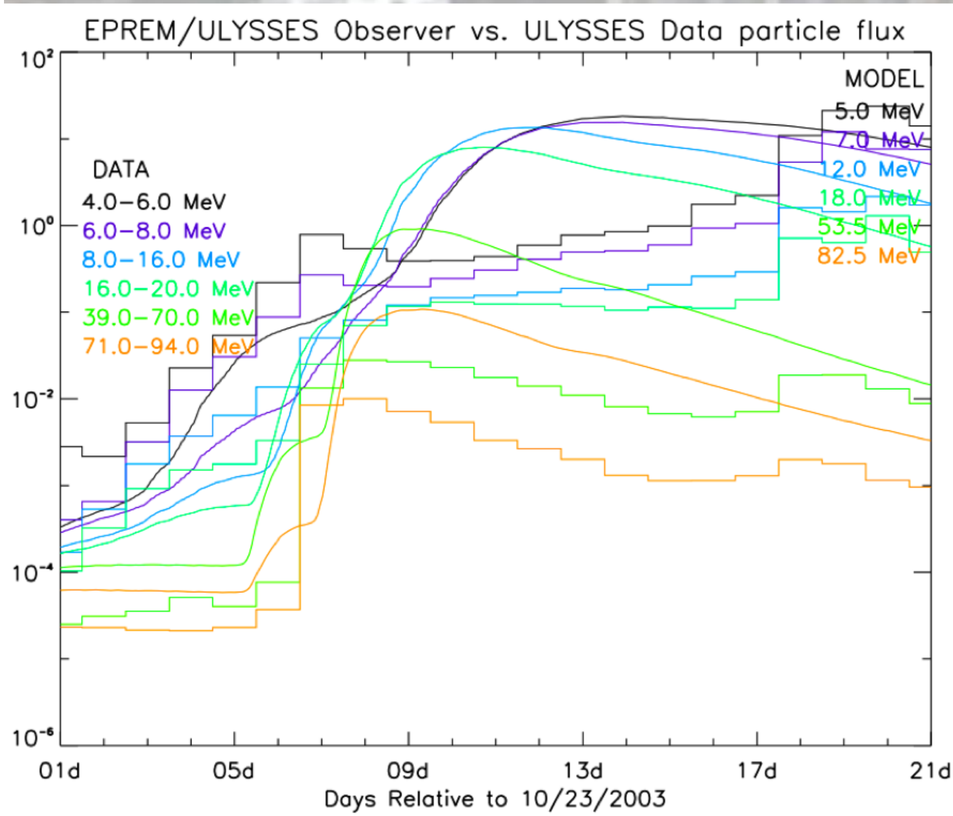
Heliosphere conditions for Oct/Nov 2003 SEP event



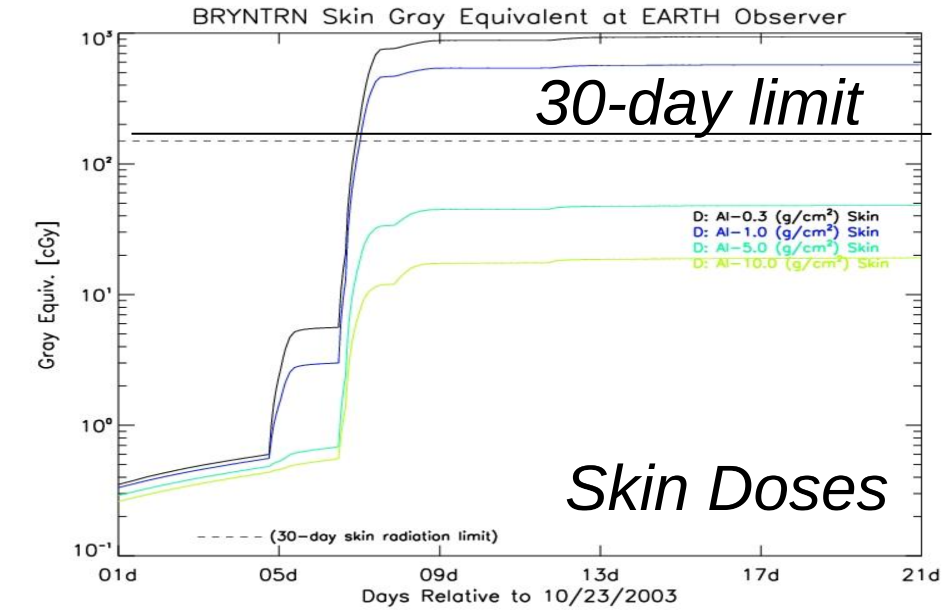


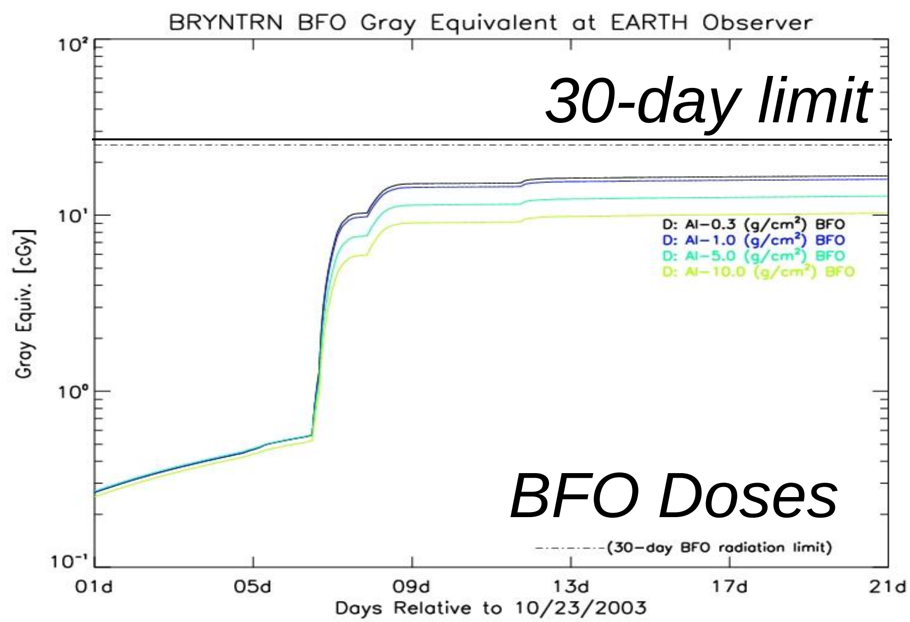
Earth and Ulysses fluxes: October/November 2003

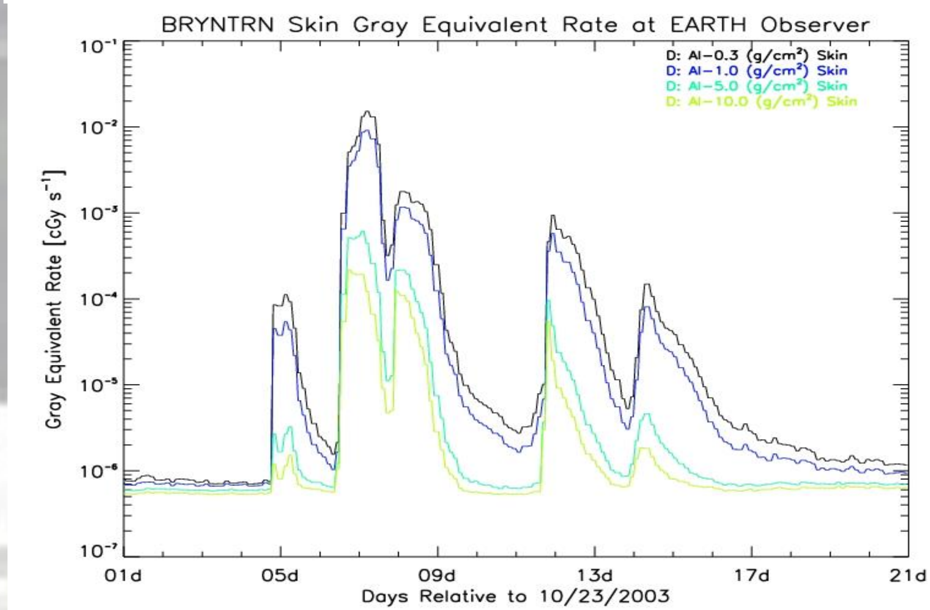


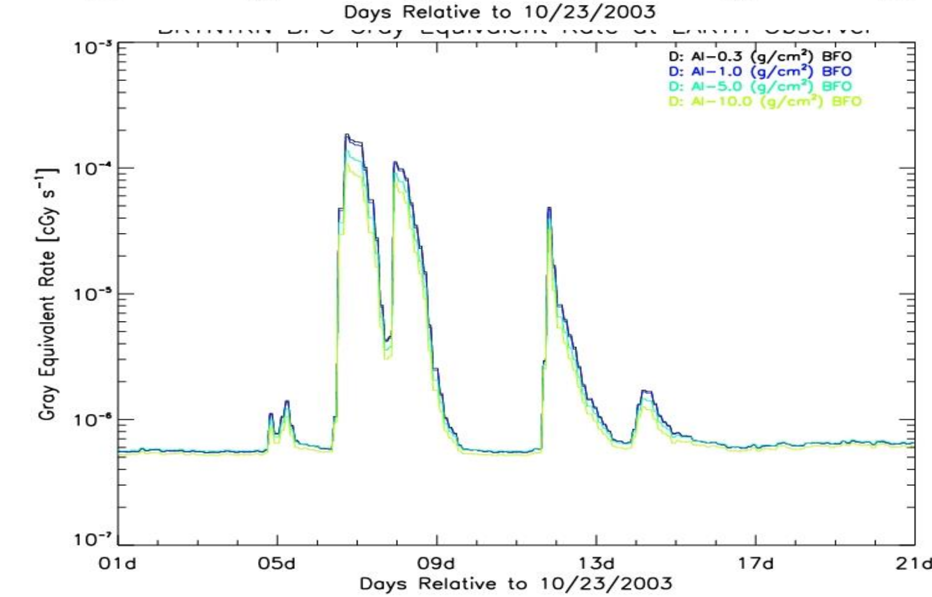


Earth Gray Equivalent Doses: October/November 2003



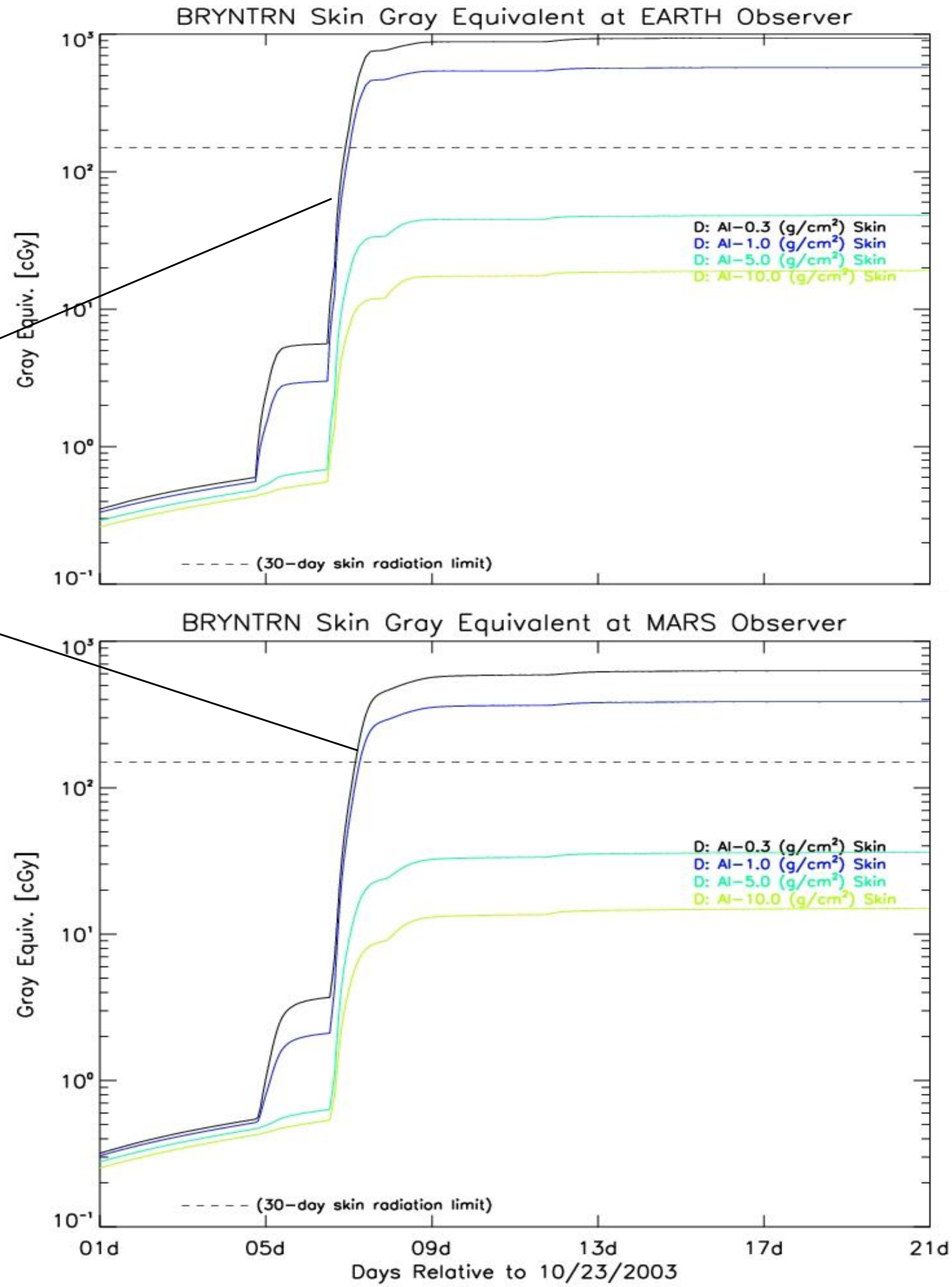




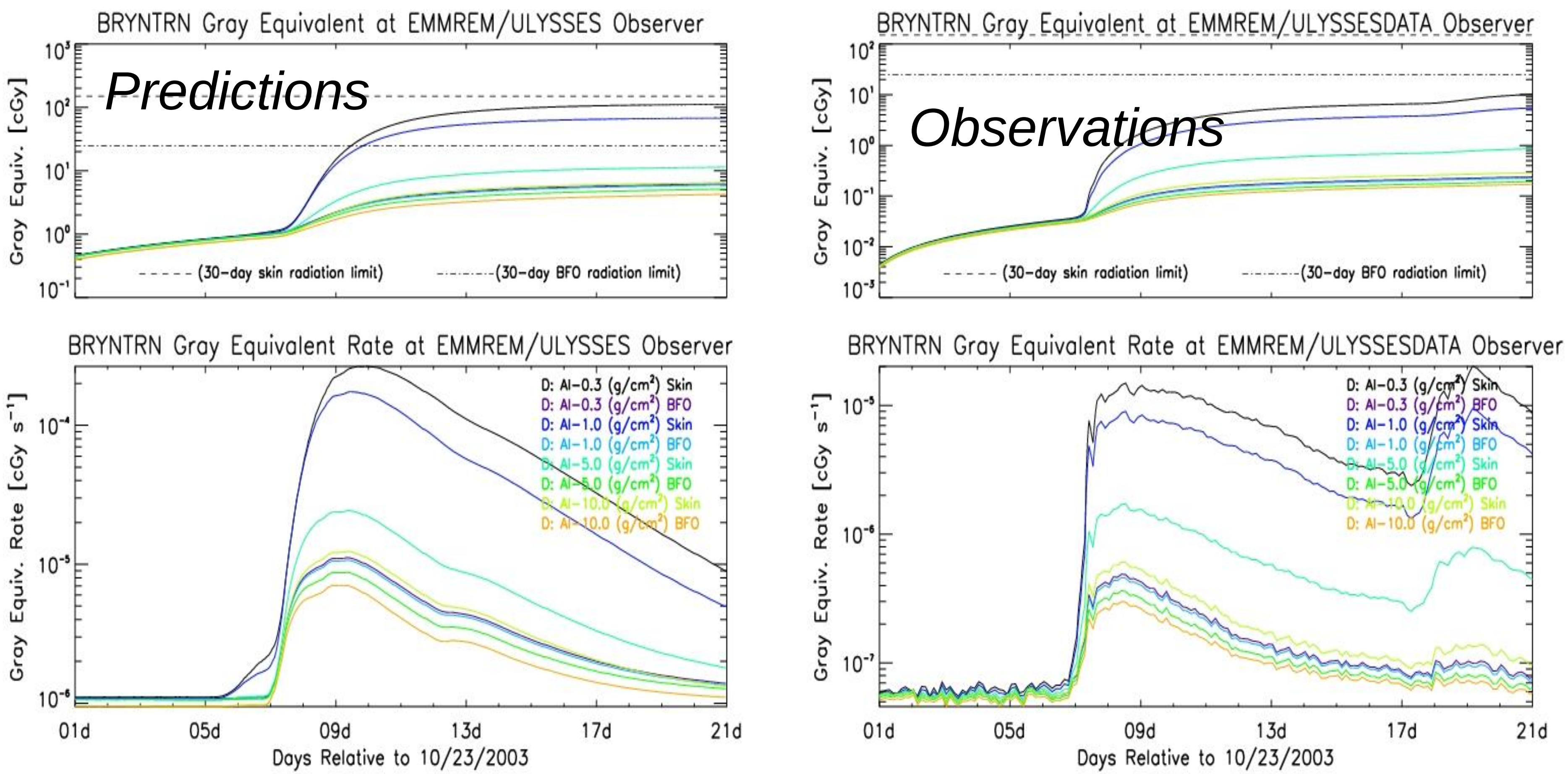


Earth Mars Comparison

Oct 2003

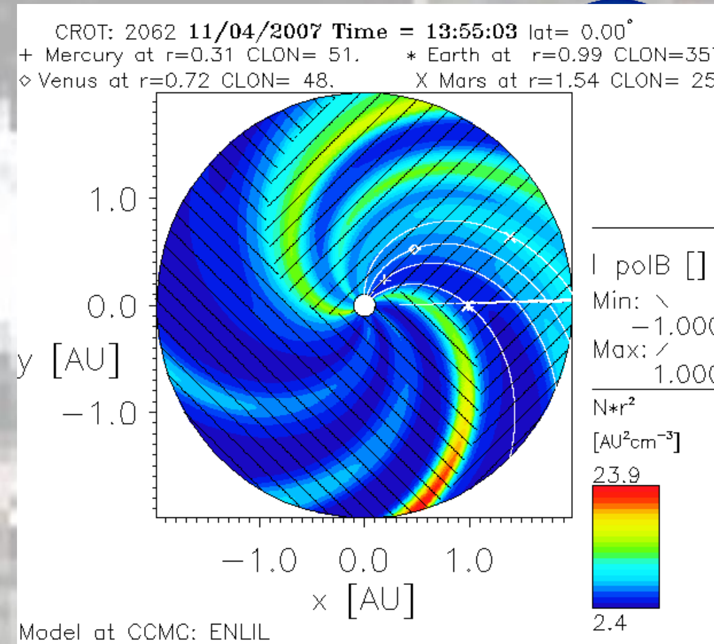


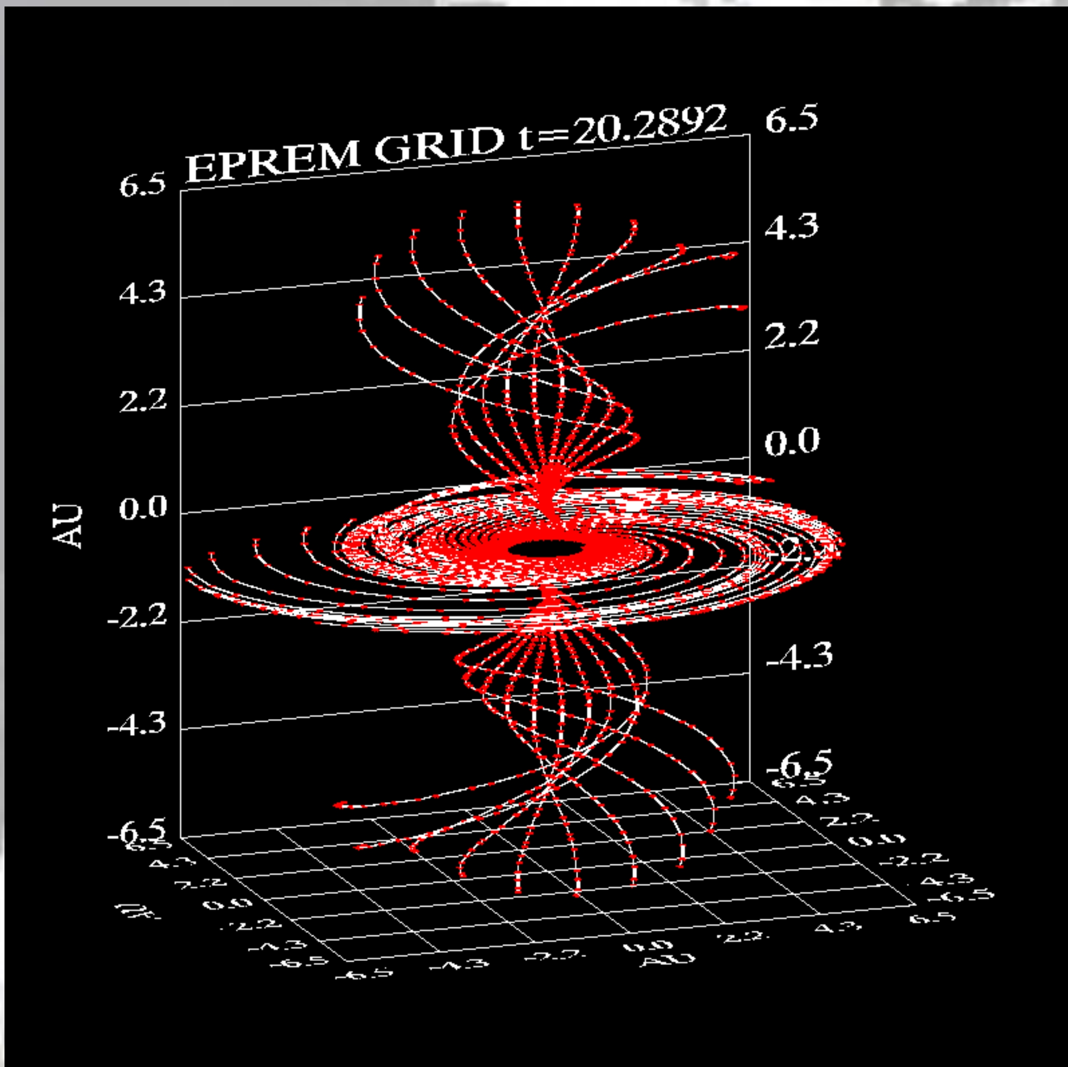
Dose Comparison at Ulysses: Oct/Nov 2003

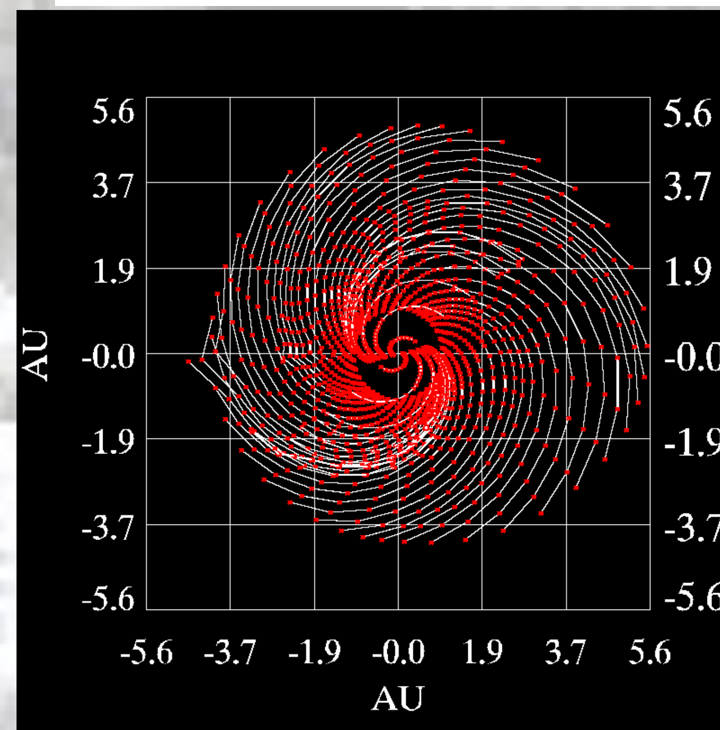


Predicted doses are an order of magnitude higher than observed

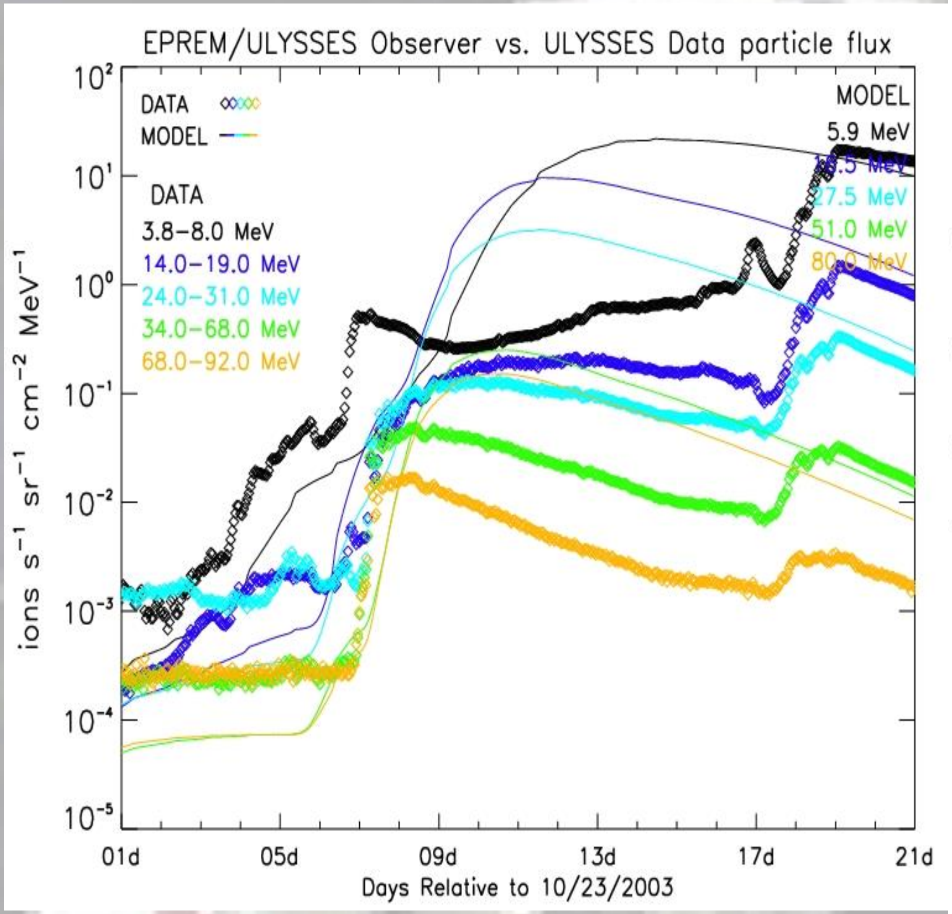
Coupling to MHD

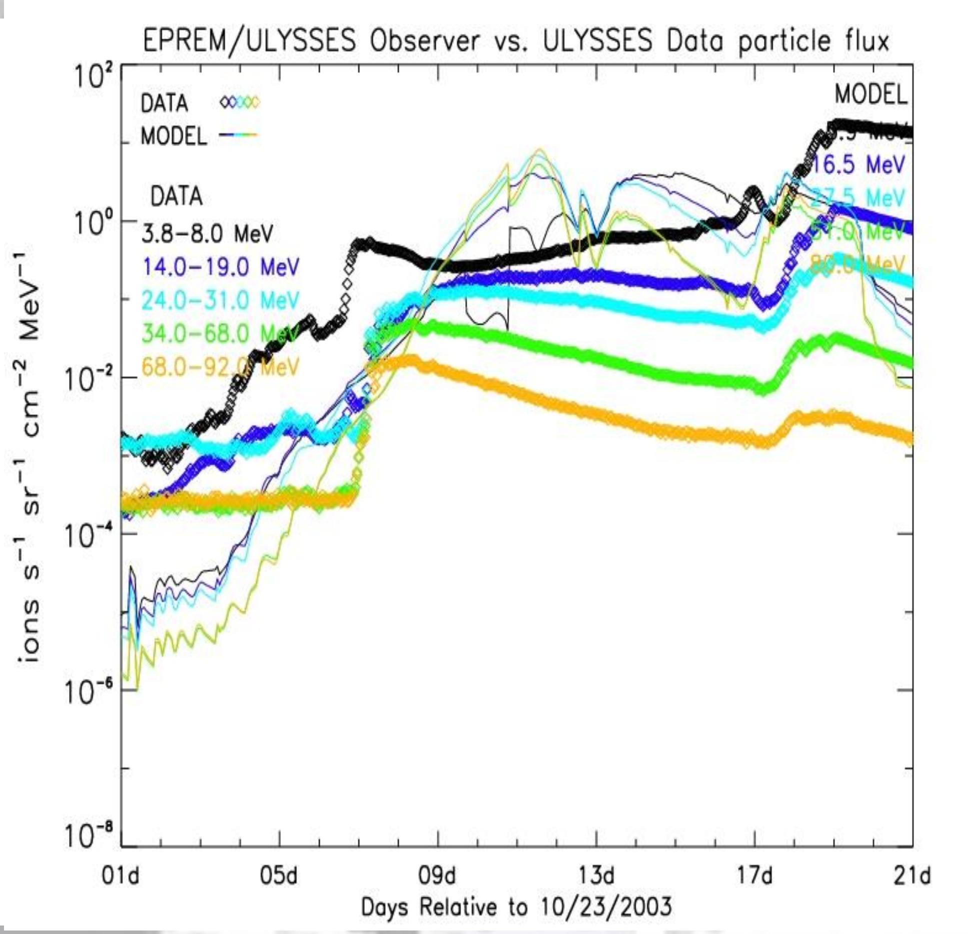






MHD Coupling: Energetic Particles at Ulysses

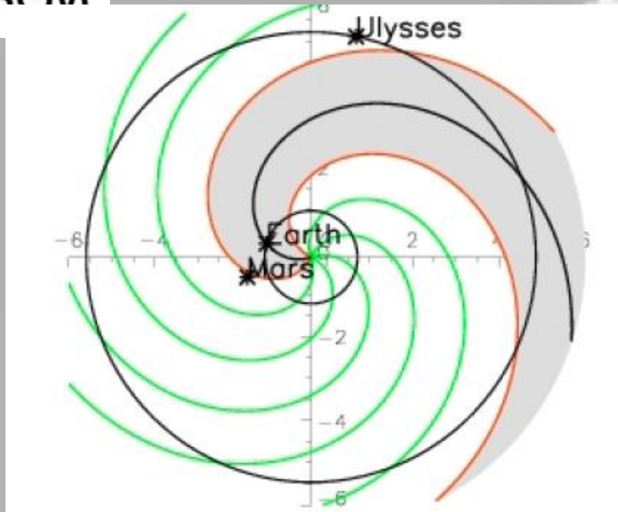


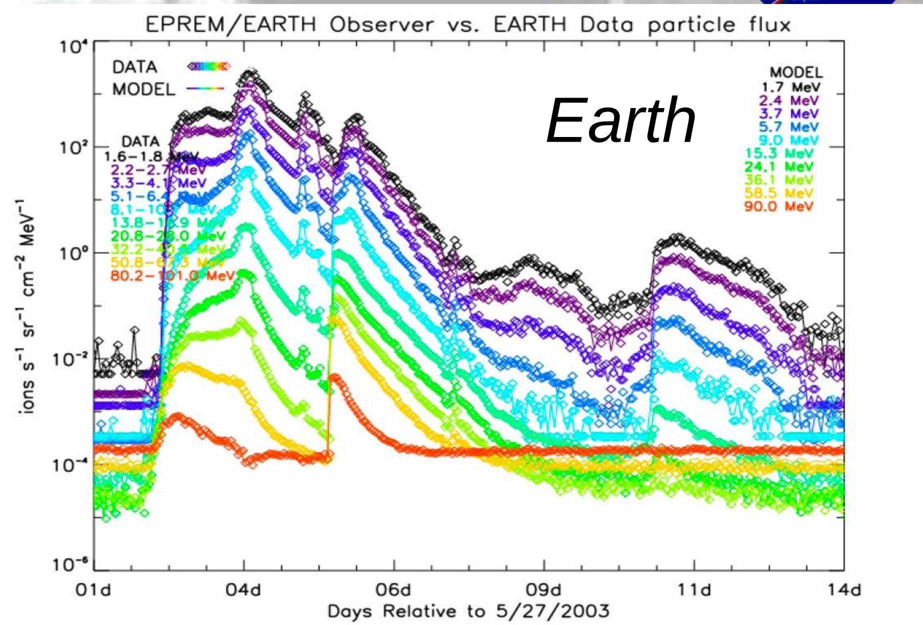


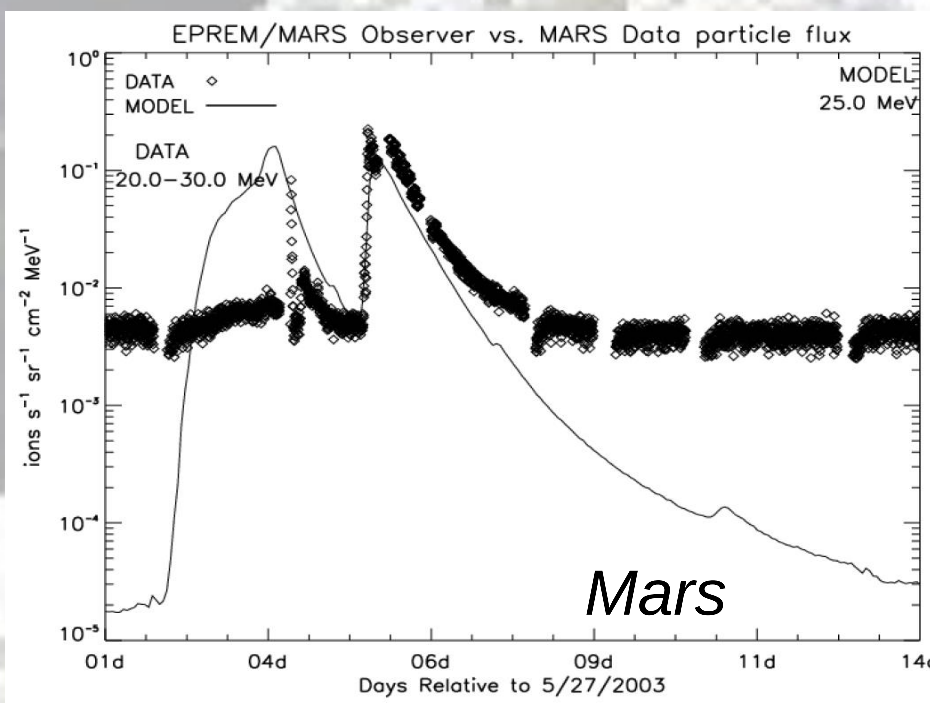
Without Enlil coupling

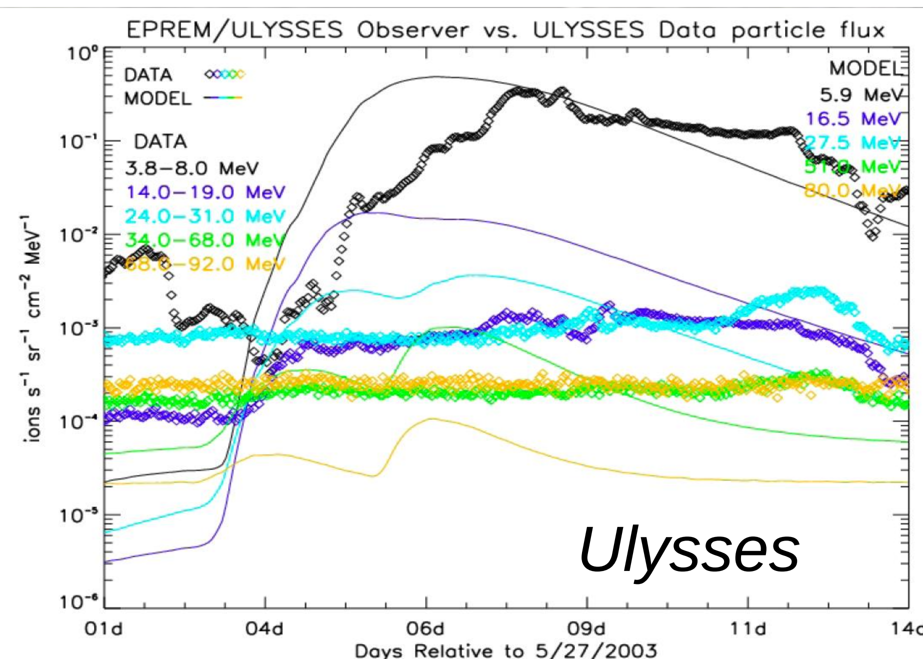
With Enlil coupling

Propagation to Mars









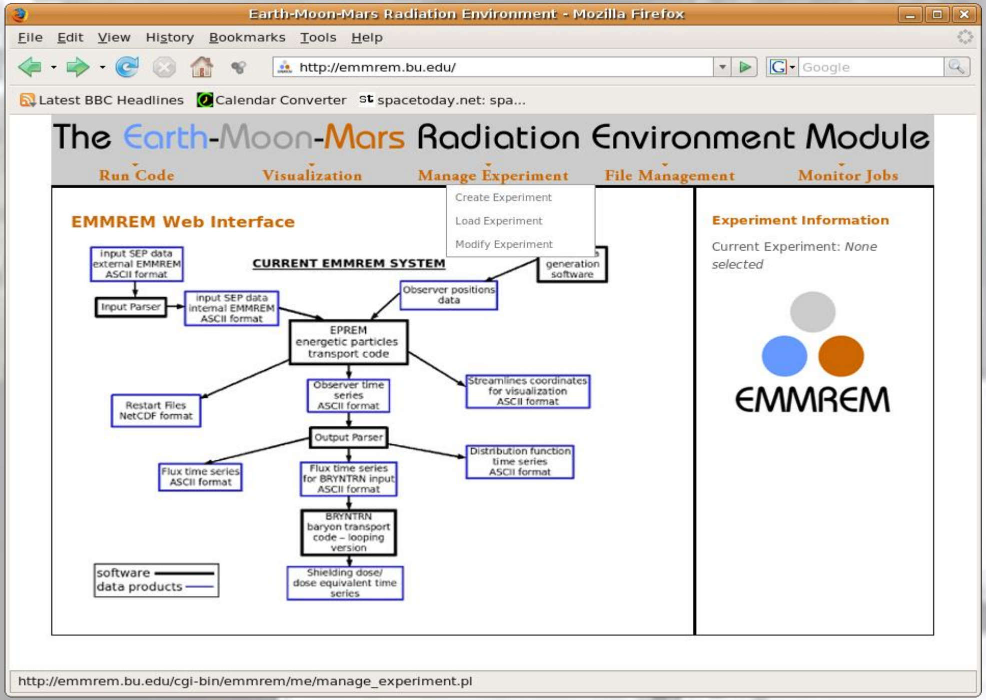
EMMREM User Community

Delivered first version of EMMREM framework to Space Radiation Analysis Group (SRAG) at Johnson Space Center

- Discussing development of operational interface to their models

Discussions ongoing with Community-Coordinated Modeling Center (CCMC) and NOAA

Developing a web interface to EMMREM



EMMREM Questions

- What are the radial gradients of SEPs and the radiation characteristics?
- What physical processes need better specification to improve SEP prediction based on observational boundary specification?
- How does event time evolution influence risk assessment?
- How well do our models characterize the radiation environment at the Moon (and Mars)?

Summary

- First version of EMMREM developed
  - Included interplanetary primary transport
  - Secondary transport (BRYNTRN for near-real-time capabilities
  - MHD coupling now taking shape
- Soon to come on-line
  - Simulated Particle Events
  - Mars Scenarios
  - Earth Scenarios
  - Lunar Validation

Mars Scenario

- **Mars atmosphere calculations delayed until the looping BRYNTRN code module was fully implemented into EMMREM due to manpower considerations**

  - BRYNTRN calculations for incident SPE protons have been incorporated into a lookup table, which provides effective dose, and organ dose and dose equivalent for a wide variety of SPE proton energies, on a per incident particle basis

  - One only needs to select a location on the Martian surface, fold in the actual spacecraft/rover/habitat geometry, and fold in the actual measured SPE spectrum in order to do radiation exposure estimates for any desired scenario

GCRs from HZETRN

HZETRN 2005 Code

- **A 3-layer version of that incorporates Mars atmosphere shielding effects has been configured to calculate Galactic Cosmic Ray (GCR) dose and dose equivalent for use in estimating radiation exposures for Mars surface and atmosphere scenarios**
  - ***Mars CO_2 atmosphere (15 depths: 0-300 g/cm^2)***
  - ***Al spacecraft/habitat (10 depths: 0-100 g/cm^2)***
  - ***Body tissue (CAM model geometry)***

Earth Scenario
Earth Atmosphere

- **BRYNTRN and HZETRN 2005 codes do not yet include meson production and transport, which are important for very deep penetration problems, such as transport through Earth's atmosphere, therefore, the decision has been made to use a 3-dimensional Monte Carlo code, HETC-HEDS, which does include meson and muon production**
- **Calculations will begin in June 2009, after the current sets of Mars atmosphere calculations are completed**

Earth Scenario
Earth Atmosphere

- **We will limit the HETC-HEDS calculations to certain altitudes in Earth's atmosphere relevant for commercial and high altitude air travel**
  - ***Federal Aviation Administration has for many years sponsored transport code development for aircraft/aircrew radiation exposure estimations***
  - ***Many sets of calculations of radiation doses in Earth's atmosphere, obtained with a variety of codes, available in the open, published literature***
- **HETC-HEDS calculations will be in the form of a look up table**
  - ***Calculations will be completed by October 31, 2009***

Lunar Validation

- Characterization of the CRaTER detector included comparisons of HETC-HEDS transport code predictions with calibration measurements using protons, conducted at the cyclotron at Massachusetts General Hospital, and comparisons of HETC-HEDS calculations with CRaTER calibration runs using Si and Fe beams provide by the NASA Space Radiation Laboratory (NSRL) at BNL
- Benchmark comparisons with MCNPX for protons

Lunar Validation

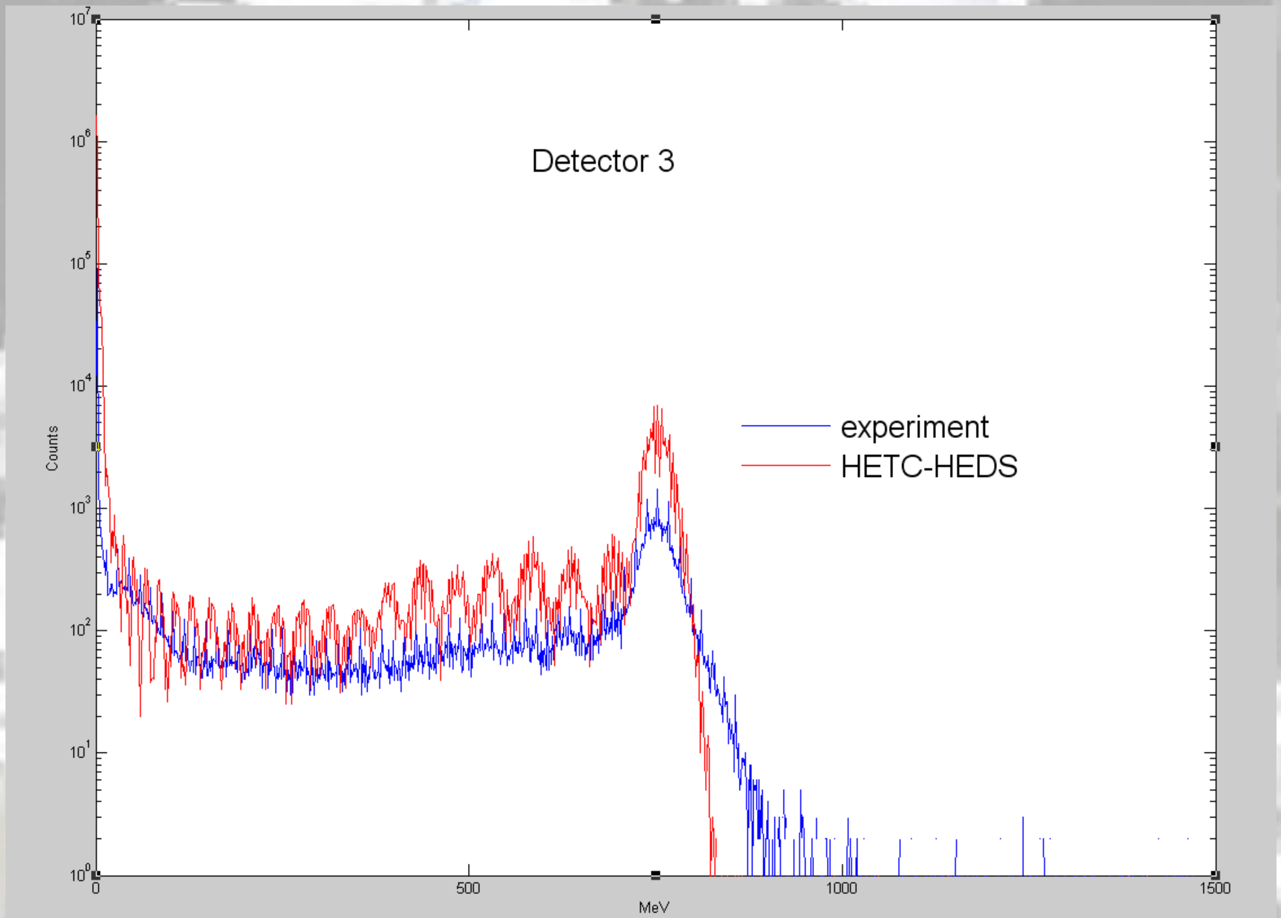


Figure 42. *Detector 3 Response for 650 MeV/nucleon Fe Beam*

Earth Scenario
LEO

- **BRYNTRN and HZETRN are routinely used by SRAG at NASA to calculate radiation exposures in low-Earth orbit (LEO) for STS and ISS analyses and applications**
- **No need to carry out specific calculations for LEO scenarios since they would be redundant**

GCRs from HZETRN

- **Lookup table used because calculations involving the relevant GCR spectra cannot be done in near real time simulations :**

  - GCR spectrum varies little from day to day; no significant dose variations over periods of weeks to months

  - Large spread in interplanetary magnetic field conditions; large numbers of GCR ion species and their many reaction product secondary particles may be transported through more than 500 g/cm^2 of atmosphere and shield materials

GCRs from HZETRN

- **HZETRN 2005, the NASA standard code for these types of calculations, is export-controlled and not publicly available**

- HZETRN 2005 was selected for use in the project, over earlier, publicly released versions of HZETRN, because it is the most up to date and complete version available

- Its use for this project is approved and licensed by NASA Langley Research Center

GCRs from HZETRN

- **Badhwar-O'Neill GCR model for interplanetary magnetic field potentials ranging from the most highly probable solar minimum (450 MV) to solar maximum conditions (1800 MV) in the solar cycle is used as input into the calculations**

  - ***Standard one used for space operations by the Space Radiation Analysis Group (SRAG) at NASA Johnson Space Center***

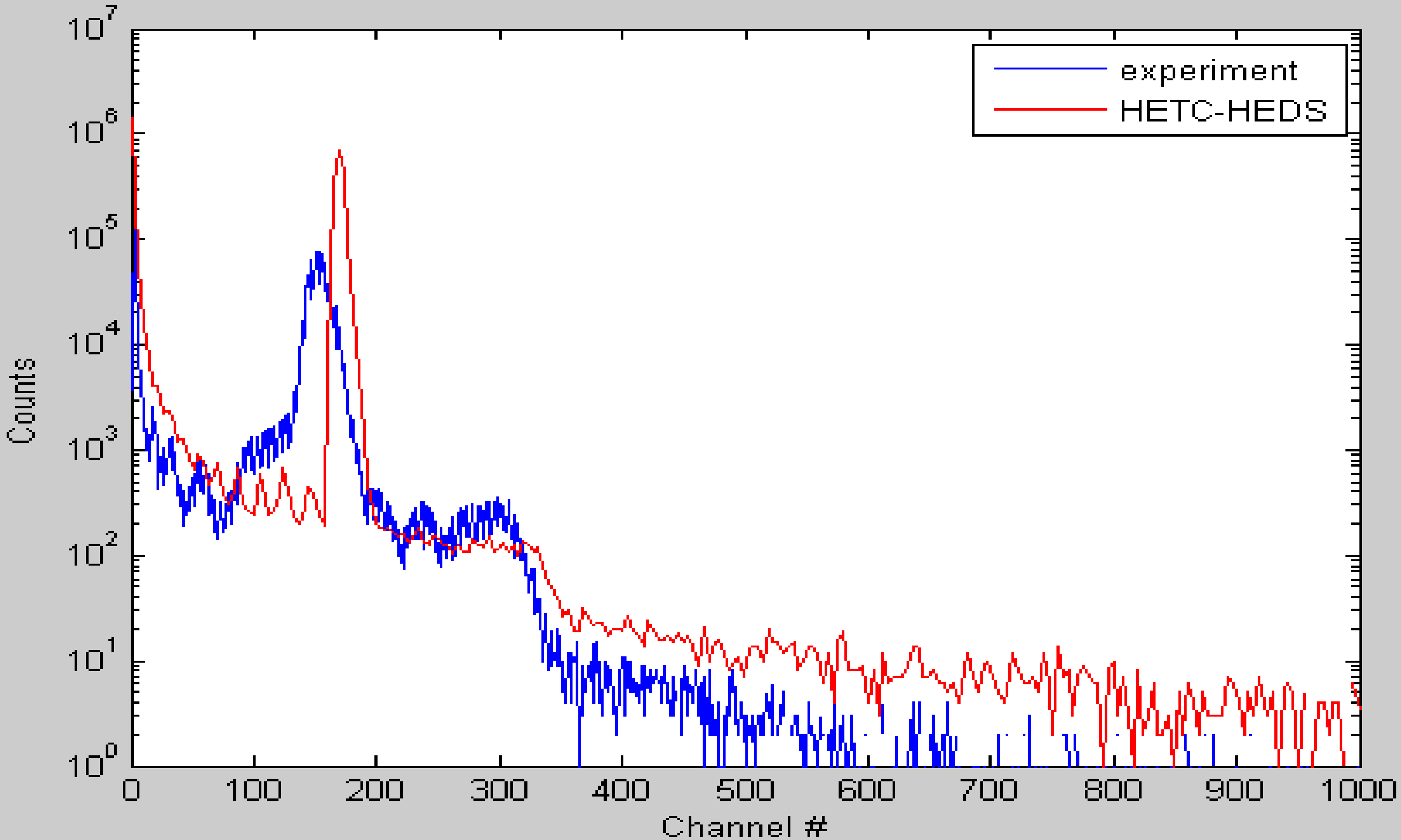
Mars Scenario

- **The 3-layer BRYNTRN version has also been configured by Cucinotta and Kim at NASA Johnson Space Center for use in calculating dose in <u>Silicon</u> for comparison with future dosimeter measurements anywhere on the surface of Mars**
  - ***Mars CO_2 atmosphere depths: 0-300 g/cm^2***
  - ***Accounts for 2π exposure on Mars surface***

Lunar Validation

- **Plan was to use Linear Energy Transfer (LET) measurements of the lunar radiation environment provided by the LRO/CRaTER originally scheduled for launch in late 2008**
  - ***Mission has been delayed and the current LRO launch window is late May 2009. LET measurements in lunar orbit would then presumably begin being available by later in 2009***

993.6A MeV Si—D 1



Lunar Validation

200 MeV Protons (MGH)

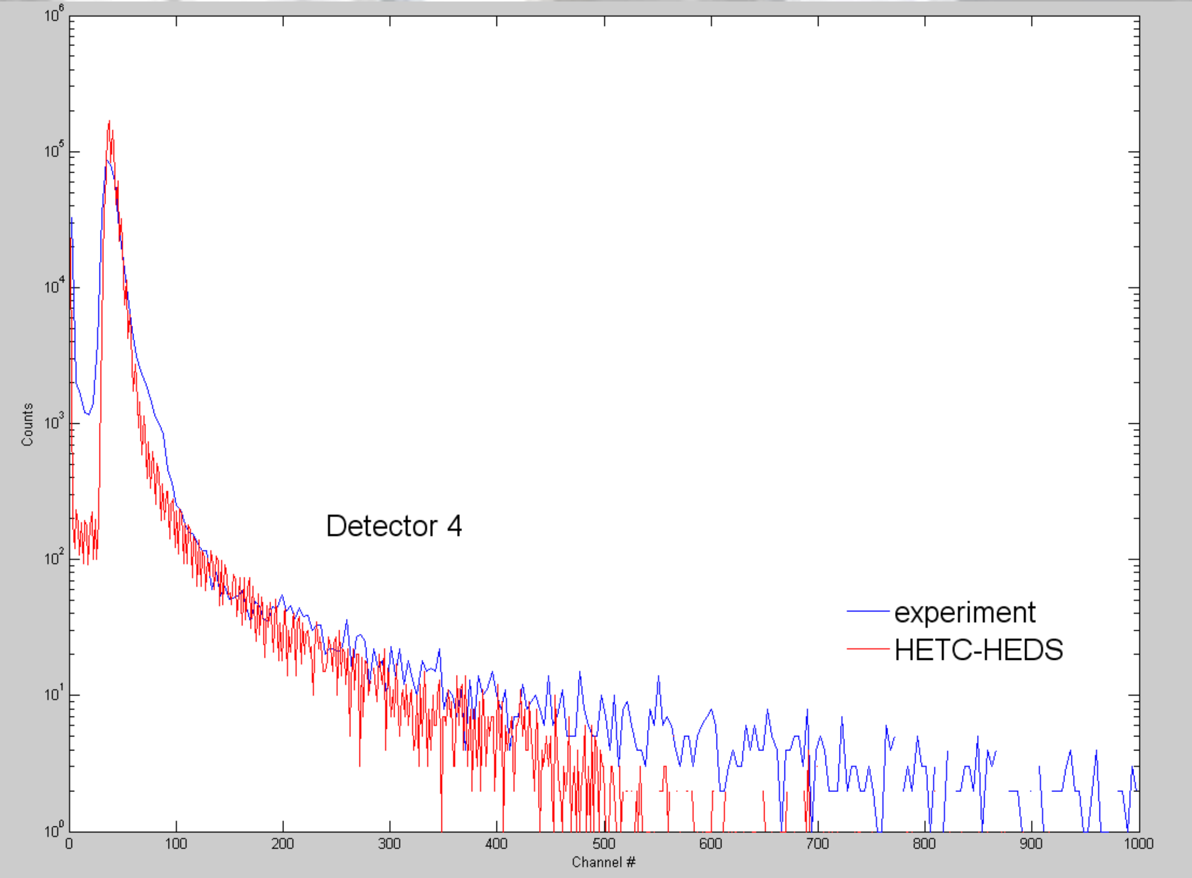
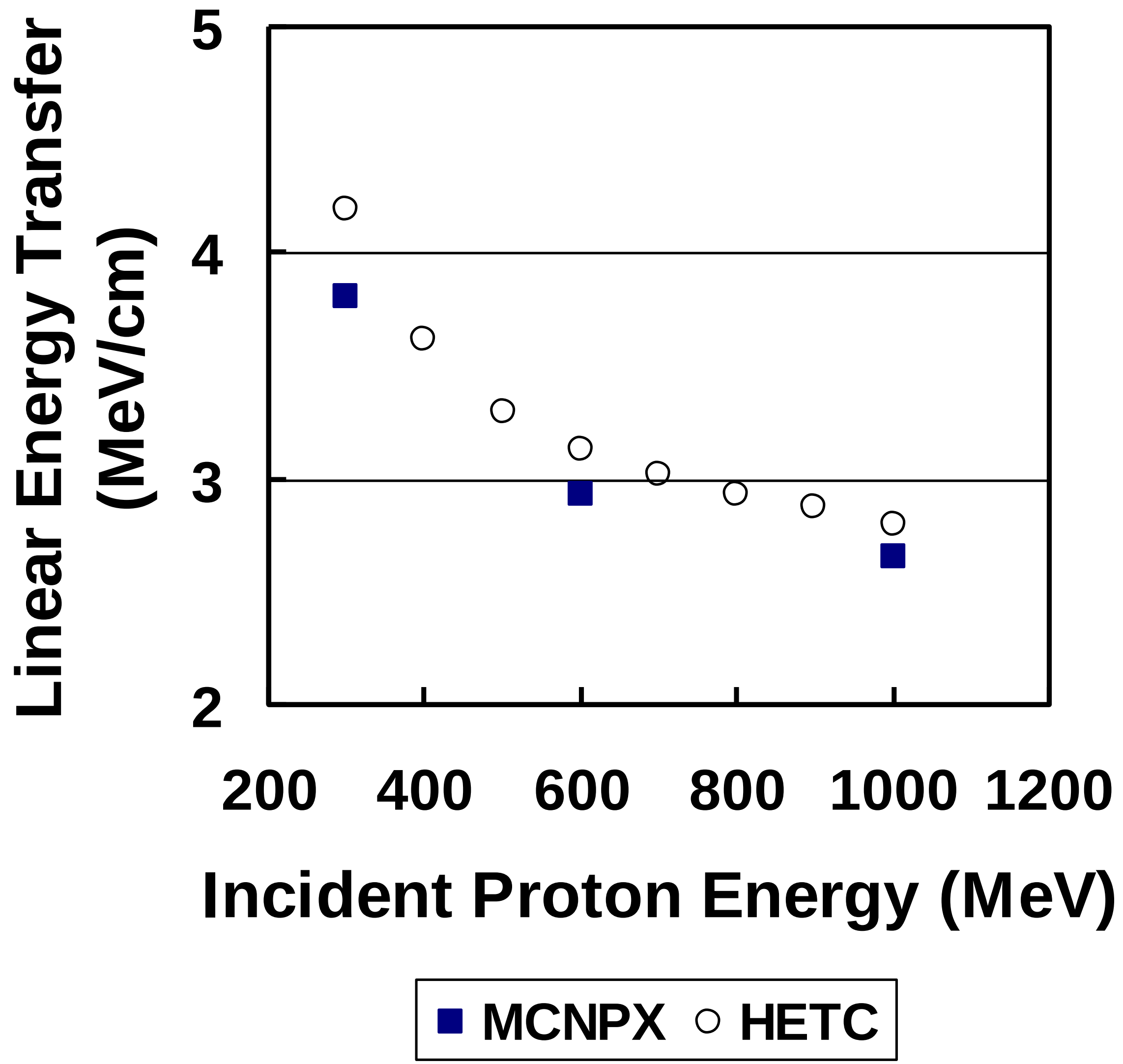
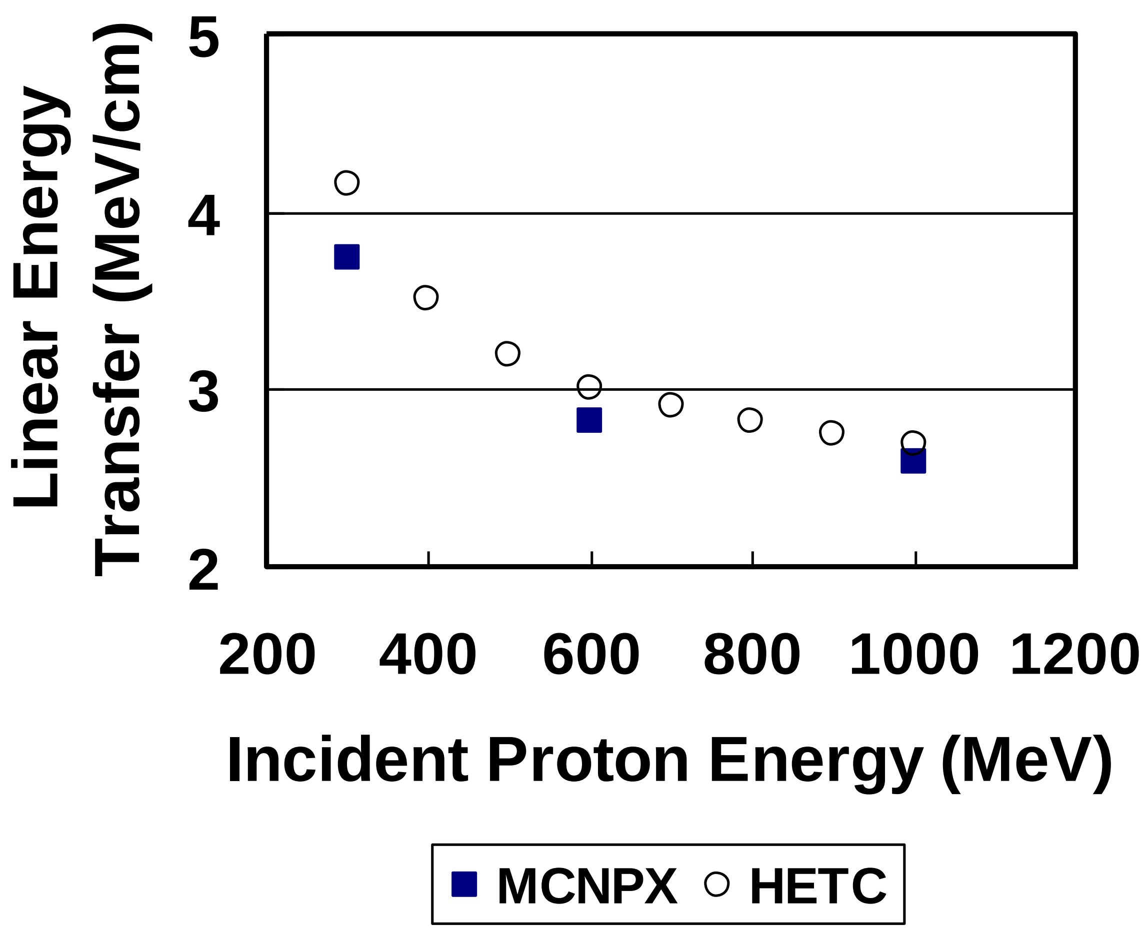


Fig. 15. Comparison of detector 4 response between HETC-HEDS and experiment

LET in 5.4 cm TEP Element



LET in 2.7 cm TEP Element



Lunar Validation

- **Tables of calculated LET spectra in CRaTER for the anticipated GCR spectrum of particles with incident energies from 20 MeV/nucleon to several GeV/ nucleon, during LRO operations, have been modeled for use in data analyses during and after the CRaTER mission**

  - ***Comparisons of the measured LET spectra from the mission will be made with these LET calculations***

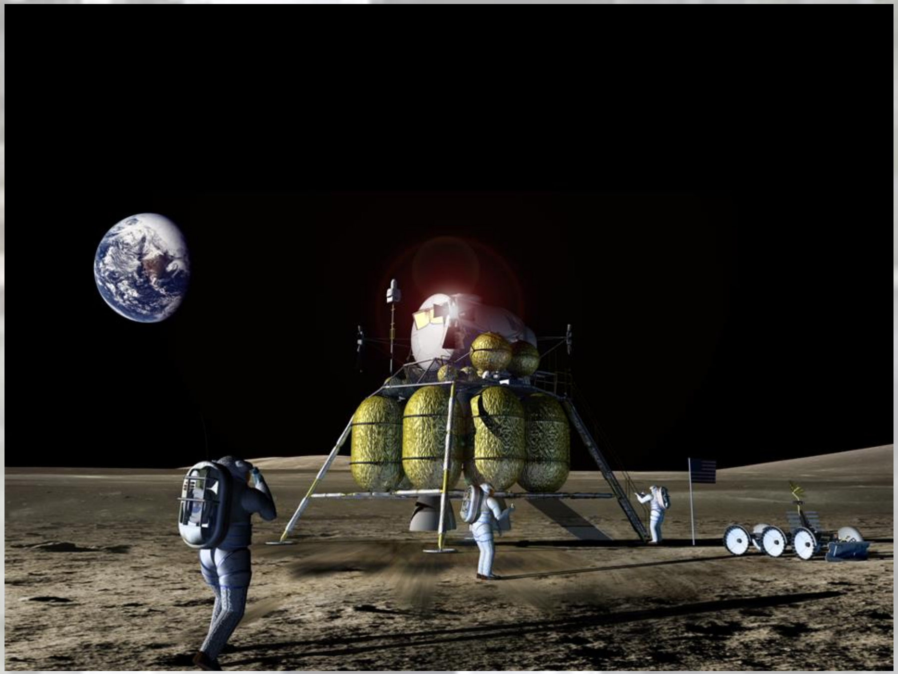
Earth Scenario

Scenarios

Lessons Learned

The NASA Vision for Space Exploration

- NASA will carry out missions returning to the moon in next decade
  - Sortie missions ~14 days by 2020
  - Long duration missions up to 240 days by 2022
- Missions to Mars will occur towards 2030 building on the lunar program
- Radiation protection requirements including dose limits for lunar missions are now being formalized
  - Protection against large solar proton events are a major near-term goal
- Proposed NSBRI Acute Countermeasures Team requires Risk initial assessment focus



Cucinotta and Durante, *The Lancet- Oncology* (06)
courtesy of John Frassanito and associates

Characterization and Forecasting

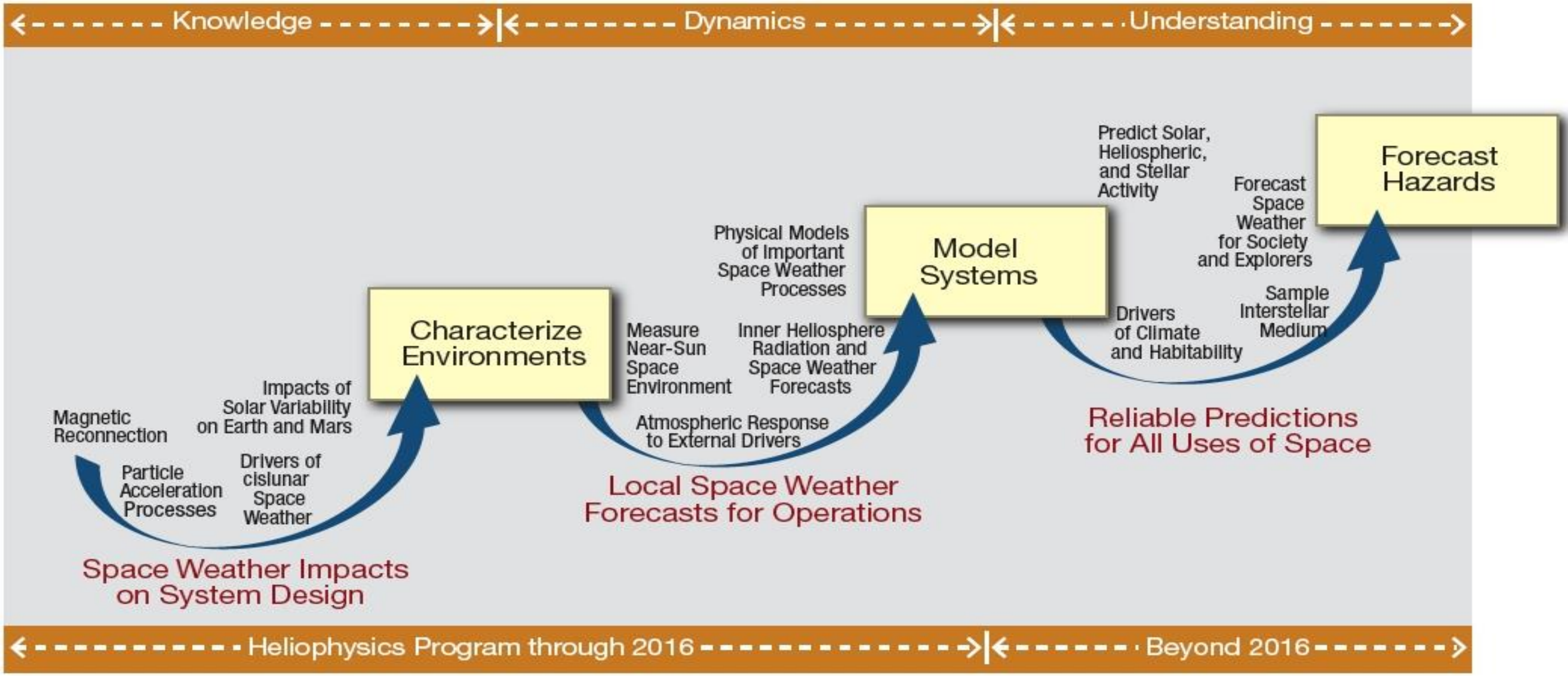


Figure 6.1- From Observation to Prediction for Space Weather. The Heliophysics program will contribute practical knowledge for issues that affect our technological society. The first development phase is already underway, utilizing current program assets and near-term launches. Subsequent phases will develop the new knowledge base, understanding, and capability to provide reliable space-weather predictions.

Integrated Risk Projection

EMMREM

Mitigation:

- Shielding materials
- Radioprotectants
- Pharmaceuticals

Space Radiation Environment

Radiation Shielding

Initial Cellular and Tissue Damage
DNA breaks, tissue microlesions

**DNA repair, Recombination,
Cell cycle checkpoint, Apoptosis, Mutation,
Persistent oxidative damage, & Genomic Instability**

Tissue and Immune Responses

Risks:
**Chronic: Cancer, Cataracts,
Central Nervous System,
Heart Disease
Acute: Lethality, Sickness,
Performance**

Risk Assessment:
- Dosimetry
- Biomarkers
- Uncertainties
- Space Validation

**$Risk_j$
(age,sex,mission)**

Major Questions for Acute Risk Models

- What are the dose-rate modification (DRM) effects for SPE Acute risks?
- What are the Relative Biological Effectieness (RBE's) for protons and secondaries?
- How do DRM and RBE's vary with Acute risks?
- Are there synergistic effects from other flight stressors (microgravity, stress, bone loss) or GCR on Acute risks?
- For which Acute risks are countermeasures needed?
- How can the effectiveness of Acute countermeasures be evaluated and extrapolated to Humans?

Acute Radiation Risks Research

- Overall Objectives
  - Accurate Risk assessment models support
    - Permissible Exposure Limits (PEL) Determination
    - Informed Consent Process
    - Operational Procedures
      - Dosimetry
      - EVA timelines
      - Solar Forecasting Requirements
    - Shielding Requirements
    - Countermeasure (CM) Requirements
- Approach
  - **Probabilistic Risk Assessment applied to Solar Particle Events (SPE)**
  - **Models of acute risks used to evaluate acute CMs for SPE and Lunar Surface conditions**
  - **EMMREM provides a tool to evaluate and assess acute risks**

Activities

- Develop central **EMMREM module** for predicting time-dependent radiation exposure based on **BRYNTRN and HZETRN** code developed at NASA Langley and the **HETC-HEDS Monte Carlo code** developed at Oak Ridge National Laboratory and the University of Tennessee.

- Develop **interfaces between EMMREM and direct observations** of particle radiation. Observations used as direct input to predict radiation exposure at the Earth, on the Moon, Mars and in interplanetary space environments.

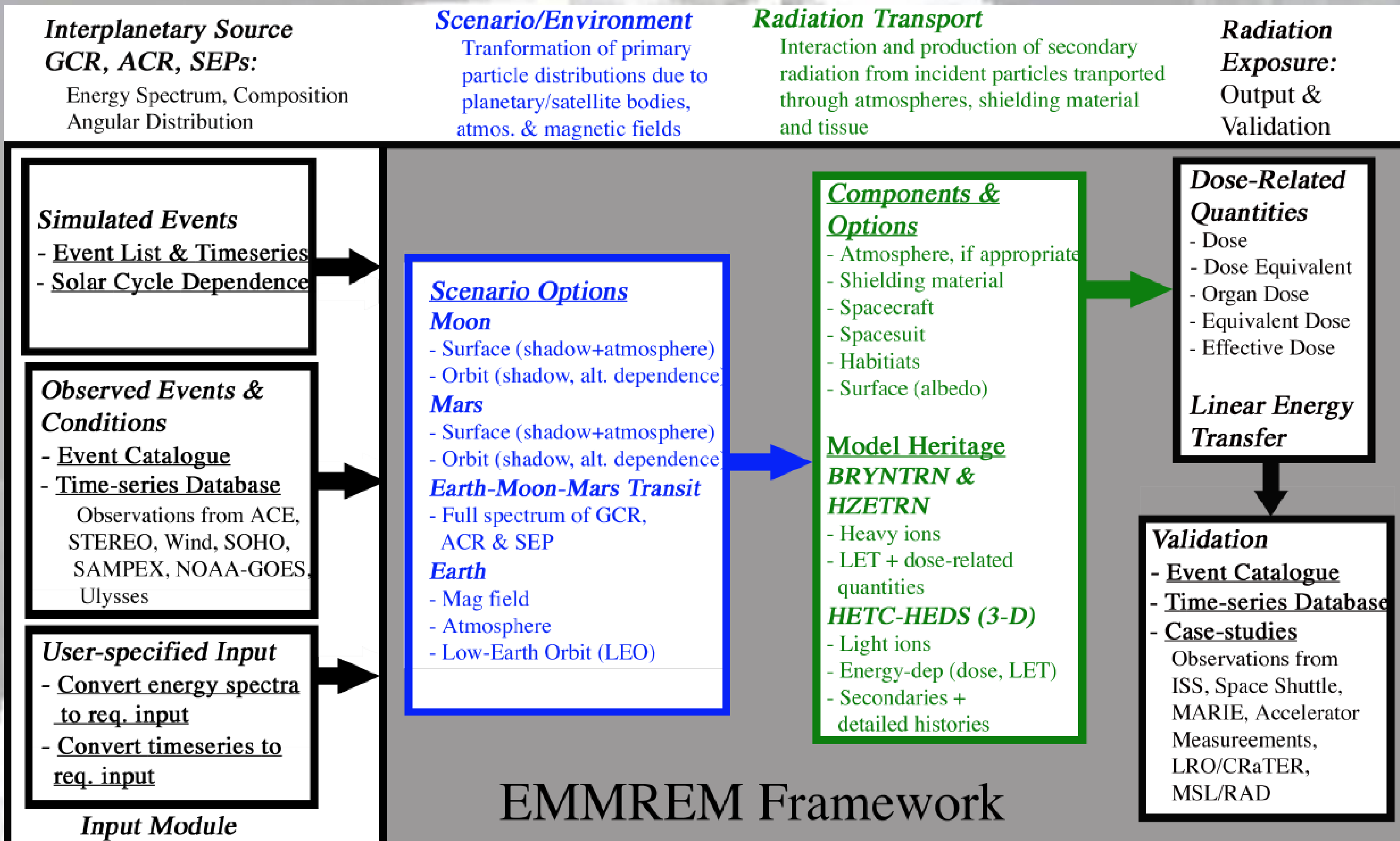
- Develop **interfaces between EMMREM and models** of particle radiation (energetic particle transport).

- Significantly reduce radiation exposure uncertainties through comprehensive validation

BRYNTRN Accomplishments

- **EMMREM specific version of the BRYNTRN code (Looping BRYNTRN) has been delivered**
  - **Uses a discrete ordinates solution method in one dimension to solve 1-D Boltzmann Equation**
  - **Transports protons and their secondaries (neutrons, protons, deuterons, tritons, ^{3}He and alpha particles) through a shield of arbitrary composition and thickness**
  - **Transport either mono-energetic beams or spectra that are distributed in energy**
  - ***Code is capable of performing near real-time simulations of SEPs that provide organ doses and dose equivalents, using proxies for the actual organs, for thinly shielded spacecraft***
  - ***Used for various studies involving several large historical SEP events***

EMMREM Framework



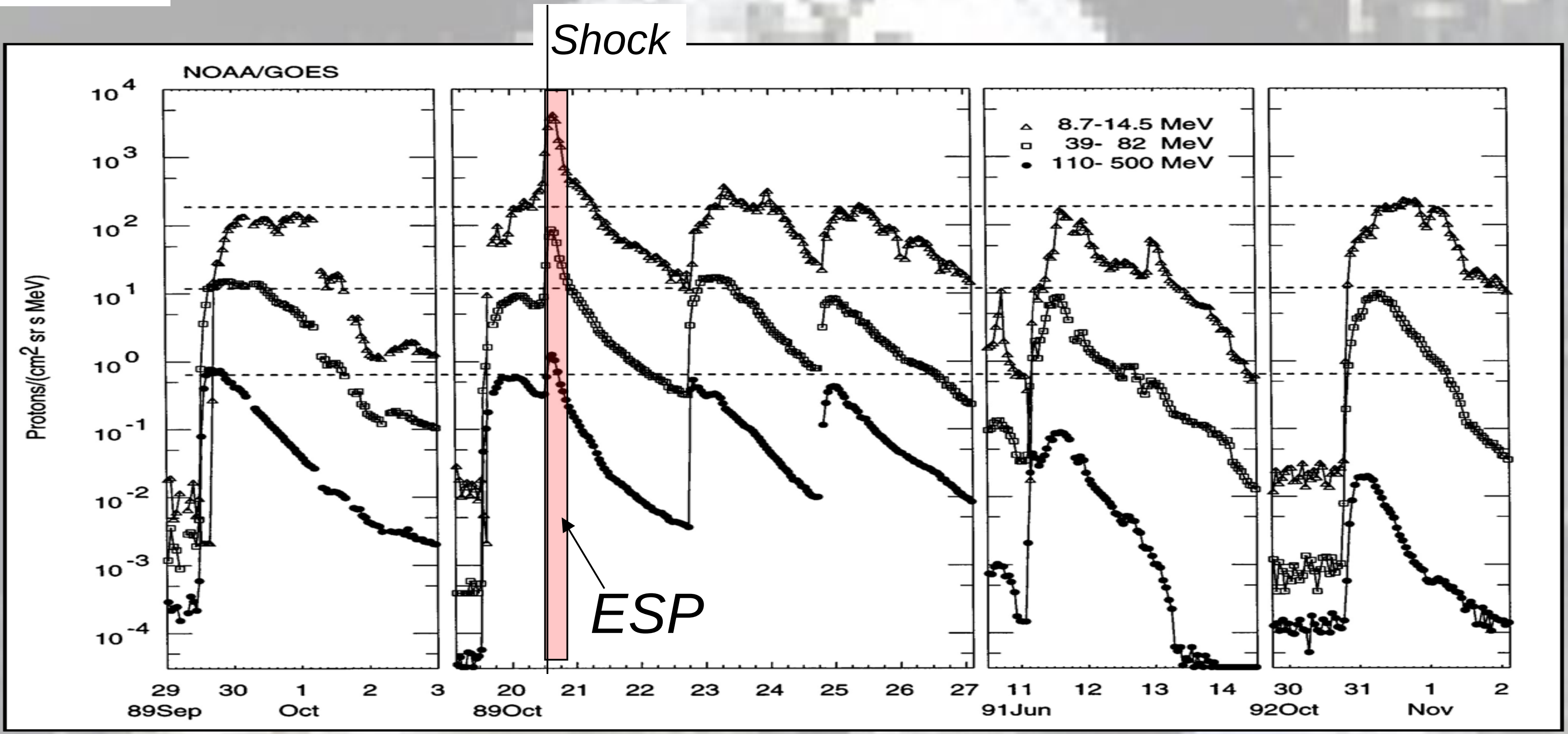
Observations and Validation

- Validation
  - LRO/CRaTER (Moon)
  - MSL/Rad (Mars)
  - Odyssey/MARIE (Mars)
  - Shuttle measurements (Earth)

Instruments and Energy Coverage

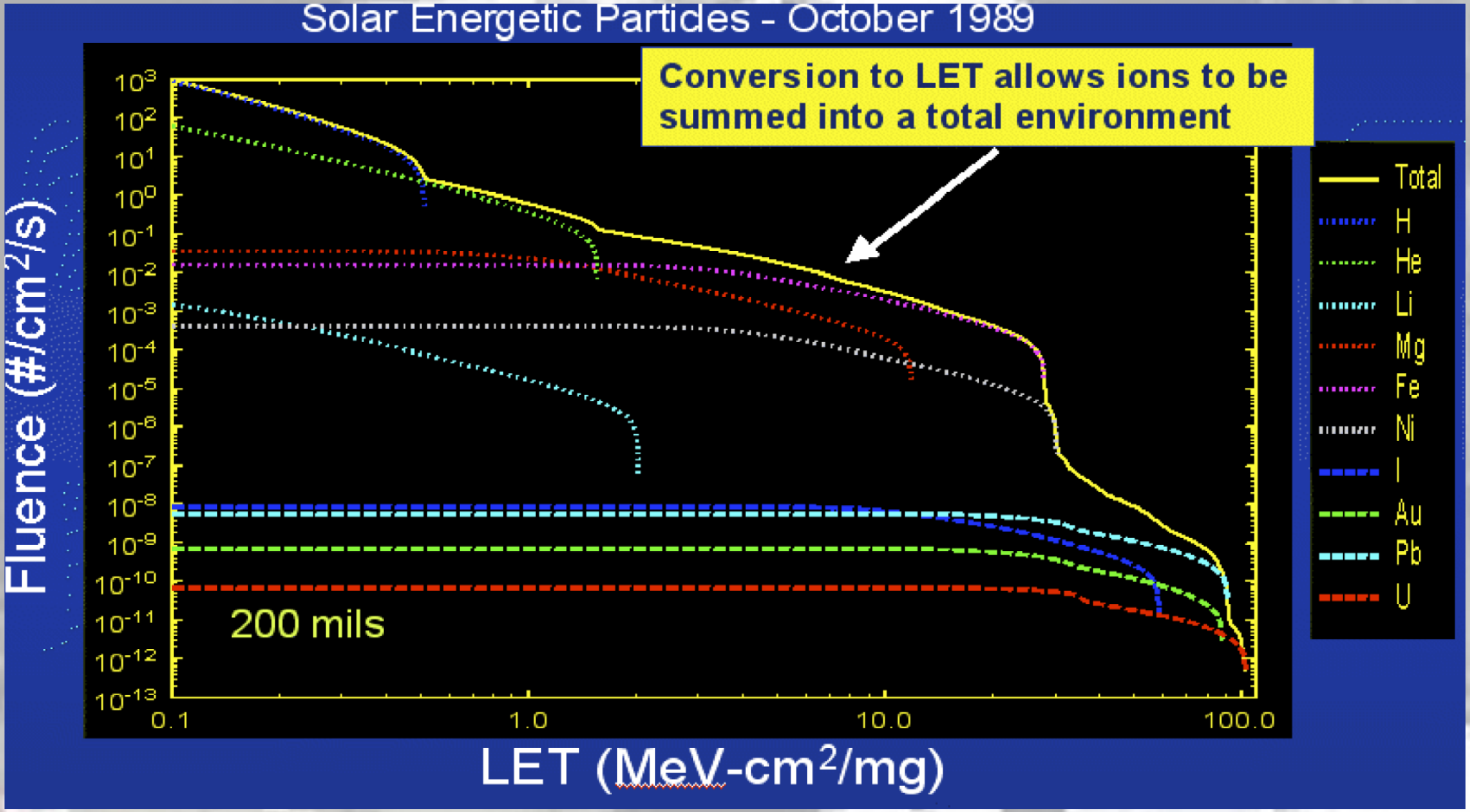
		Energy Range (MeV or MeV/nucleon)	
S/C	**Instr.**	**Ions (H/He – Fe)**	**Electrons**
ACE	ULEIS	0.04 – 9.7	…
ACE	SIS	7.0 –90	…
SAMPEX	PET	19 – 400	1.2 – 8.0
GOES	EPS	0.8– 500	0.6 - >2
Wind	STICS	0.006 – 0.2	…
Wind	STEP	0.02 – 2	…
SoHO	COSTEP	4 – 150	0.2 – 15
STEREO	SEPT	0.02 – 7.0	0.02 – 0.4
STEREO	SIT	0.03 – 2.0	…
STEREO	LET	1.5 – 30	…
STEREO	HET	– 100	– 5.0
Ulysses	KET	4 to >2000	2 to >10
LRO	CRaTER	LET (~1 to >100)	
MSL	RAD	~2-200	0.15-15
Odyssey	MARIE	LET (1-30 keV/μm)	

Connecting Observed SPEs and the Radiation Environment



- SEPs accelerated in Coronal Flares (Impulsive Events) or shocks driven by CME (Gradual Events)
- Impulsive events observed when connected to flare site
- Shock accelerated particles populate a broad range of latitudes in front of shock
- Simulataneous SEP and Energetic Storm Particles associated with Interplanetary Shocks pose a significant radiation hazard

LET Spectra characterize exposure scenarios

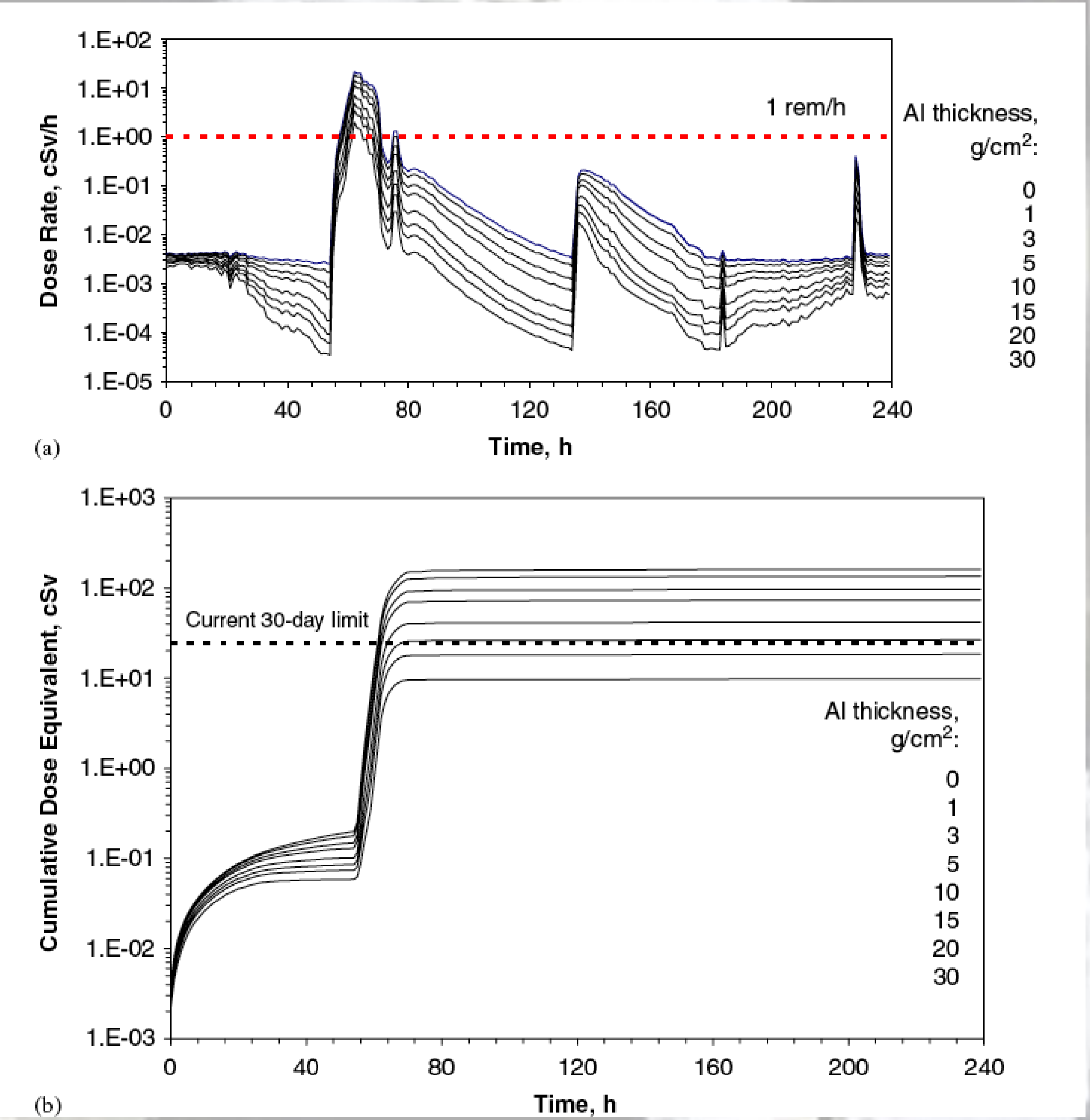


Unique exposure scenarios result from specific events (October, 1989 shown here) depending strongly on interplanetary energy spectra and composition. EMMREM reduces uncertainties in our understanding of radiation exposure, which is critical for future mission planning.

Radiation Exposure from Large SPE Events

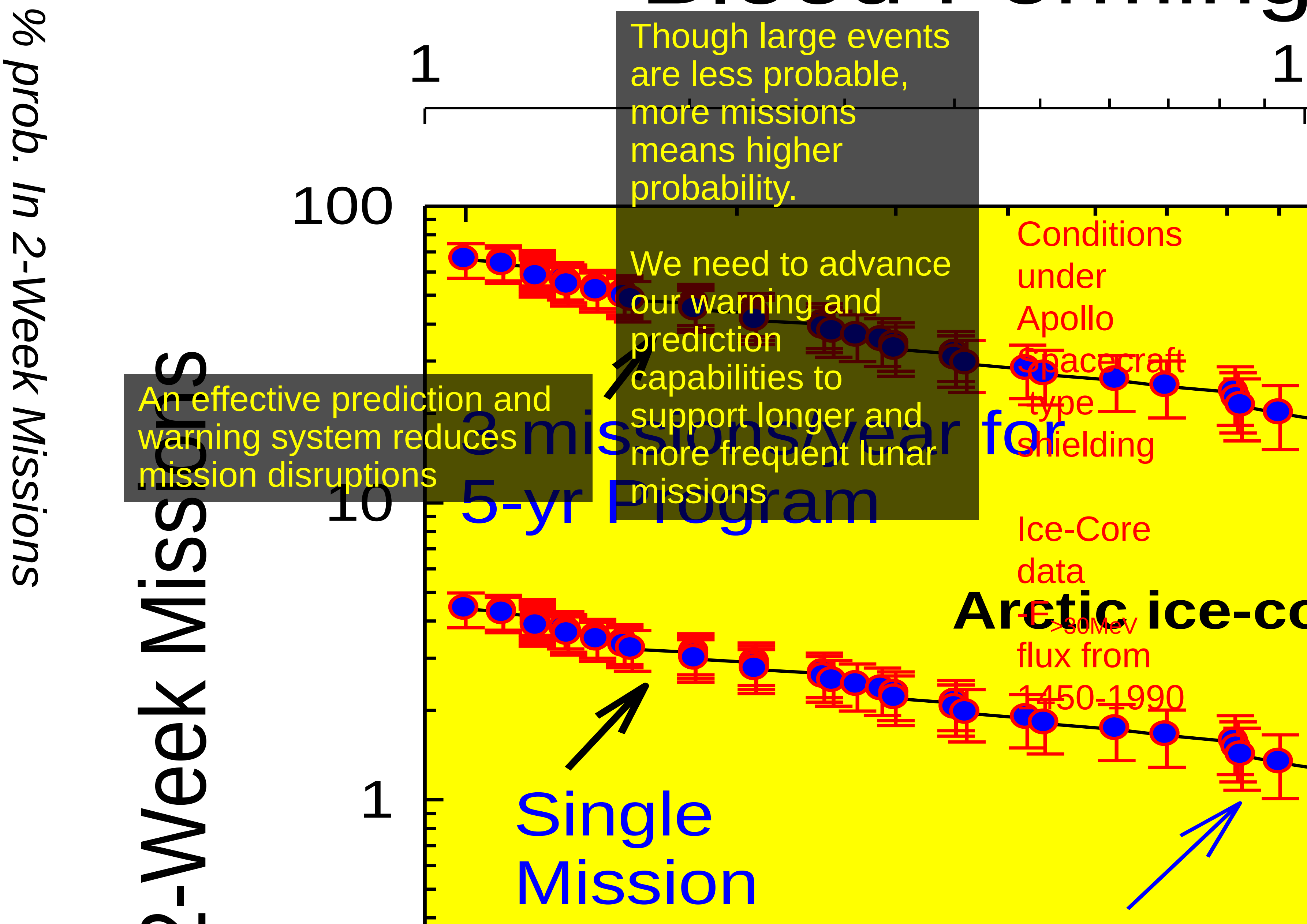
BFO dose rate during Aug.. 1972 SPE Event

Cumulative dose

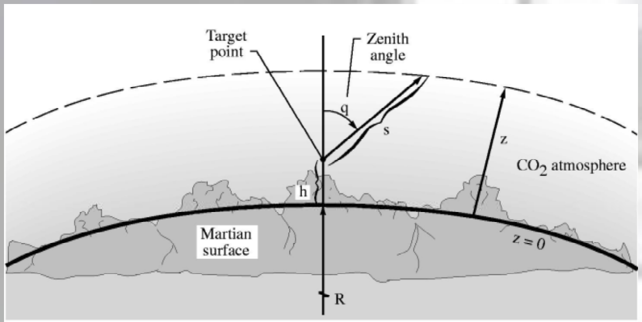


Myung-Hee et al., 2006

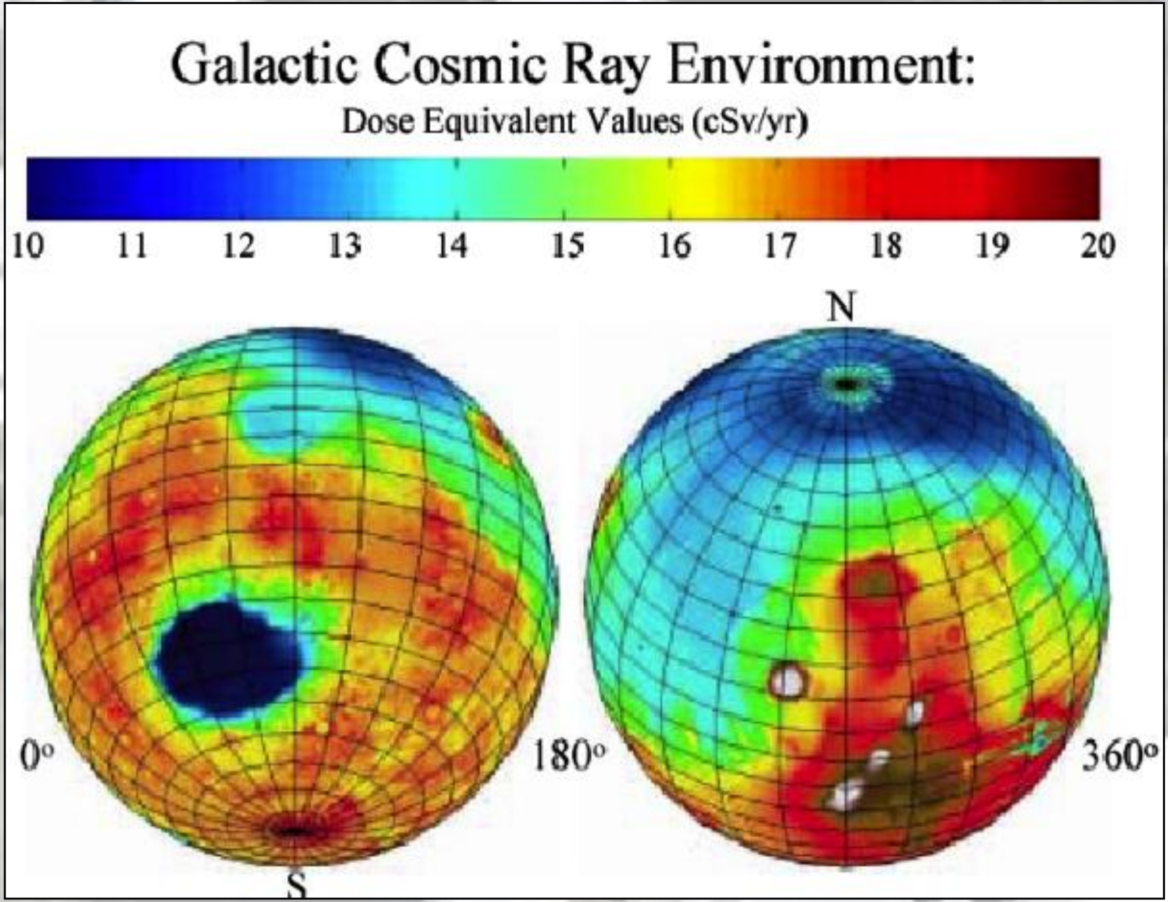
Blood Forming



Mars Scenarios



Model prediction of Dose Equivalent from exposure to GCRs, calculated for solar maximum conditions. Note the strong dependence of radiation exposure on the Martian topography. (Cucinotta et al. 2004)

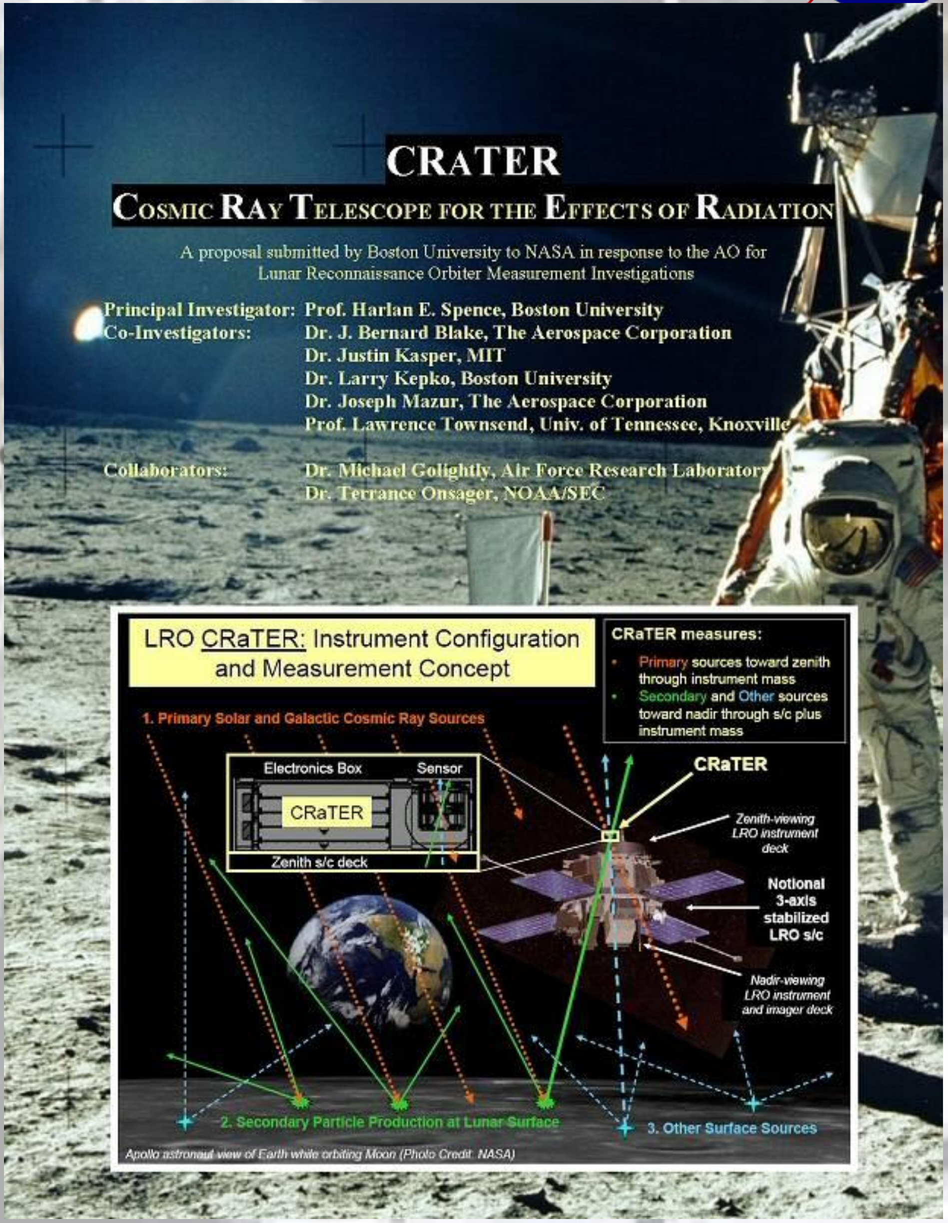


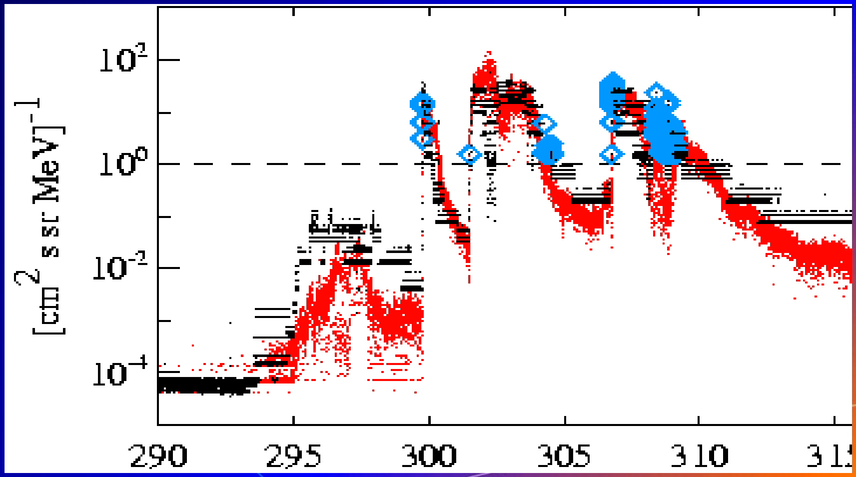
Science/Measurement Overview

CRaTER Objectives:

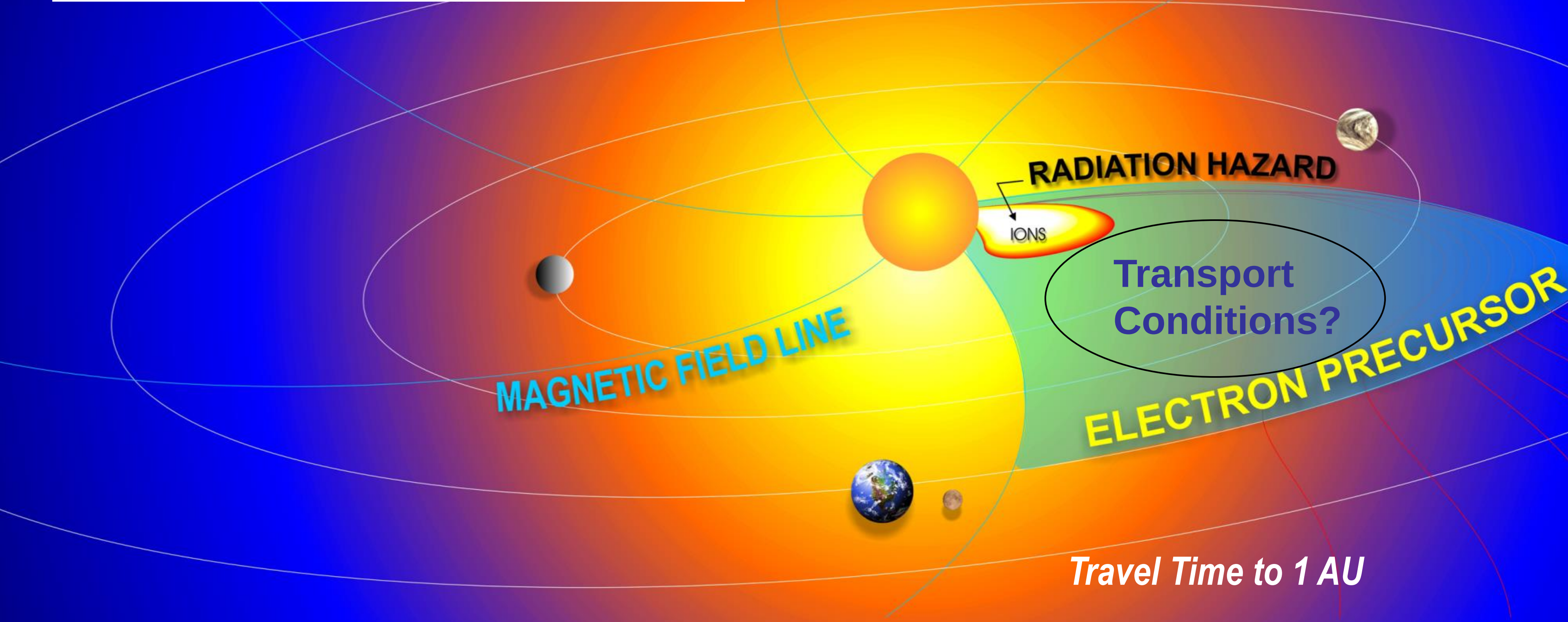
"To characterize the global lunar radiation environment and its biological impacts."

"…to address the prime LRO objective and to answer key questions required for enabling the next phase of human exploration in our solar system. "





1h Advance *Proton* *Intensity Forecast* (Black, Blue: Warnings Issued) *Tested Successfully* for 2003, including Halloween Events



Travel Time to 1 AU

Relativistic Electrons: ~10 Min

50 MeV Protons: 30-80 Min

[Posner, *Space Weather, in press* 2007]

Summary

- EMMREM will provide a module to characterize the Earth-Moon-Mars and Interplanetary Radiation Environments
- EMMREM central to NASA and the Vision for Space Exploration
- Addresses Key Questions about Acute time-dependent Radiation Characterization
- Observation and Simulation (Particle transport) Driven
- Validation central to EMMREM
  - LRO/CRaTER (Moon)
  - MSL/Rad (Mars)
  - Odyssey/MARIE (Mars)
  - Shuttle measurements (Earth)

BRYNTRN

- **Developed at the NASA Langley Research Center**
- **Uses a discrete ordinates solution method in one dimension to solve 1-D Boltzmann Equation**
- **Transports protons and their secondaries (neutrons, protons, deuterons, tritons, ^{3}He and alpha particles) through a shield of arbitrary composition and thickness**
- **Transport either mono-energetic beams or spectra that are distributed in energy**

Radiation Environment Characterization

The effects of energetic particle radiation on the human body are heavily dependent on the type and energy of the radiation, as well as the tissue being irradiated. These effects include cancer, degenerative tissue diseases, damage to the central nervous system, cataracts, and hereditary risks. The relative ability of energetic particles to cause biological damage is expressed as a quality factor, *Q, which is a function of the Linear Energy Transfer (LET), or energy absorbed per distance traveled by a given particle through a medium. (For human tissue, this medium is approximated by water.) The LET is a function of particle atomic mass, charge (A and Z) and energy. For example, heavy elements such as Fe generally have large Q, even at relatively high energies, and therefore pose a serious safety hazard even though they are a fraction of the overall flux.*

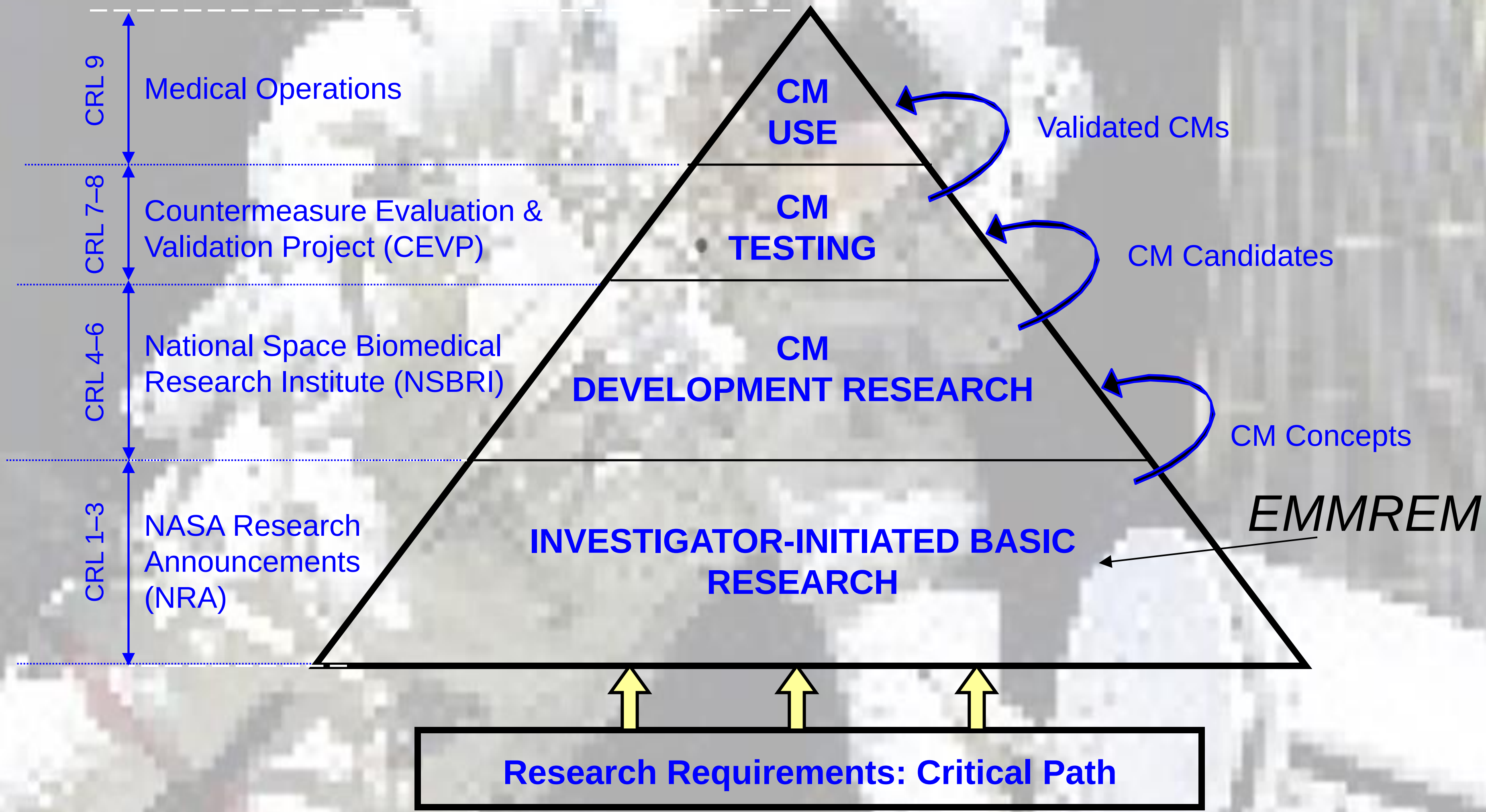
The following dose-related quantities *(EMMREM output) are defined as follows:*

- *Dose (D): Mean energy absorbed per unit mass*
- *Dose Equivalent (H): Dose multiplied by a weighting factor (quality factor, Q) characterizes long-term radiation effects such as cancer*
- *Organ Dose (D_T): Dose averaged over entire mass of a given organ or tissue (T)*
- *Equivalent Dose (H_T): Organ Dose multiplied by a weighting factor characterizing long-term radiation effects depending on specific types of radiation (proton, neutron, alpha, etc)*
- *Effective Dose (E): The sum over all irradiated organs of the equivalent doses times a weighting factor for long-term radiation effects*
- *Linear Energy Transfer (LET): Mean energy loss by charged particle per unit distance traveled*

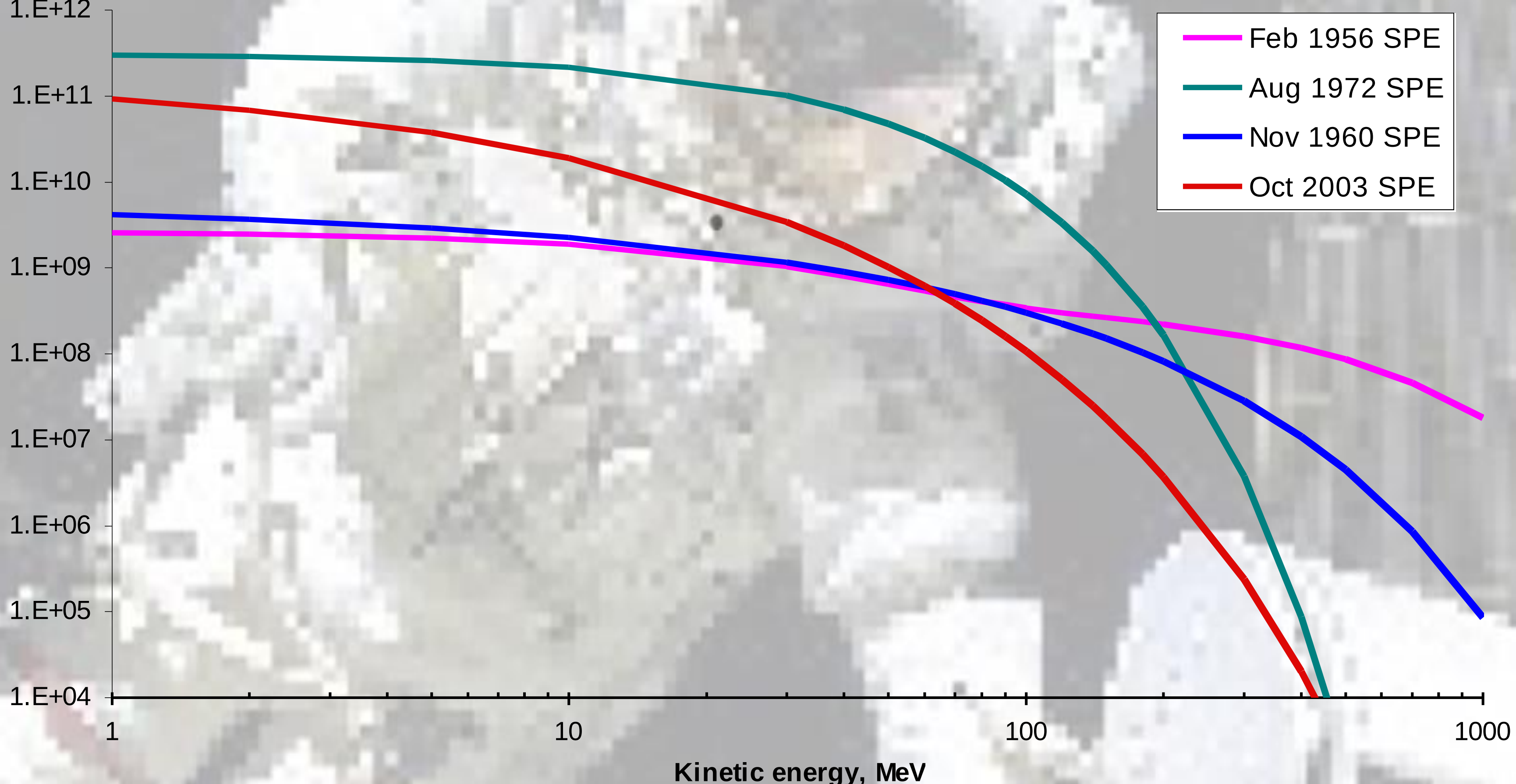
Constellation Program

- New NASA Program for human exploration missions
  - Near term focus development of Crew Exploration Vehicle replacing Space Shuttle for missions to the ISS and onto moon

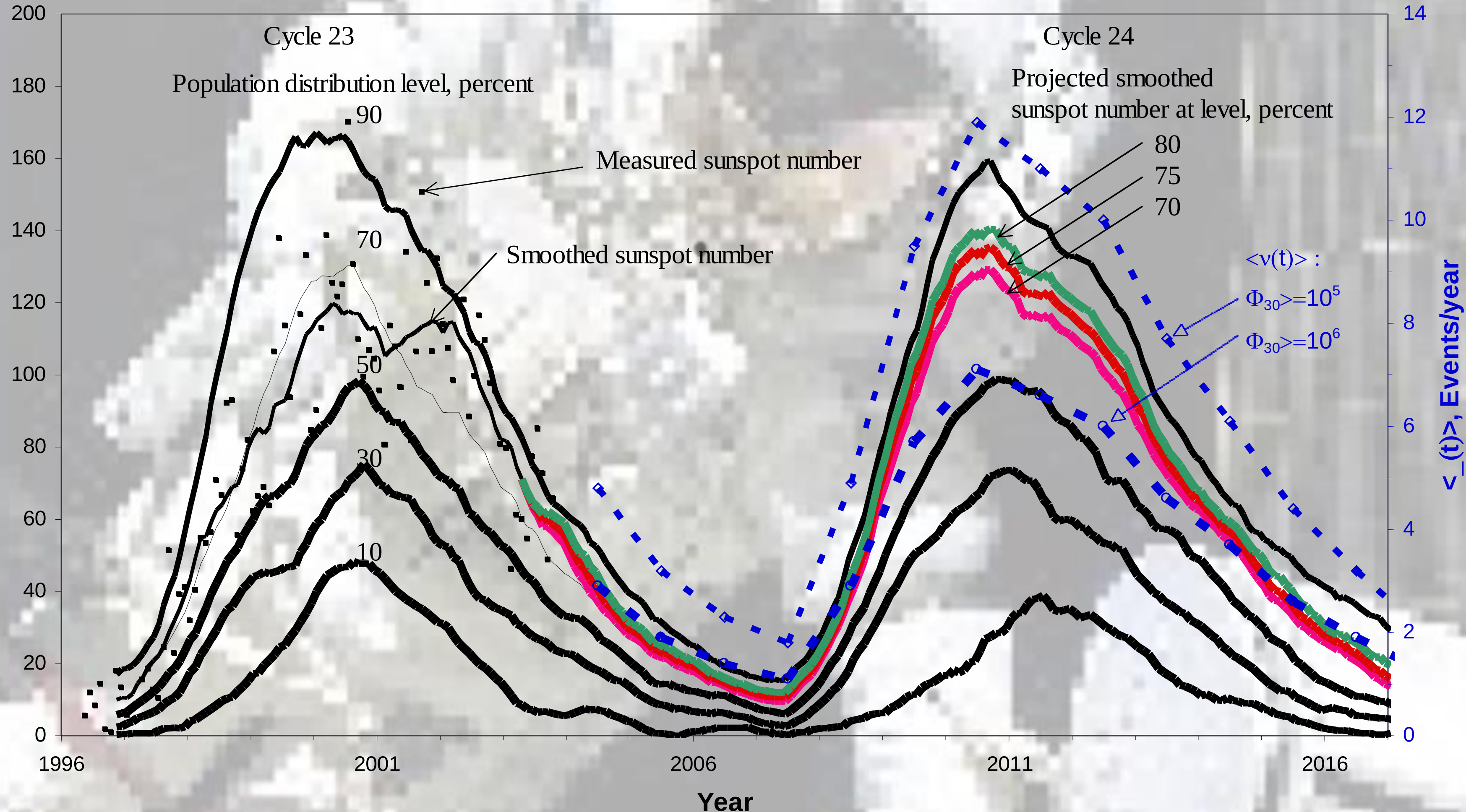
Countermeasure Development Process



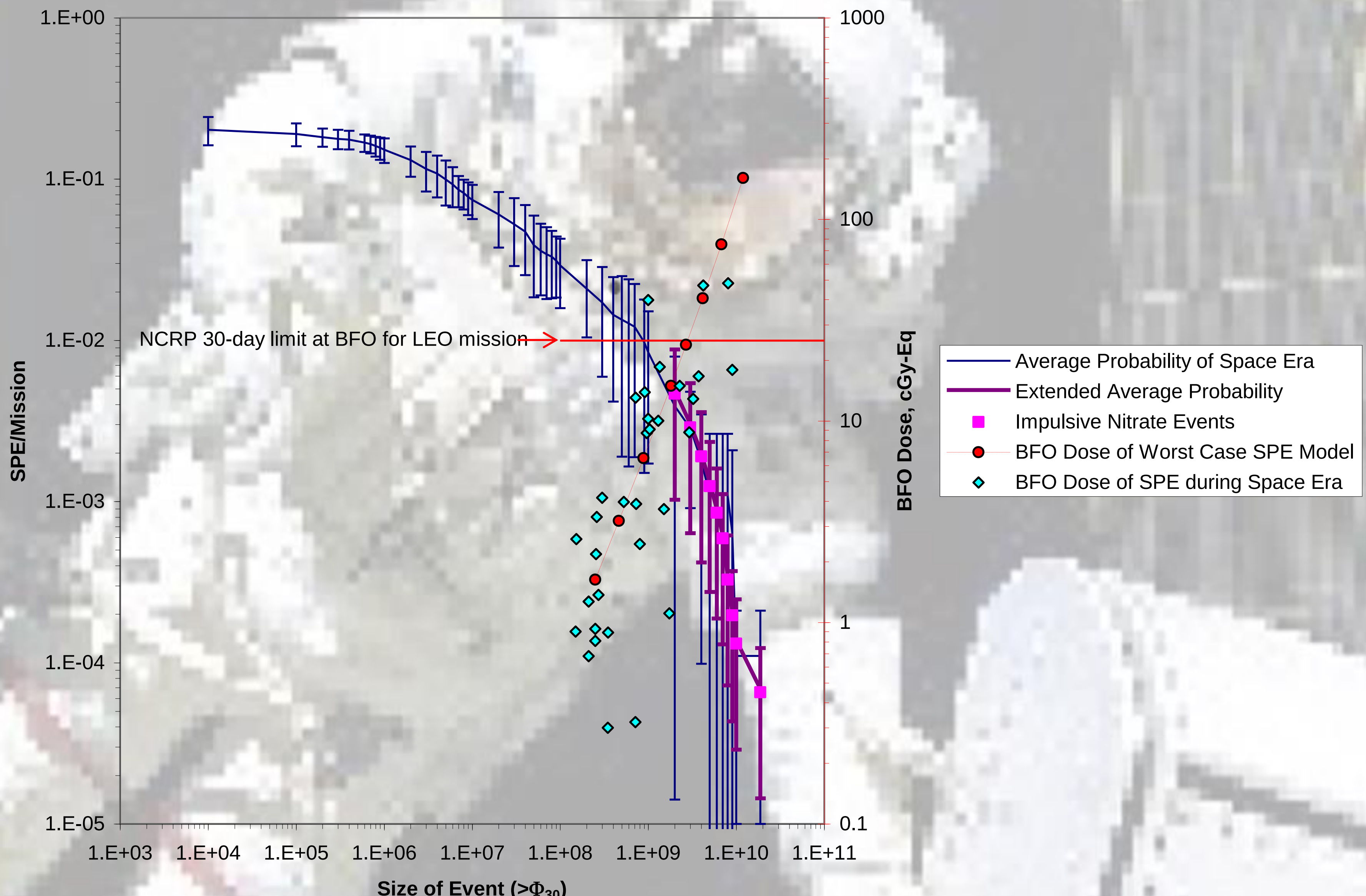
Large SPE Integral Fluence Spectra at 1AU



Projections of Cycles and Mean Occurrence Frequency of SPE



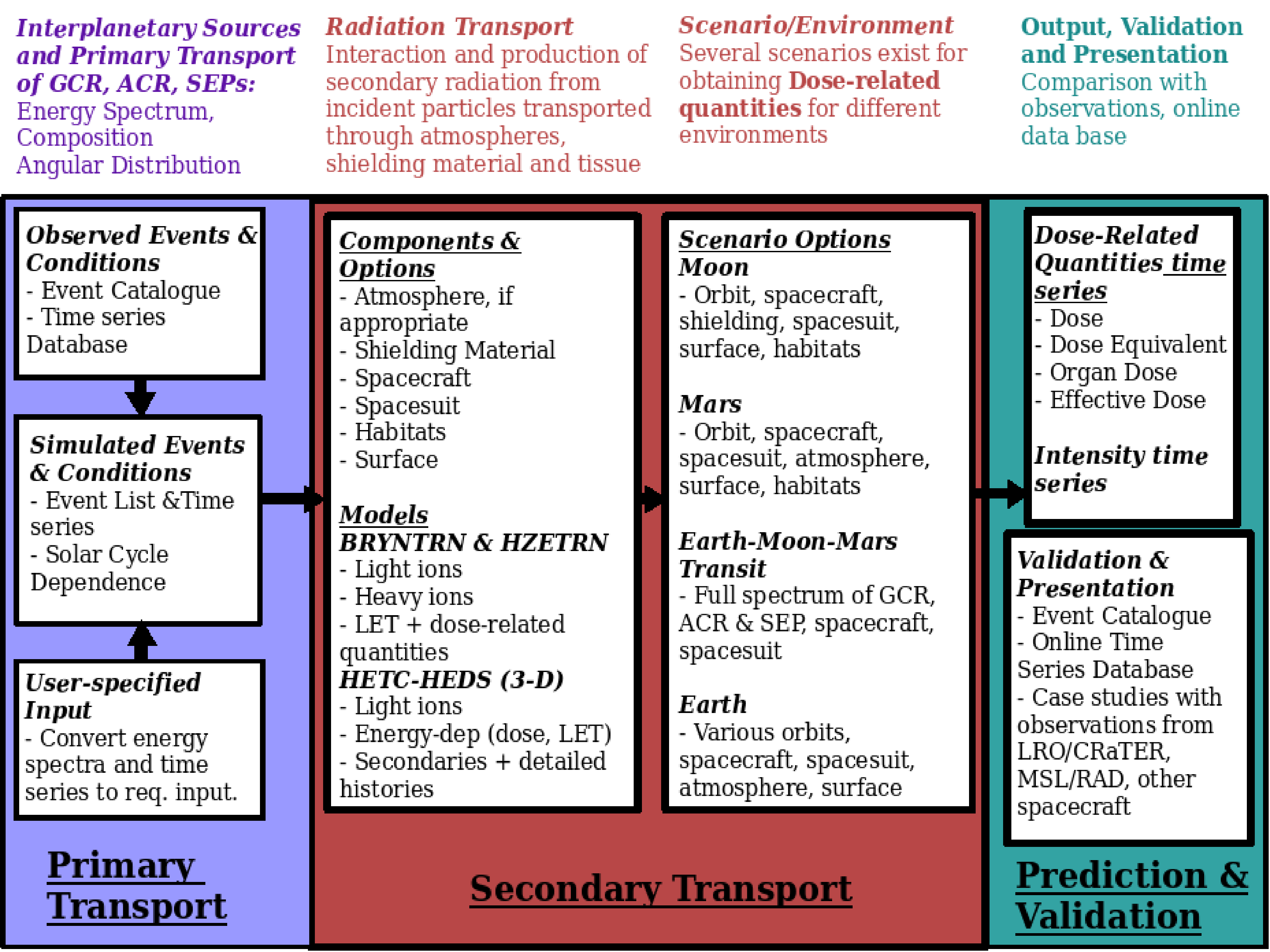
SPE Probability in 1-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



NASA Space Radiation Program Goal:

To live and work safely in space
with acceptable risks from radiation

Risk is not measured-It is predicted by a model


Interplanetary Sources and Primary Transport of GCR, ACR, SEPs:
Energy Spectrum, Composition Angular Distribution
Radiation Transport
Interaction and production of secondary radiation from incident particles transported through atmospheres, shielding material and tissue
Scenario/Environment
Several scenarios exist for obtaining Dose-related quantities for different environments
Output, Validation and Presentation
Comparison with observations, online data base
Observed Events & Conditions
- Event Catalogue
- Time series Database
Simulated Events & Conditions
- Event List &Time series
- Solar Cycle Dependence
User-specified Input
- Convert energy spectra and time series to req. input.
Primary Transport
Components & Options
- Atmosphere, if appropriate
- Shielding Material
- Spacecraft
- Spacesuit
- Habitats
- Surface
Models
BRYNTRN & HZETRN
- Light ions
- Heavy ions
- LET + dose-related quantities
HETC-HEDS (3-D)
- Light ions
- Energy-dep (dose, LET)
- Secondaries + detailed histories
Scenario Options
Moon
- Orbit, spacecraft, shielding, spacesuit, surface, habitats
Mars
- Orbit, spacecraft, spacesuit, atmosphere, surface, habitats
Earth-Moon-Mars Transit
- Full spectrum of GCR, ACR & SEP, spacecraft, spacesuit
Earth
- Various orbits, spacecraft, spacesuit, atmosphere, surface
Secondary Transport
Dose-Related Quantities time series
- Dose
- Dose Equivalent
- Organ Dose
- Effective Dose
Intensity time series
Validation & Presentation
- Event Catalogue
- Online Time Series Database
- Case studies with observations from LRO/CRaTER, MSL/RAD, other spacecraft
Prediction & Validation

EMMREM is urgent for the following National, NASA, NSF and LWS Objectives

- Our objective is vital to "*Implement a sustained and affordable human and robotic program to …, and prepare for human exploration*" (a vision established by the **President's Space Exploration Policy Directive**, NPSD31) and directly relevant to the LWS program strategic goal 3: "*The need for a predictive model for radiation exposure anywhere on the surface or in the atmosphere of Earth, on the Moon, on Mars, and in interplanetary space between Earth and Mars*" (in sec 1.1of the NRA).
- Innovative software technology that provides critical knowledge of radiation exposure in support of human and robotic exploration and thus a key element of the **National Objective** to "*Develop innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration*" and **NASA's objective** to "*Develop and demonstrate … other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations*".
- Important to **NASA's objective** to "*Explore the Sun-Earth system to understand the Sun and its effects on Earth, the Solar System, and the space environmental conditions that will be experienced by human explorers …*".
- Relevant to the **National Space Weather program**'s goal to *"validate and enhance space weather models to improve specification and prediction capabilities,…"*..
- Complements and enhances **NSF's Science and Technology Center for Integrated Spaceweather Modeling (CISM)** by predicting radiation exposure from the large-scale space weather events simulated as a part of CISM. EMMREM leverages research at the heart of National space weather program for the development of a module important for NASA's Vision for Exploration Program.

Radiation Hazards

- Galactic Cosmic Rays (GCRs)
  - Steady Background
  - Career limit in ~ 3 years
- Solar Energetic Particles (SEPs)
  - Acute Sources
  - ESPs versus impulsive component
  - Time-dependent response