Earth-Moon-Mars Radiation Environment Module (EMMREM):

A Tool For Energetic Particle Fluxes and Radiation Doses Prediction In the Inner Heliosphere

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5th CCMC Community Workshop, Key Largo, FL, Jan 25-29 2010

http://emmrem.bu.edu

Overview

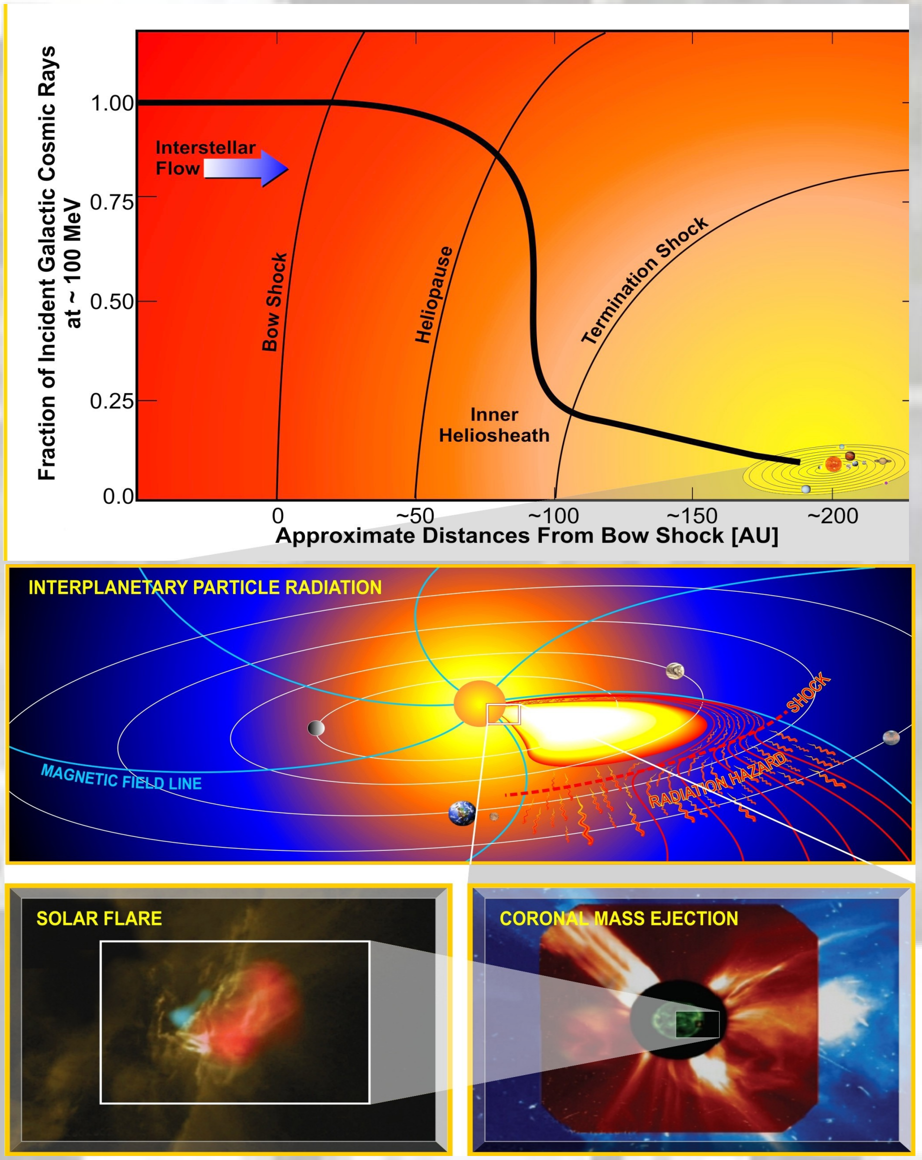
- Motivation for the EMMREM project
- Introduction to the EMMREM framework functionality.
  - Primary Particle Transport
  - Secondary Particle Transport
- Current developments
- Web interface to the models – current and future work
- EMMREM at CCMC
- Summary

Motivation: Interplanetary Reality

- Galactic Cosmic Rays (GCRs) Steady Background
  - Modulated by Solar activity
  - Career limit for astronauts reached in ~ 3 years

- Solar Energetic Particles (SEPs)
  - Acute Sources
  - Impulsive (Flares) and Gradual (CMEs)
  - Time-dependent response

Bottomline: GCRs and SEPs are the main sources of radiation hazard in atmospheres and interplanetary space.



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Motivation: Renewed Push for Space Exploration

- New NASA Lunar manned missions in next decade
  - Short 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
- Protection against large solar proton events (SPE) is a major near-term goal

Bottomline: We need to characterize the heliospheric radiation environment in order to be prepared to send long term missions.

EMMREM Framework

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

Primary Transport

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.

Secondary 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

Prediction & Validation

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

Schwadron et al., Space Weather Journal, 2010

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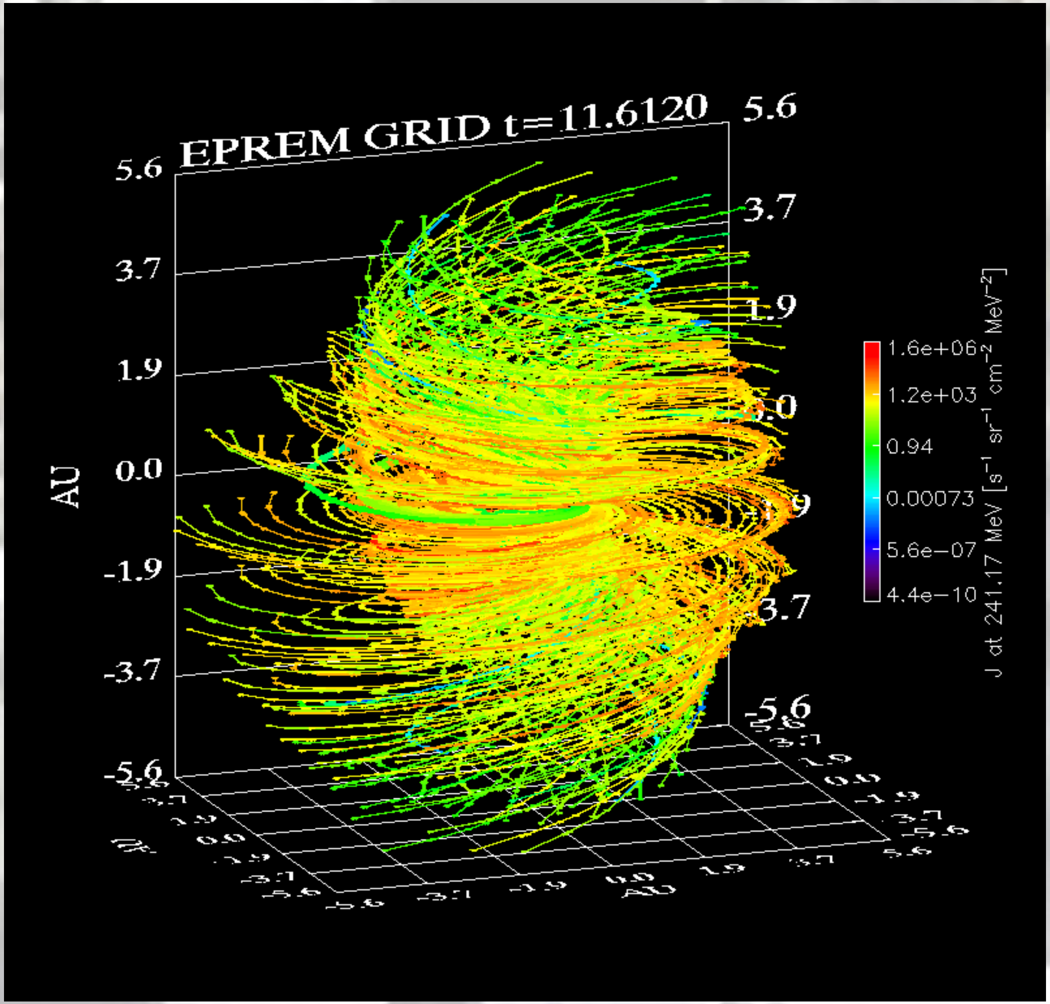
EMMREM: Primary Transport

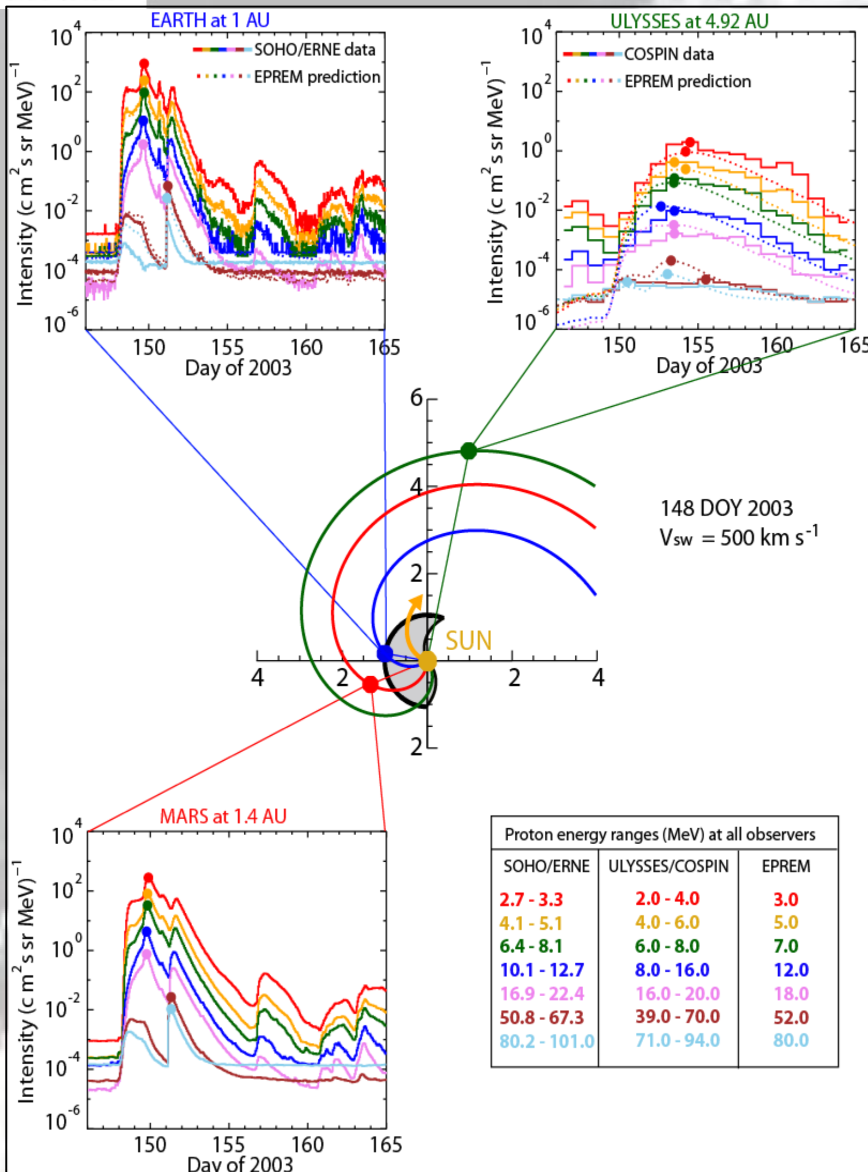
EMMREM

- The Energetic Particle Radiation Environment Module (EPREM) - a physical 3D kinetic model for the transport of energetic particles.
- Capable of simulating the transport of protons, electrons, and heavier ions.
- Currently, driven by data at 1 AU (GOES, SOHO/ERNE).
- Currently run on an event-by-event basis
- Solves for particle transport along field lines in the Lagrangian grid (Kota, 2005)

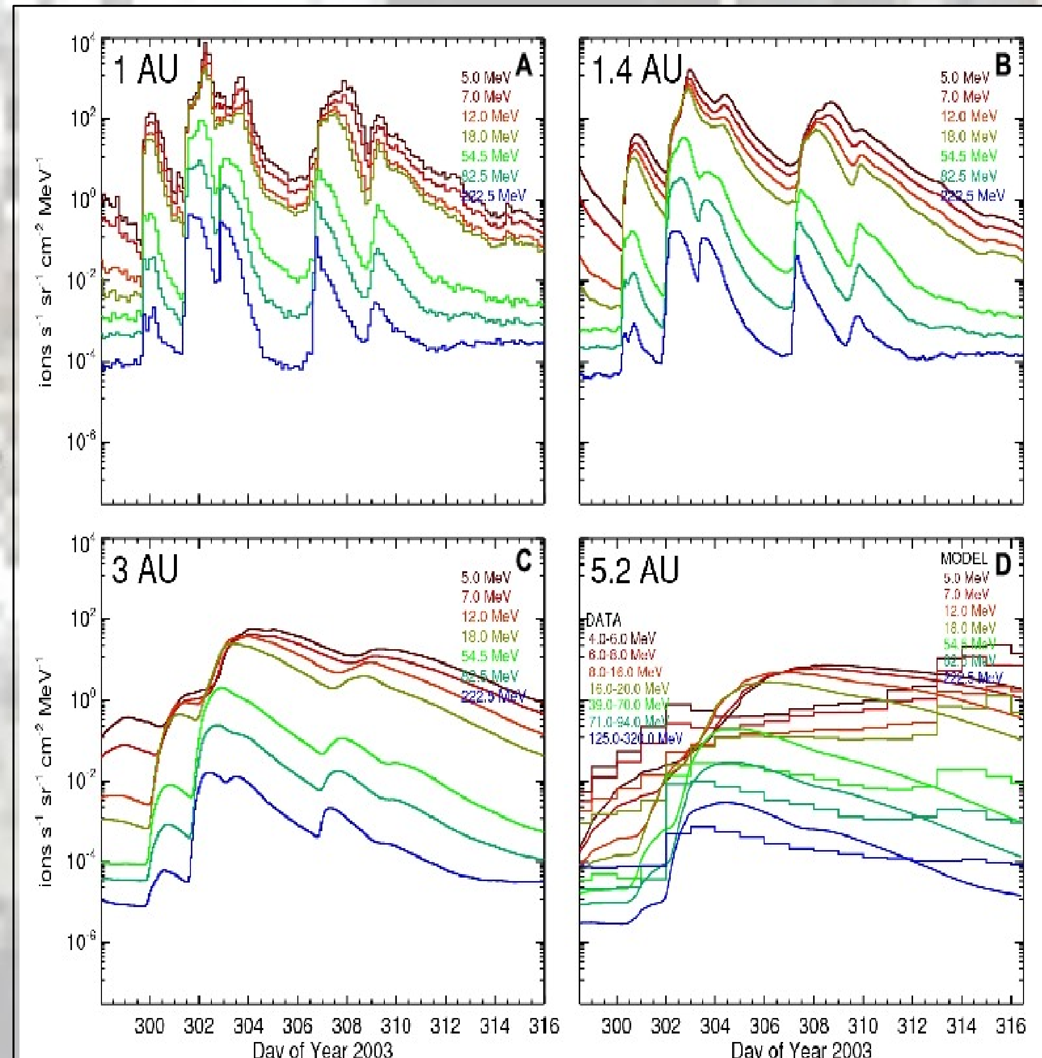


- Model also includes perpendicular diffusion and gradient and curvature drift

EPREM simulations



Dayeh et al., submitted to SWJ



Kozarev et al., submitted to SWJ

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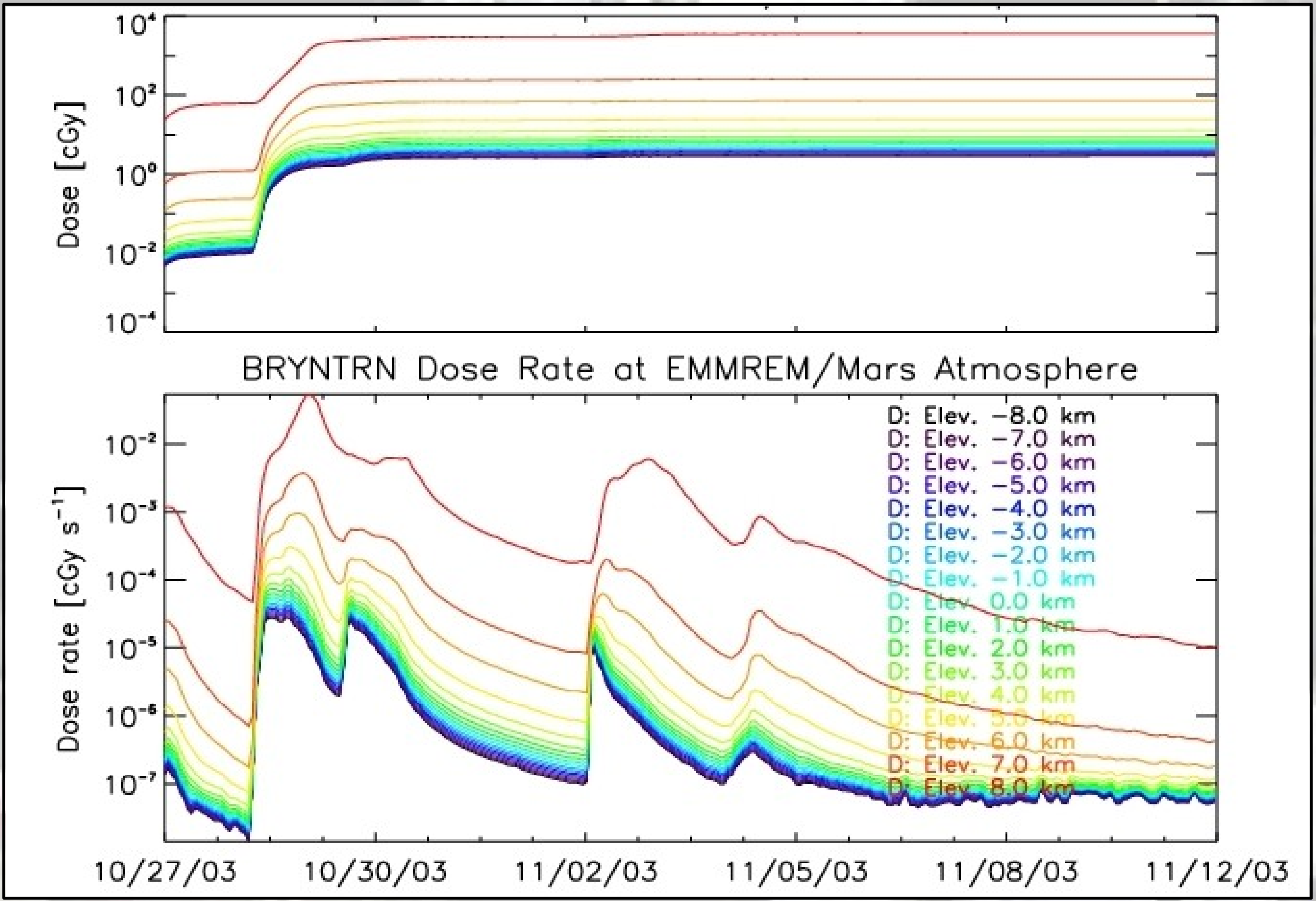
EMMREM: Secondary Transport

- **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 – GCR and SEP organ doses in low atmosphere (~10 km)
  - Moon – LET look-up tables for comparison with CRaTER
  - Mars – GCR and SEP organ doses in atmosphere and shelters
  - Interplanetary - GCR and SEP organ doses for spacecraft shielding

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.

Dose rate and dose at Martian atmospheric heights



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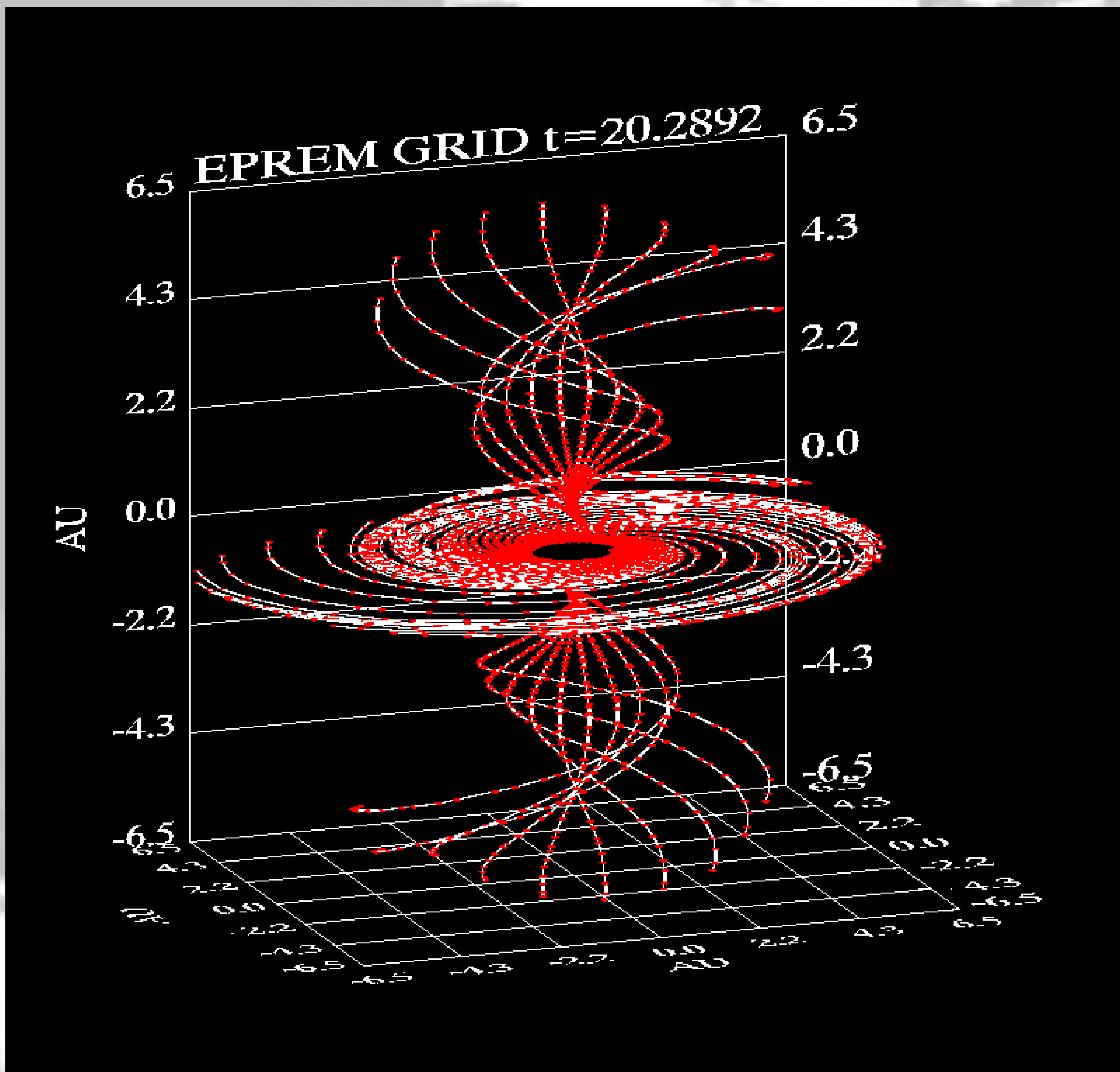
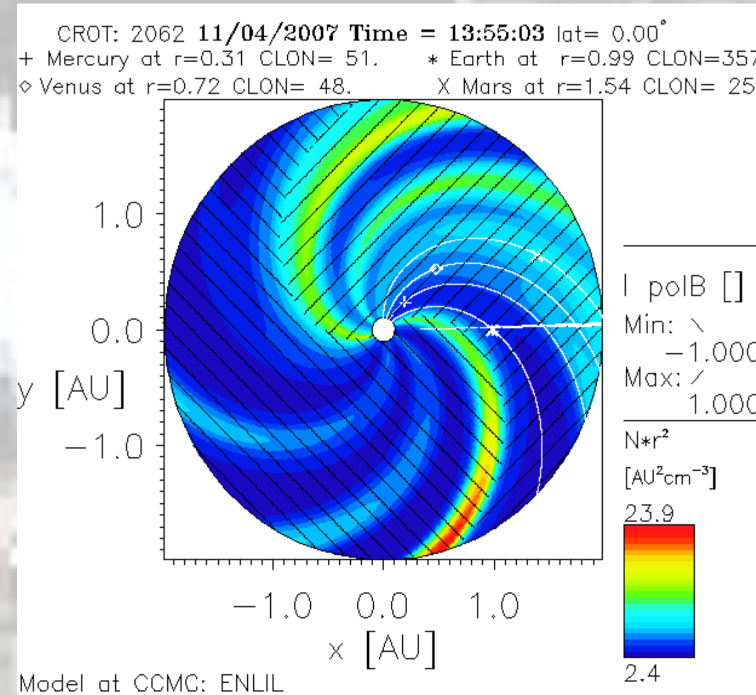
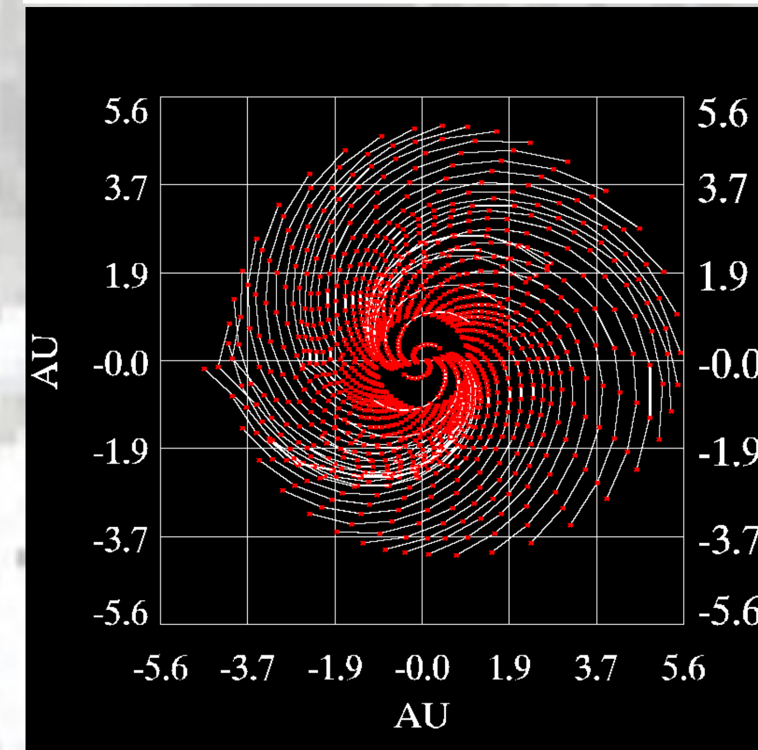
Coupling to MHD

EMMREM

Efforts underway to validate coupling b/n EPREM and WSA/Enlil







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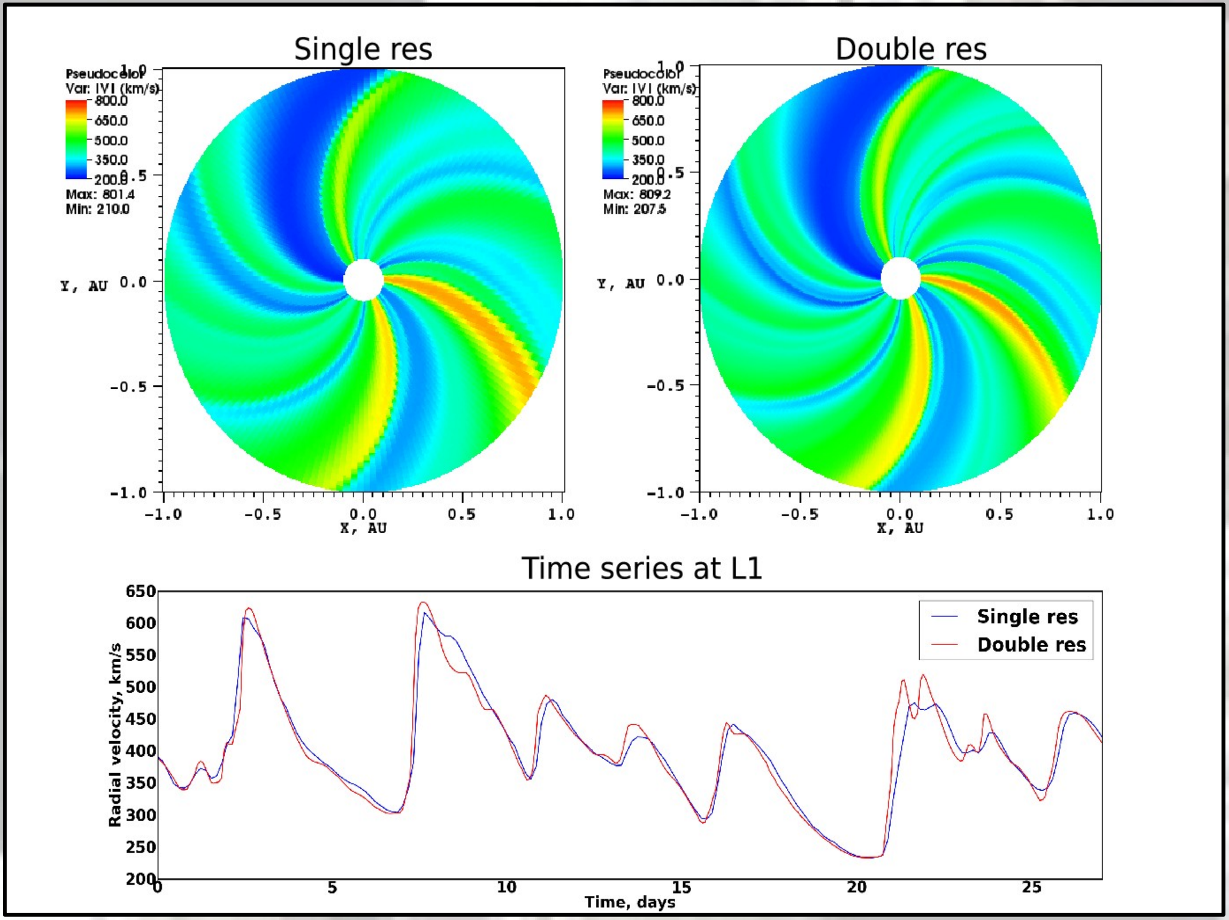
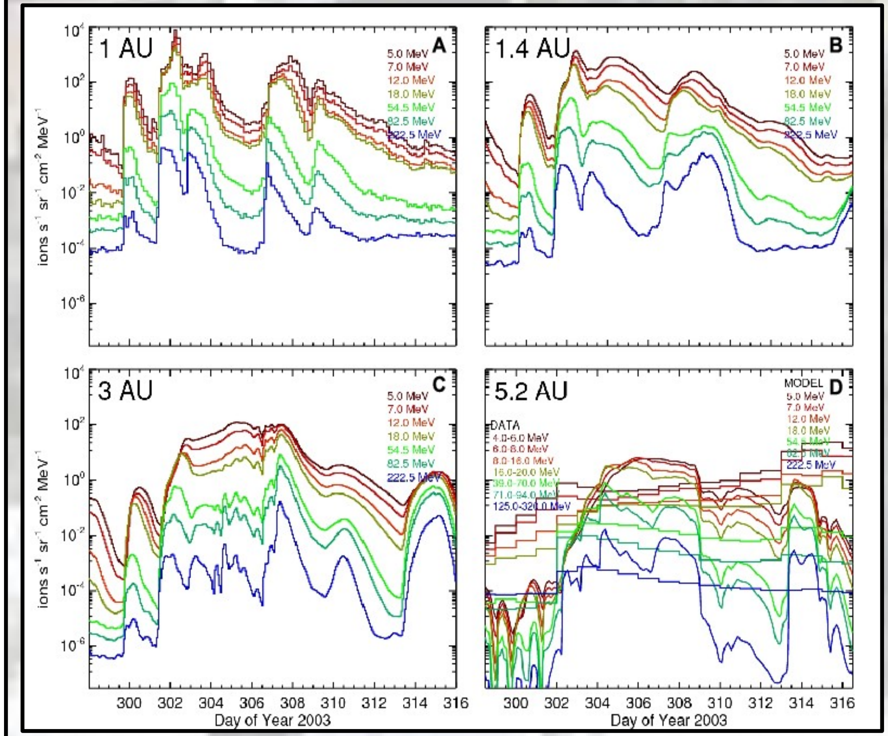
Coupling to MHD

- Testing coupling to WSA/Enlil results with cone model CMEs
- Coupling to a new MHD code being developed at BU (LFM-helio) underway





Kozarev et al., submitted to SWJ

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EMMREM Questions

- What are 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)?
- How to reduce radiation exposure uncertainties?

EMMREM User Community

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

- EMMREM delivered and installed at the Community-Coordinated Modeling Center (CCMC)

- BRYNTRN is running in real time. Working on coupling between BRYNTRN and the ReleASE model.

- First version of a web interface to EMMREM providing runs on request is online at http://emmrem.bu.edu

- EMMREM website could serve as an integration/visualization tool for energetic particles datasets.

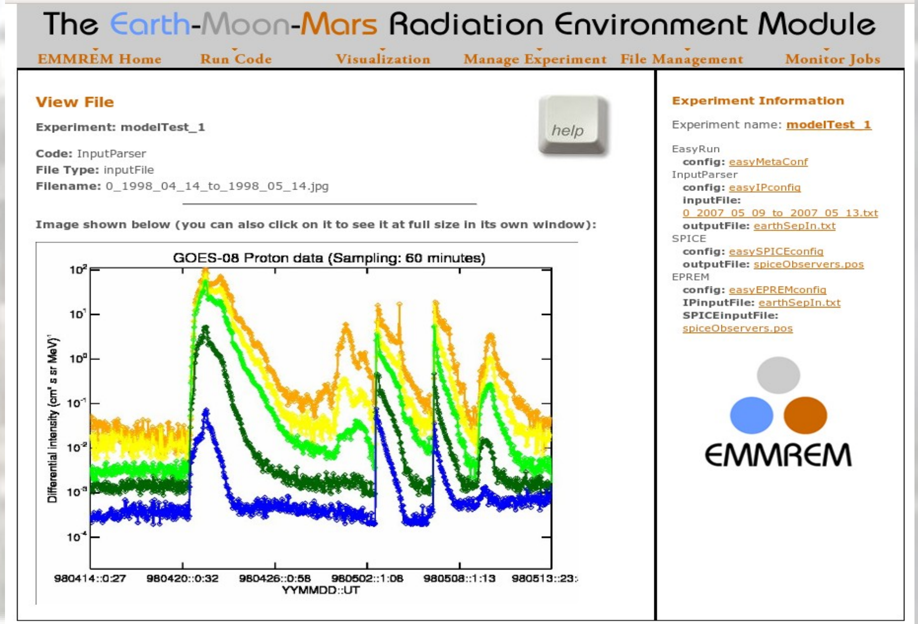
Technical Notes on EMMREM System

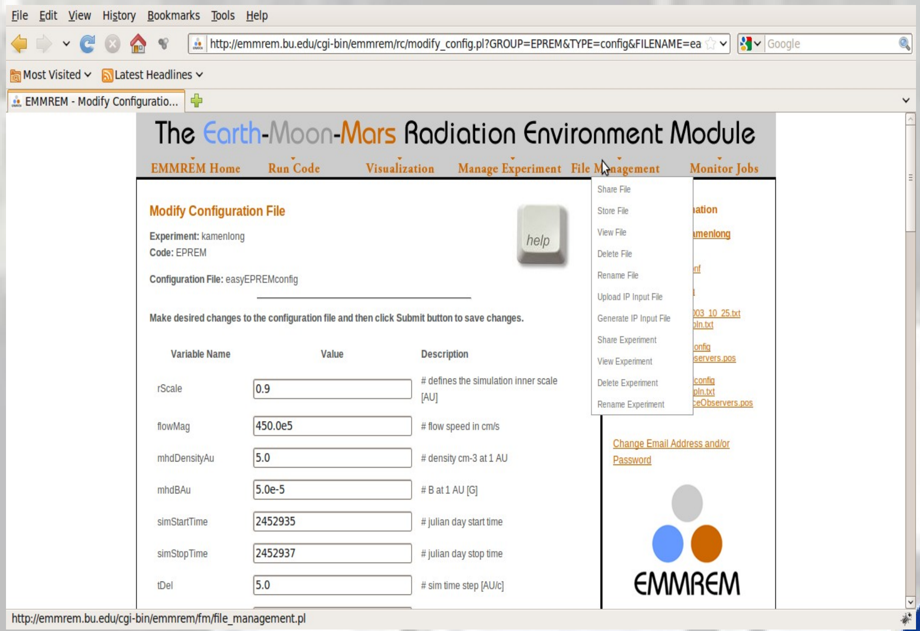
- Models are written in C, Fortran, IDL;
- System designed in a modular fashion;
- Every module is independent;
- Input/output ascii files in self-descriptive format (XML-like)
- System is controlled via bash shell scripts;
- Visualization software written in IDL.

EMMREM Web interface

• **Currently available:**
- GOES proton input
- EPREM runs on request
- BRYNTRN runs on request
- Sim results visualization

• **New functionality soon:**
- Mars radiation environment
- LET specra for comparison with CraTER
- Earth atmospheric radiation environment
- Catalogue of historical events with radiation environment information





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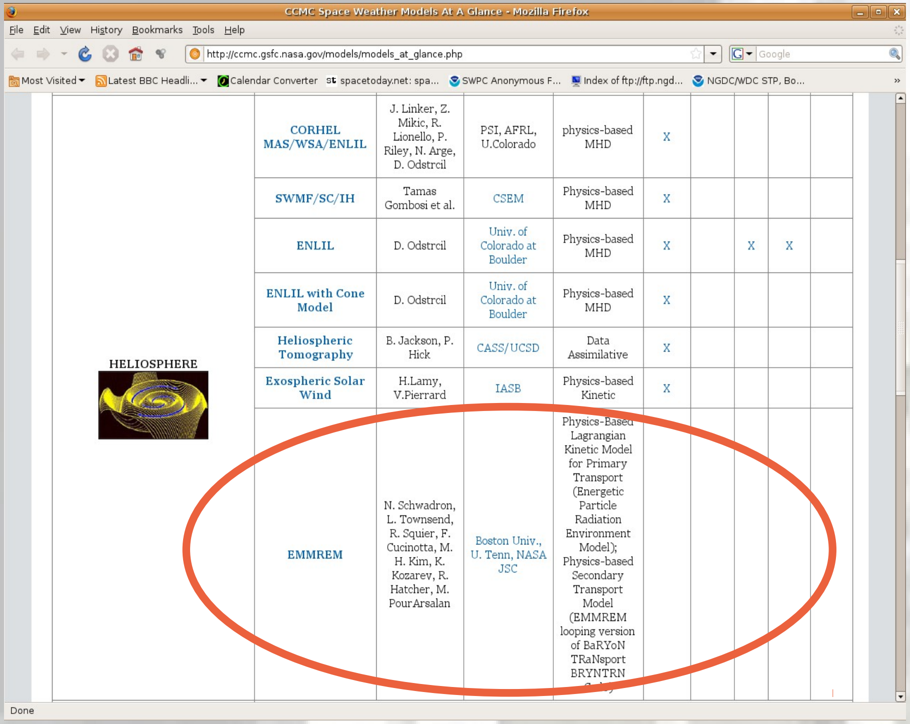
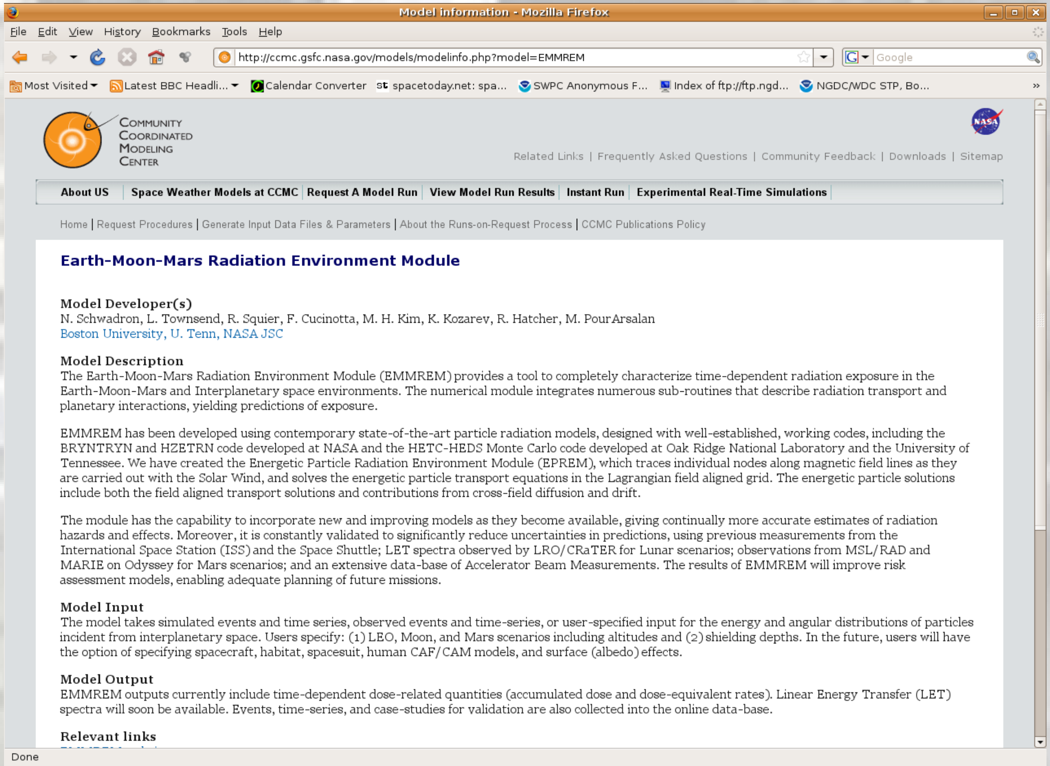
EMMREM at CCMC



HELIOSPHERE	CORHEL MAS/WSA/ENLIL	J. Linker, Z. Mikic, R. Lionello, P. Riley, N. Arge, D. Odstrcil	PSI, AFRL, U.Colorado	physics-based MHD	X				
	SWMF/SC/IH	Tamas Gombosi et al.	CSEM	Physics-based MHD	X				
	ENLIL	D. Odstrcil	Univ. of Colorado at Boulder	Physics-based MHD	X		X	X	
	ENLIL with Cone Model	D. Odstrcil	Univ. of Colorado at Boulder	Physics-based MHD	X				
	Heliospheric Tomography	B. Jackson, P. Hick	CASS/UCSD	Data Assimilative	X				
	Exospheric Solar Wind	H.Lamy, V.Pierrard	IASB	Physics-based Kinetic	X				
	EMMREM	N. Schwadron, L. Townsend, R. Squier, F. Cucinotta, M. H. Kim, K. Kozarev, R. Hatcher, M. PourArsalan	Boston Univ., U. Tenn, NASA JSC	Physics-Based Lagrangian Kinetic Model for Primary Transport (Energetic Particle Radiation Environment Model); Physics-based Secondary Transport Model (EMMREM looping version of BaRYoN TRaNsport BRYNTRN					

Delivered and installed EMMREM successfully.



More information about the model at:

http://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=EMMREM

EMMREM at CCMC - suggestions

- In the long-run more practical to have this tool running and used through the CCMC instead of only at BU.

- In the common interest to have accessible predictions of space radiaton

- We have limited machines on which uses can run the system. The CCMC has much more access to good and updated computing resources.

- Possible porting of that toolbox to the CCMC.

- The EMMREM tools we have developed could serve to integrate energetic particles data from different missions.

Summary

- First version of EMMREM developed
  - Included interplanetary primary transport
  - Secondary transport (BRYNTRN for near-real-time capabilities, Look-up tables from BRYNTRN, HZETRN, HETC-HEDS
  - MHD coupling now taking shape
- Web interface nearing completion.
- Soon to come on-line
  - Simulated Particle Event catalog
  - Mars Scenarios
  - Earth Scenarios
  - Lunar Validation

Summary

- EMMREM up and running at the CCMC
- Developing use of MHD model results in the coupling to the energetic particle solver in EMMREM
- Have a coupling between BRYNTRN and the REleASE model (this will run in real time soon)
- We have a set of webtools that can be passed on to the CCMC

EMMREM

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

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)

GCRs from HZETRN

HZETRN 2005 Code

- **A 3-layer version 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)***

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 (417 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***

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

- **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**

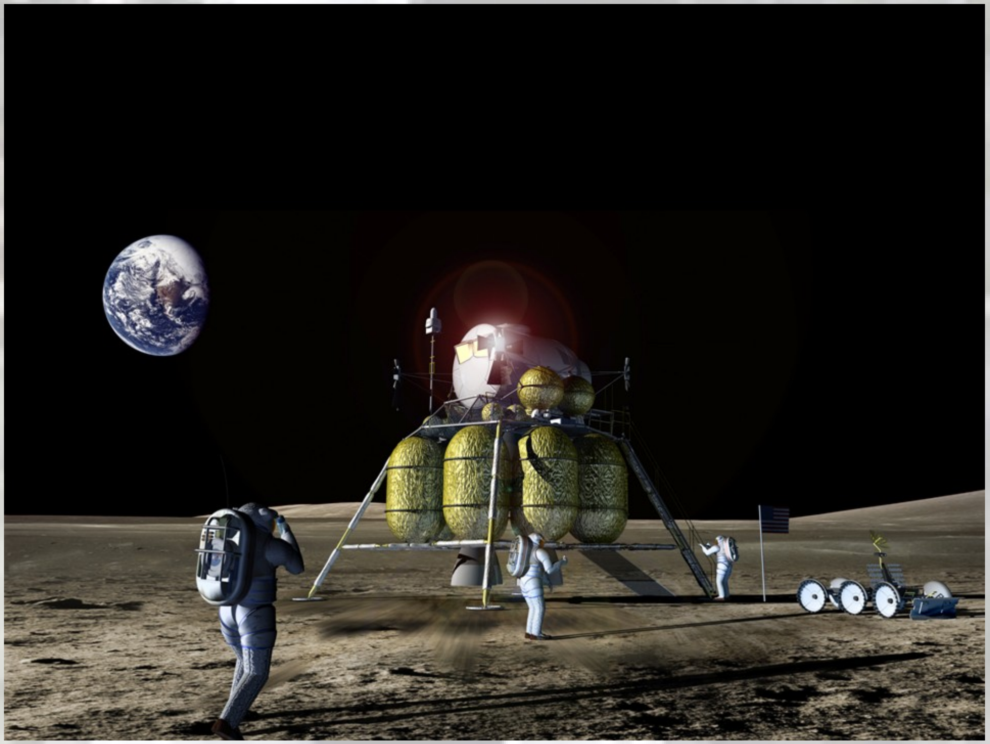
  - Comparisons of the measured LET spectra from the mission will be made with these LET calculations

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 Silicon 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*
- *BRYNTRN calculations for incident SPE protons have been incorporated into a lookup table. Output: effective dose, organ dose and dose equivalent for 0.1-2000 MeV/nuc, on a per incident particle basis*

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

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.

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