Earth-Moon-Mars Radiation Environment Module (EMMREM)

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Abstract—We are preparing to return humans to the Moon and setting the stage for exploration to Mars and beyond. However, it is unclear if long missions outside of Low-Earth Orbit (LEO) can be accomplished with acceptable risk. The central objective of our project, the Earth-Moon-Mars Radiation Exposure Module (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. EMMREM will provide the ability to predict radiation exposure on the surface or atmosphere of Earth, on the Moon, Mars, and in interplanetary space between Earth and Mars. EMMREM is being designed for broad use by researchers to predict radiation exposure by integrating over almost any incident particle distribution from interplanetary space. EMMREM is being developed using contemporary state-of-the-art particle radiation models. Beyond this, it will have the capability to incorporate new and improving models, as they become available, to give continually improved estimates of radiation hazards and effects. EMMREM will be comprehensively validated using direct and contemporaneous measurements near Earth, at the Moon and Mars to significantly reduce uncertainties in radiation exposure predictions. EMMREM will characterize the extremes, statistics, and variations over time of radiation exposure caused by solar energetic particles and cosmic rays. The results of EMMREM will improve risk assessment models so that future human exploration missions can be adequately planned for. This makes EMMREM highly relevant to NASA's Vision for Space Exploration and the Living With a Star Programs. [1] [2]

TABLE OF CONTENTS

1. INTRODUCTION

Space radiation hazards (Figure 1) pose one of the most serious issues to future human and robotic exploration to the Moon and beyond:

- **Galactic Cosmic Rays (GCRs)** are an ever-present background radiation that originate from outside our solar system and produce chronic but not acute exposures. GCRs are extremely difficult to shield against outside the protection of Earth's atmosphere and magnetosphere. Astronauts under nominal shielding (*e.g.,* a few gm/cm^2 of aluminum) could accumulate a career limit due to GCRs in roughly 3 years. We need to understand the current constraints imposed by GCRs as a function of mission transit time, shielding materials and thickness, and develop better techniques to shield them.

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- Large **Solar Energetic Particle events (*SEP events,*** defined here to include ions; also referred to as Solar Particle Events, SPEs**)** are also extremely dangerous to astronauts outside Earth's atmosphere and magnetosphere. To mitigate the hazard SEPs pose, we must develop the ability to predict when and where they will occur, and we must provide adequate shielding against them.
- There are **unique radiation environments** at each planet or satellite. At Earth, we have thoroughly characterized locations of the radiation belts, which allows us to mitigate the hazard they pose by transiting them rapidly. For future human and robotic exploration of other planets and satellites, we must characterize the planetary radiation environments so that appropriate mitigation strategies and adequate shielding are designed.

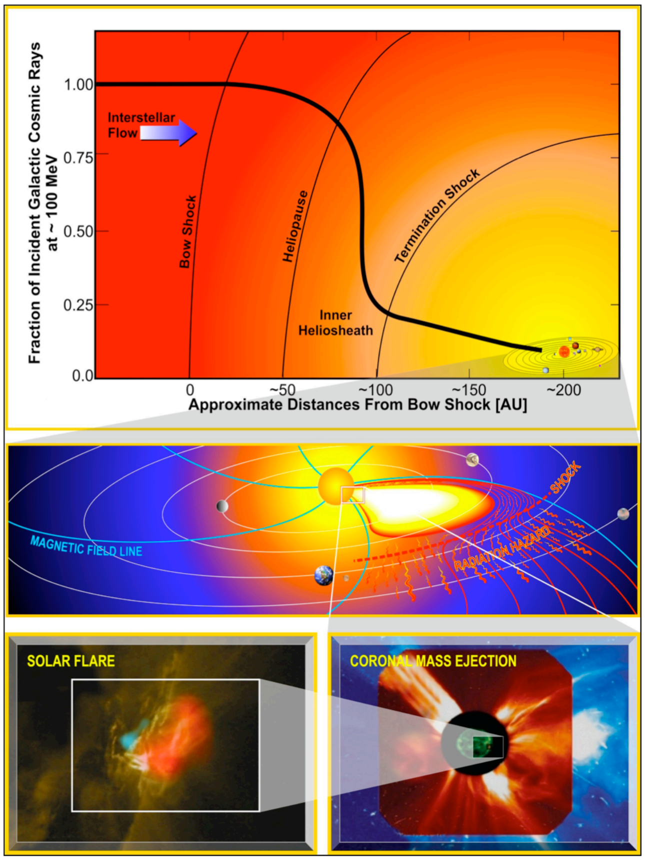

Figure 1: EMMREM will provide a numerical module to completely characterize time-dependent radiation exposure from the hazards posed by space radiation: galactic cosmic rays from outside our solar system (top), from flares (bottom left) and shocks (middle) often driven by coronal mass ejections (bottom right).

Shielding is often considered the answer to space radiation hazards. However, for very high-energy radiation (> 100 MeV), shielding may make matters worse by producing secondary, penetrating particles, such as neutrons and nuclear fragments, that, for some types of shields, increase the hazard [1].

The radiation hazard is potentially severe, but not sufficiently well characterized to determine if long missions outside of Low-Earth Orbit (LEO) can be accomplished with acceptable risk [2]. Radiation hazards may be over- or under-stated through incomplete characterization in terms of net quantities such as accumulated dose. Time-dependent characterization often changes acute risk estimates [3, 4, 5, 6]. For example, events with *high accumulated doses*, but sufficiently *low dose-rates* (<30 rad/hr) pose significantly *reduced* risks. More complete characterization depends on models that take into account time-dependent radiation effects according to organ type, primary and secondary radiation composition, and acute effects (vomiting, sickness and, at high exposures, death) versus chronic effects (such as cancer). To reduce uncertainties in predictions, radiation exposure models must be tested with direct observations. This requires detailed knowledge of radiation detectors and accurate detector response models [7].

2. The EMMREM Project

The EMMREM project (Figure 2) will be carried out through three primary activities:

1. **Development of EMMREM's central Time-dependent Radiation Exposure Module.** Our module for predicting time-dependent radiation exposure (Linear-Energy-Transfer, LET, spectra and dose-related quantities) is being designed with well-established, working codes including the BRYNTRN and HZETRN code developed at NASA Langley [8] and the HETC-HEDS Monte Carlo code developed at Oak Ridge National Laboratory and the University of Tennessee [9]. Development of these codes is currently under the auspices of the NASA Space Radiation Transport Code Development Consortium (NASA NRA-01-OBPR-05). NASAs Exploration Systems Management Directorate (ESMD) is making a large investment in biologically based risk assessment models that will replace inaccurate organ dose equivalent models of risk. The development of these models will evolve well beyond the time frame of this project. In EMMREM, we focus on coupling advanced models of SEPs to the ESMD's models of acute radiation sickness and acute lethality from SEPs to provide biologically based risk assessments.
2. **Development of EMMREM's Interface with Particle Radiation Observations**: Direct observations of particle radiation (SOHO, ACE, Wind, STEREO, SAMPEX, NOAA-GOES and Ulysses) and selected simulations will be used as direct input to predict radiation exposure. The 3-D observations by STEREO will be used fully to characterize and predict radiation exposure in events contemporaneously observed at the Moon and Mars by LRO/CRaTER and MSL/RAD. Observations and simulations will be studied to characterize the extremes, statistics, and time variations of radiation exposure caused by SEPs and CRs.
3. **Significant Uncertainty Reduction through Comprehensive Radiation Exposure Validation.** EMMREM will be validated extensively to reduce and understand its uncertainties. For this purpose, we will

use previous measurements from the International Space Station (ISS) and the Space Shuttle; LET spectra observed by LRO/CRaTER for Lunar scenarios; observations from MSL/RAD and MARIE on Odyssey for Mars scenarios; and an extensive data-base of Accelerator Beam Measurements. Detailed detector response models will be developed to support these extensive validation efforts.

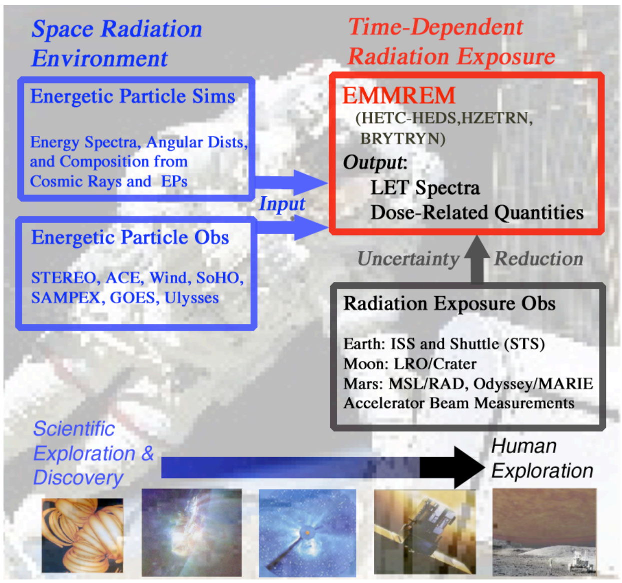

Figure 2: EMMREM will provide an important link from Space Science to Space Exploration Programs by characterizing time-dependent radiation exposure from simulated and observed particle radiation. EMMREM will significantly reduce current uncertainties in radiation exposure through comprehensive validation.

3. Relevance and Urgency

We are preparing to return humans to the Moon and setting the stage for exploration to Mars and beyond. These ambitious goals create new urgency for the LWS Program and the National Space Weather Program to develop predictive capabilities for radiation hazards that pose among the most significant risks to future human exploration. EMMREM is urgently needed to reduce uncertainties in current human risk assessment models. EMMREM is broad and deeply relevant to National, NASA, NSF and LWS objectives. Further, the scientific depth of the project advances prediction, characterization, and ESMD leveraged assessment capabilities while also advancing exploration and understanding of energetic particle acceleration in evolving space plasmas.

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).
- EMMREM is an 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*".
- EMMREM makes the connection from Sun-Solar System Connection science and LWS's advancing enterprise of scientific exploration and discovery to a practical module to understand the space environmental conditions experienced by future human explorers. EMMREM is thus 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 ...".*
- Our project is also relevant to the **National Space Weather program**'s goal to *"validate and enhance space weather models to improve specification and prediction capabilities,...".* Energetic particle models run as part of this effort are validated with observations from the network of solar-heliospheric missions. In addition, we provide a framework to inter-compare and validate new models of the radiation environment as they become available.
- EMMREM 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.

4. EMMREM Framework

The EMMREM framework (Figure 3) consists of four pieces:

- The *interplanetary source input* provides the interplanetary energy spectrum, composition and angular distributions (SEPs, ACRs and GCRs) based on select simulations, observed events and interplanetary conditions, or user-specified input. We will develop a database (available online) of simulated and observed events and time-series.
- The *Scenario/Environment sub-module* transforms the interplanetary source energy spectra, composition and angular distributions based on shadowing by the planetary body and deflection/trapping by planetary magnetic fields.
- The *Radiation Transport sub-module* describes the interaction of incident ionized particles with atmospheres, shielding material and tissue, including production of secondary forms of radiation, utilizing output from the Scenario sub-module. Users may specify a variety of shielding materials, habitat/spacecraft/spacesuit and human geometries

including the Computerized Anatomic Female/Male (CAF/CAM) models.

- *EMMREM output* include time-dependent dose-related quantities and Linear Energy Transfer (LET) spectra. Events, time-series, and case-studies for validation are also collected into the online data-base.

Website and on-line functionality. The framework in Figure 3, will provide the basis for a web-page providing the public and scientific community access to the functionality of EMMREM. The web-page will provide links for users to choose specific simulated events and time-series, observed events and time-series, or user-specified input for the energy and angular distributions incident from interplanetary space. Users specify: (1) LEO, Moon, and Mars scenarios including altitudes and/or orbits; (2) shielding materials, optional spacecraft, habitat, spacesuit, human CAF/CAM models, and optional surface (albedo) effects. Module output are retrievable as time-series and time-averages. These may be compared to observed events (LRO/CRaTER, MSL/RAD, MARIE, ISS, Space Shuttle) or accelerator measurement case studies.

5. EMMREM COMPONENTS

The core sub-modules of EMMREM for computing time-dependent radiation exposure are broken up into a Scenario Sub-Module that specifies the environmental factors introduced by planetary/satellite bodies and a Transport Sub-Module describing the interactions in atmospheres/shielding/tissue and production of secondary radiation.

The Scenario Sub-Module (SSM) includes all relevant databases and models necessary for full and accurate depiction of ambient radiation environments, both in deep space and planetary surfaces. These include models of (1) Earth's atmosphere and magnetic fields, (2) the atmosphere, weak magnetic field and regolith composition of Mars, and (3) lunar regolith composition. For operations on planetary surfaces (Earth, Moon, and Mars) or in orbits around them, the effects of shadow shielding provided by the planetary mass are accounted for. We account for neutron albedo resulting from particle interactions with the underlying planetary surfaces. For operations in deep space, such as transits to the Moon or Mars, updated models and databases necessary to develop the scenario sub-module are currently available to the Radiation Transport Code Development Consortium (lead by CoI, L. Townsend) and have received extensive use in previous, related analyses by consortium members [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

EMMREM's Transport Sub-Module (TSM) utilizes both the 1-D deterministic HZETRN transport code [25] or BRYNTRN for SEPs and the 3-D, Monte Carlo HETC-HEDS transport code [9].

The *HZETRN (High Z and Energy TRaNsport)* code is

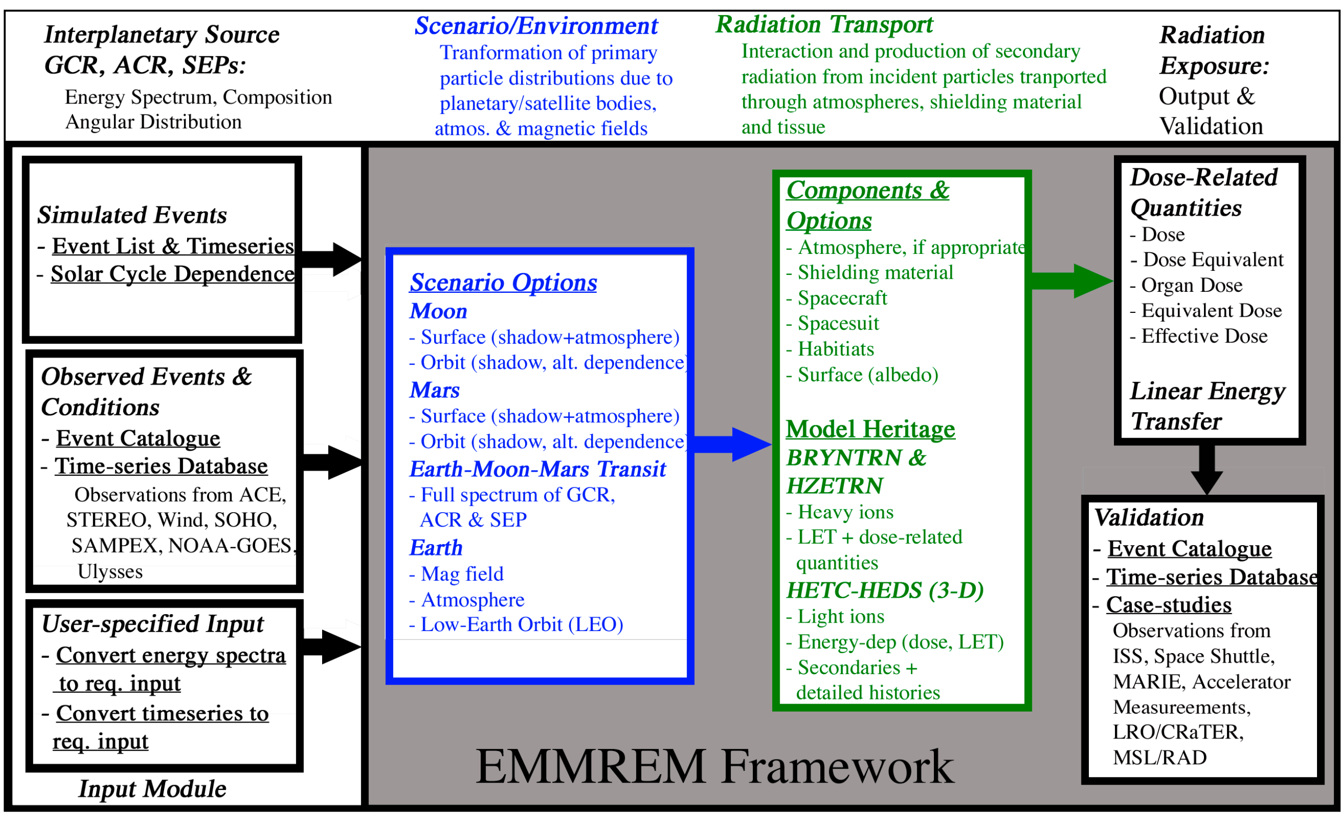

Figure 3: EMMREM is a flexible module with well-defined interfaces for predicting radiation exposure in the Earth, Moon, Mars and interplanetary space environments based on input of an energy spectrum, composition and angular distribution of energetic particles and cosmic rays.

being developed at NASA Langley Research Center as a science application and engineering design tool for radiation shielding studies. HZETRN can be used to predict LET spectra and dose related quantities (absorbed dose, dose equivalent) for a wide variety of space radiation protection scenarios. Comparisons of HZETRN predictions of dose and dose equivalent behind various materials in space agree to within 20% of the measured values on several space missions in low Earth orbit [26, 27, 28, 29]. The HZETRN code grew from a 29-ion isotopic grid used in the 1980's and early 1990's [25] to a 32-ion isotopic grid to include all light ions several years later [31]. The HZETRN code has recently been extended to include the full isotopic dependence of the primary GCR [27]. The present code includes all of the abundant nuclei in the GCR environment with fluxes greater than about $10^2/(\mathrm{cm}^2\ \mathrm{yr})$ and nuclei produced in fragmentation events with production cross-sections greater than about 1 mb. Several nuclei with smaller primary abundances or production cross-sections of scientific interest are also included in the expanded HZETRN code. More recently, HZETRN has been extended to include angular deflection of heavy ions through multiple scattering [32] and bi-directional neutron transport [33]. The ESMD is making a large investment in HZETRN developments for engineering shielding analysis applications. The EMMREM code will follow a modular design allowing for inclusion of updated versions of HZETRN as they are released by ESMD.

The BRYNTRN (BaRYoN TRaNsport) code is a deterministic, coupled proton-neutron space radiation transport model that transports incident protons and their secondary products (protons, neutrons, deuterons, tritons, helions, and alphas) through shields of arbitrary composition and thickness [25]. EMMREM uses BRYNTRN to compute transport effects primarily due to SEPs.

The 3-D, Monte Carlo, radiation transport code HETC (High Energy Transport Code), originally developed at Oak Ridge National Laboratory (ORNL), was recently extended to include transport of energetic heavy ions (found in the GCR, ACR and SEP distributions) by developing and incorporating an HZE particle event generator capable of providing nuclear interaction data for use in HETC [34]. The extended code is now called HETC-HEDS (HETC-Human Exploration and Development of Space) [9]. The event generator predicts the interaction product yields, production angles and energies using nuclear models and Monte Carlo techniques. HETC-HEDS simulates the particle cascade, computing the trajectories of the primary particles and all secondary particles generated during nuclear collisions. The particles considered by HETC-HEDS may be arbitrarily distributed in angle, energy, and space. HETC-HEDS uses a combinatorial geometry package so almost arbitrary geometries are allowed. Each particle in the cascade (heavy ions, protons, neutrons, π^+, π^-, μ^+, or μ^-) is followed until it escapes from the geometric boundaries, undergoes nuclear collision or absorption, comes to rest due to energy losses, or decays. Neutrons produced below a given cutoff, usually 20 MeV, and photons produced in the cascade or from de-excitation gammas are not transported. Instead, the information is stored for transport by other codes such as MORSE [35] or MCNP [36] and EGS [37]. HETC-HEDS provides a complete cascade history.

The EMMREM Transport Sub-Module will be developed along three parallel paths: (1) using only HZETRN for GCRs or BRYNTRN for SEPs; (2) using only HETC-HEDS; and (3) using a combination of the two codes where the primary and secondary HZE (High Z) particles are transported by HZETRN and the primary light ions and secondary light ions and neutrons are transported by HETC-HEDS. The advantage of using the HZETRN or BRYTNRN is computational speed. Although transport of the HZE particle components are well represented by the 1-D or deterministic 3-D approximations, stochastic 3-D treatments (provided by 3-D Monte-Carlo codes such as HETC-HEDS) are necessary to accurately describe transport of light ions and neutrons. We investigate methods of combining these codes, using the faster HZETRN or BRYNTRYN code to transport heavy ions, and using the more accurate HETC-HEDS code to transport light ions and neutrons. Radiation exposures to human crews are computed using the Computerized Anatomic Female/Male (CAF/CAM) models [38], which NASA currently employs for estimating radiation exposures and associated risk.

6. ENERGETIC PARTICLE OBSERVATIONS

Table 1: Instruments and Energy Coverage

		Energy Range (MeV or MeV/nucleon)	
S/C	**Instr.**	**Ions (H/He – Fe)**	**Electrons**
ACE	ULEIS [39]	0.04 – 9.7	…
ACE	SIS [40]	7.0 –90	…
SAMPEX	PET [41]	19 – 400	1.2 – 8.0
GOES	EPS [42]	0.8– 500	0.6 - >2
Wind	STICS [43]	0.006 – 0.2	…
Wind	STEP [44]	0.02 – 2	…
SoHO	COSTEP [45,46]	4 – 150	0.2 – 15
STEREO	SEPT [47]	0.02 – 7.0	0.02 – 0.4
STEREO	SIT [47]	0.03 – 2.0	…
STEREO	LET [47]	1.5 – 30	…
STEREO	HET [47]	– 100	– 5.0
Ulysses	KET [48]	4 to >2000	2 to >10
LRO	CRaTER [49]	LET (~1 to >100)	
MSL	RAD	~2-200	0.15-15
Odyssey	MARIE [50]	LET (1-30 keV/μm)	

We will utilize energetic particle, solar wind plasma, and magnetic field measurements obtained by the fleet of currently operating and future spacecraft comprising the

Heliophysics Great Observatory (e.g., ACE, Wind, SAMPEX, SoHO, Ulysses, STEREO, and EPS on NOAA-GOES) to measure key properties of large SEP events, ESP events, and the trends/variations of GCRs. Table 1 summarizes the energy coverage of various instruments that will be used in this study. High quality data for many of these instruments during several large SEP/ESP events of cycle 23 are or will be made available to the public via the ACE Science Center by R. A. Mewaldt.

7. VALIDATION AND UNCERTAINTY REDUCTION

Validation will be a critical component of the EMMREM project, providing significant uncertainty reduction and quantification. Rigorous and comprehensive validation studies are conducted in the environments where risks need to be assessed: in LEO (ISS and Shuttle measurements), in the lunar environment (LRO/CRaTER), and in the Mars environment (MSL/RAD and MARIE/Odyssey). Detailed detector response models are developed to support validation studies and a final EMMREM validation & uncertainty document is prepared.

Low Earth Orbit: ISS and Space Shuttle Measurements. We will validate EMMREM by comparing model output with time-dependent measurements on the Space Shuttle beginning with STS-34 in 1990 made with tissue equivalent proportional counters (TEPC's) and other measurements made on the Russian space station Mir and International Space Station [28, 29]. The TEPC measurements, extending for more than a solar cycle, provide time resolved data of the GCR and trapped protons in LEO of dose, dose equivalent and lineal energy spectra. TEPC's do not measure LET directly and instead measure the surrogate quantity lineal energy (y) where y is related to the energy deposited in a 1-micron diameter volume. Detailed Monte-Carlo simulations using microdosimetric and track structure computational approaches [51, 52, 53] are needed to make a comprehensive comparison to flight measurements with TEPCs in LEO or future exploration missions.

The Moon: LRO/CRaTER. EMMREM will be validated by comparing predictions based on contemporaneously observed and simulated GCR and SEPs spectra with LET spectra measured by CRaTER. CRaTER is a part of the Lunar Reconnaissance Orbiter (LRO) mission, which will be launched late in 2008. CRaTER

- measures and characterizes LET spectra of GCRs and SEPs (particularly above 10 MeV);
- investigates the effects of shielding by measuring LET spectra behind different amounts and types of areal density, including tissue-equivalent plastic.

Contemporaneous measurements by ongoing/planned missions (ACE, STEREO, SOHO, Wind, SAMPEX, Ulysses, NOAA-GOES) are used to specify GCR and SEP spectra. EMMREM outputs are directly compared to the LET spectra observed by CRaTER. Any disagreement between observations and model results elucidate weaknesses in the model physics, or the understanding of the modelled interactions, and will be used as feedback for improvement. CRaTER will provide unprecedented GCR/SEP LET spectra. Every event above 10 MeV will be analyzed, allowing unprecedented tests of particle simulations, and the mapping of particle observations through EMMREM to predict radiation exposure. Ultimately, these validation efforts will constrain models and radiation exposure characterization to Mars and throughout the inner heliosphere.

We will explore the use of near-real-time energetic particle measurements to drive simulations, and provide predictions of radiation exposure. A near-real-time pipeline into EMMREM for radiation exposure diagnostics provides a tool to evaluate mitigation strategies, and derive requirements for missions that must provide operational systems in future human exploration.

Mars: MARIE. SEP and GCR dose predictions from EMMREM will be validated against dose measurements from the Martian Radiation Environment Experiment (MARIE) on the 2000 Mars Odyssey Orbiter (launched April, 2000). These measurements will provide EMMREM validation near Mars, on its surface, and in the interplanetary space between the Earth and Mars.

Mars: MSL/RAD. EMMREM predictions will be compared to observations of the Radiation Assessment Detector (RAD) on the Mars Science Laboratory (MSL) mission (launch Dec, 2009). RAD is an energetic particle spectrometer consisting of a solid-state detector stack and CsI calorimeter. RAD uses the dE/dx vs E method to measure energetic ions ($2 \leq Z \leq 26$), protons, and helium in the range of ~2-200 MeV/nuc (energy ranges depend slightly on species). RAD also measures electrons (150 keV-15 MeV) and includes separate plastic and CsI scintillators to detect neutrons and gamma rays. Validation of EMMREM's Mars atmospheric transmission and radiation transport is a key element of the project. RAD measurements provide comprehensive validation of EMMREM predictions of light ions, heavy ions, and neutrons.

Large SEP events may contribute significantly to the total dose (perhaps as much 0.6 Sv) at the Martian surface, largely due to secondaries. These radiation exposures approach, and in some cases exceed, career limits for LEO operations. As such, validating EMMREM's SEP radiation exposure predictions at the Martian surface is an extremely important effort. The validation of EMMREM by RAD will provide critical insight to improve SEP models and radiation exposure predictions used for future risk assessment models.

Accelerator Beam Measurements. EMMREM case studies are performed using particle projectiles incident on thick targets and resulting in nuclear fragments, secondary neutrons and other particle production. These EMMREM case studies are validated against data from comparable experiments accumulated by the Measurements Consortium of the NASA SRSP for a wide range of projectile and target nuclei at a range of energies spanning the peak of the GCR spectrum. Particle production has been measured as a function of fragment charge and energy (from which LET, dose and dose equivalent are calculated) for thin elemental targets and thick materials. The thin elemental target data are used to validate EMMREM's fragmentation model source terms; the thick target data are used to validate EMMREM and provide direct tests of shielding effectiveness.

8. SUMMARY

The 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. EMMREM will provide the ability to predict radiation exposure on the surface or atmosphere of Earth, the Moon, or Mars, and in interplanetary space between Earth and Mars. EMMREM will make these predictions given the energy spectrum, angular distribution, and elemental composition of particle radiation incident from interplanetary space. EMMREM will be comprehensively validated to significantly reduce uncertainties in radiation exposure predictions. The results of EMMREM will improve risk assessment models so that future human exploration missions can be adequately planned for.

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BIOGRAPHY

Nathan Schwadron is professor of astronomy at Boston University. He works on a broad range of theoretical problems including the solar wind, the heliospheric magnetic field, pickup ions, cometary X-rays, energetic particles, and cosmic rays. Recent work includes: the Solar Wind Scaling Law that provides a natural explanation for slow solar wind from hotter, more radiative sources at the Sun; the Outer Source of pickup ions and Anomalous Cosmic Rays from Kuiper-Belt grains sputtered by the solar wind; a natural explanation for the common occurrence of quasi-radial magnetic fields in the heliosphere based on footpoint motions at the Sun; Heliospheric FALTS (Favored Acceleration Locations at the Termination Shock) that facilitate strong particle acceleration at the Termination Shock through large-distortions of the outer heliospheric magnetic field due to footpoint motions at the Sun; a model for the Inner Source of pickup ions based on neutralization by a large population near-solar grains; a theory for the compositional enhancements observed in slow solar wind based on the heating of large-loops in the corona; and an important source of variability in cometary X-rays that potentiates their use to remotely probe solar wind composition. Dr. Schwadron is a team member of the Ulysses, and the Advanced Composition Explorer (ACE) solar wind teams, participating in interpretation and analysis of these data as well as observations from Wind and the Cassini mission to Saturn. Dr. Schwadron is a co-Investigor on the Interstellar Boundary Explorer Mission, a lead organizer for the New England Space Science Consortium, and the principal investigator on the Earth Moon Mars Radiation Environment Module. Dr. Schwadron has a PhD in Physics from the University of Michigan (1996).