Synthesis of 3-D Coronal-Solar Wind Energetic Particle Acceleration (C-SWEPA) Modules

Executive Summary. The 3-D Coronal-Solar Wind Energetic Particle Acceleration (C-SWEPA) modules provide tools for taking the critical next step in understanding Solar Energetic Particle (SEP) events and characterizing their hazards through physics-based modeling *from the low corona through the inner heliosphere* of shocks driven by Coronal Mass Ejections (CMEs), associated particle acceleration, and particle radiation effects. *C-SWEPA's central objective is to develop and validate a numerical framework of physics-based modules that couple the low corona and Coronal Mass Ejections (CMEs) with solar wind, shocks, acceleration and composition of energetic particles, and the fluctuations and turbulence within solar wind that buffet terrestrial and planetary magnetospheres***.** *Using pre-existing EMMREM modules, we characterize time-dependent radiation exposure in interplanetary space environments.* Simulated observers (e.g., at L1, ACE, Wind, Earth, moon, Mars, etc.) provide basis for comparison with spacecraft and tools to explore simulated mission datasets (e.g., Solar Probe Plus and Solar Orbiter).

C-SWEPA fulfills the need for a transformative synthesis of LWS capabilities by bringing together an exceptional team of leading experts from five institutions in solar, heliospheric and magnetospheric physics and two successful LWS strategic capabilities: the Earth-Moon-Mars Radiation Environment Modules (EMMREM), and the Next Generation Model for the Corona and Solar Wind. C-SWEPA leverages new advancements in High Performance Computing (HPC) through the use of heterogeneous architectures (Graphical Processing Units; GPUs) and develops an innovative approach to delivering complex models that enables the CCMC to use dedicated GPU-enabled and massively parallelized systems for C-SWEPA simulations.

C-SWEPA is a transformational project providing: an integration between observationally driven modeling of CMEs, solar wind, shocks and energetic particles from the low corona through the heliosphere; incorporation of seed populations and associated compositional dependencies; new fundamental information via highly resolved inertial node-lines vital to studies of the magnetosphere (RBSP), other planetary magnetospheres and the microstates and turbulence within solar wind; and detailed models that probe the steady and disturbed corona thus paving the way for SolO and SPP studies.

C-SWEPA deliverables include two numerical systems (one at CCMC and one at UNH) that run C-SWEPA, documentation, and an intuitive interface. These systems provide: on-line availability and event scenarios from Sun-to-Earth; runs that include solar wind, CMEs, its shock(s), SEP flux time series, dose & dose-equivalent rates, integrated doses behind various layers of shielding; and results of runs available to the science community, not tied to individual users. Both EMMREM and CORHEL run at the CCMC and the associated teams have a strong history of partnering with the CCMC.

C-SWEPA answers fundamental scientific questions via four science subgroups that study the corona, solar wind, CME initiation, shocks, solar energetic particle acceleration and propagation, and solar wind waves and turbulence. Core team members have experience working together and leverage developments from CISM, EMMREM, CORHEL, and NSF's Sun-to-Ice project.

C-SWEPA provides broad impacts by advancing discovery and understanding while also promoting teaching, training of graduate students, undergraduate involvement, and participation of under-represented groups. C-SWEPA enhances the infrastructure for research and education through development of computing capabilities by the science community. By advancing tools for understanding and predicting space weather, C-SWEPA provides important societal benefits enabling expansion of space technologies.

A.2 Objectives, Relevance and Urgency. Acute space radiation hazards pose one of the most serious risks to future human and robotic exploration. Large Solar Energetic Particle events (*SEP events*, including ions; also called Solar Particle Events, SPEs) are dangerous to astronauts and equipment. To mitigate the hazard they pose, we must develop the ability to predict when and where they will occur, and we must provide adequate shielding against them.

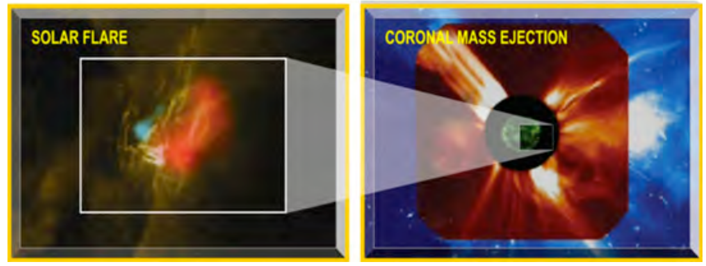

Fig. 1: *C-SWEPA develops a critical new generation of solar and heliospheric models that synthesize remote and in-situ observations, and interlinks models of solar wind, CMEs, energetic particles and their turbulent microstates that drive the magnetosphere. These coupled models predict the effects of energetic particles from flares (left) and CME shocks (right).*

C-SWEPA combines two successful LWS strategic capabilities to produce a synthesis with transformational potential on many fronts. C-SWEPA integrates the Earth-Moon-Mars Radiation Environment Modules [EMMREM, 1], describing energetic particles and their effects, with the Next Generation Model for the Corona and Solar Wind developed by the Predictive Science Inc. (PSI) group. Our goal is to develop a coupled model that describes the conditions of the corona, solar wind, CME shocks, particle acceleration and propagation via physics-based modules.

Assessing the threat of SPEs is a difficult problem. The largest SPEs typically arise in conjunction with X-class flares and very fast (>1000 km/s) coronal mass ejections (CMEs). These events are usually associated with complex sunspot groups (also known as active regions) that harbor strong, stressed magnetic fields. Highly energetic protons generated in these events travel near the speed of light and can arrive at Earth minutes after the eruptive event. The generation of these particles is, in turn, believed to be primarily associated with **the shock wave formed very low in the corona by the passage of the CME** (injection of particles from the flare site may also play a role). Whether these particles actually reach Earth (or any other point) is governed by whether the shock is magnetically connected to the location of interest, which depends the structure of the magnetic field and local shock properties.

Practical threat assessment faces many challenges. The fast arrival time of the most dangerous particles means that a useful prediction must be carried out prior to the actual flare/CME event. Many fast CMEs do not produce significant radiation storms either because few energetic particles are generated or because they miss Earth. To predict energetic particle generation by a CME, a detailed description of ambient conditions (e.g., Alfven speed) is necessary, and the shock propagation from the low corona must be modeled. An acceleration and propagation model for the energetic particles is necessary to estimate particle fluxes. Finally, a radiation transport model is required to estimate radiation dose related quantities.

C-SWEPA's central objective is to develop and validate a numerical framework of physics-based modules to couple the low corona, CMEs, shocks, solar wind, acceleration and composition of energetic particles, and the fluctuations and turbulence within the solar wind that buffets terrestrial and planetary magnetospheres. Using pre-existing EMMREM modules, we characterize time-dependent radiation exposure in interplanetary space environments. C-SWEPA provides a suite of tools to relate remote with *in situ* measurements of solar wind plasma and energetic particles from the low corona and out through the inner heliosphere. The model is set up to consider a wide-array of observers such as spacecraft and planets with trajectories from widely used SPICE files (http://naif.jpl.nasa.gov/naif/toolkit.html). Simulated observers probe the modeled coronal environment, energetic particle fluxes, MHD fluctuations, provide basis for comparison with SolO and SPP observations when they become available and provide valuable tools to explore mission datasets. Simulated observers include the Lagrangian L1 point, ACE, Wind, Earth, planets, and other distributed observers. Results of the coupled model are validated extensively by comparison to data.

C-SWEPA combines two main modules:

- **CORHEL**, for Corona-Heliosphere, a coupled set of models and tools for quantitively modeling the ambient solar corona and solar wind for specific time periods [2,3] using photospheric magnetic maps (built up from HMI magnetograms) as boundary conditions. Versions have been released to the multi-agency Community Coordinated Modeling Center (CCMC) located at NASA's Goddard Space Flight Center and to AFRL at Kirkland Air Force Base. We propose to use CORHEL to model CME eruptions in realistic coronal magnetic fields with candidate CME initiation mechanisms. We link CORHEL with EMMREM to explore the implications of CMEs for particle acceleration at shocks low in the corona and deduce the effects for the space radiation environment.

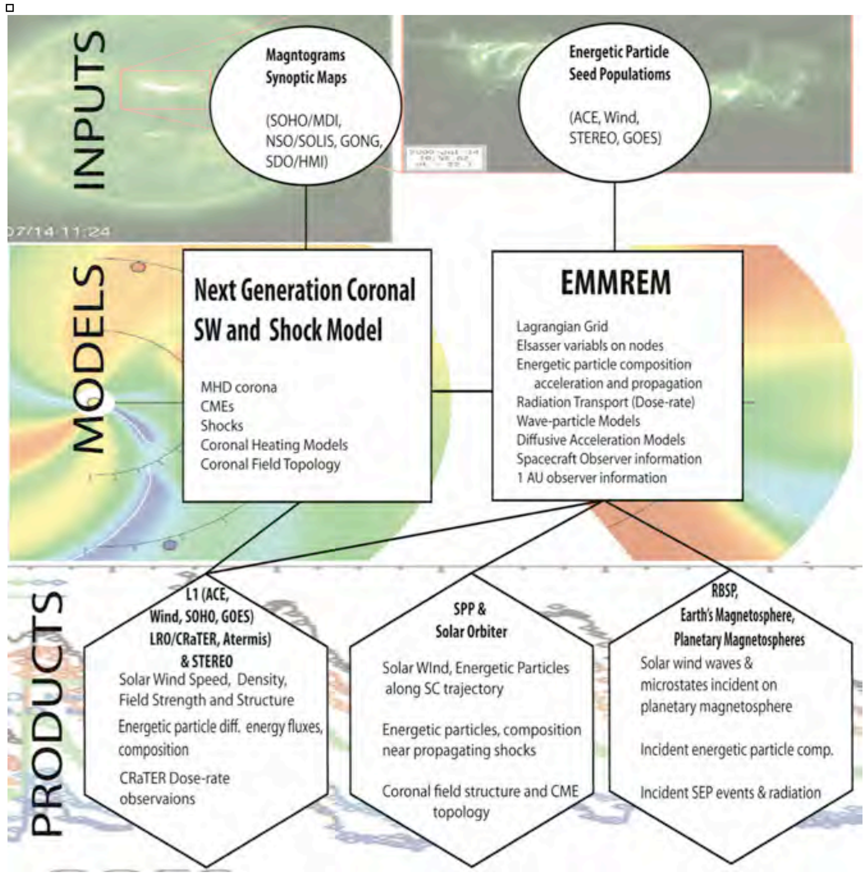

Fig. 2: *C-SWEPA links coronal conditions, transients and drivers of space weather to solar energetic particles, solar wind conditions, turbulence and time-dependent radiation exposure.*

- **EMMREM**, for Earth-Moon-Mars Radiation Environment Module, is a tool to describe time-dependent radiation exposure at Earth, the Moon, Mars, and interplanetary space environments [1]. Versions of EMMREM are running at NASA's SRAG, the CCMC, and produce near-real-time data at UNH. A component of EMMREM is the Energetic Particle Radiation Environment Module (EPREM) that is designed to couple with MHD models [4,5] and compute energetic particle distributions along a 3-D Lagrangian grid of nodes that propagate out with the solar wind. Connected lists of node-lines form magnetic field lines, which enables highly efficient computation of energetic particle distribution functions at each node. EPREM has been used to solve for pickup ion distributions [6,7,8] and energetic particle distributions [e.g., 1,9,10] based on the focused transport equation. The code has been used to span large spatial domains from 0.1 AU to 15 AU, and energies from keV up to relativistic GeV energies, which are important for the assessment of radiation hazards and dose-rates [e.g., 11]. We propose here extension of EPREM for the modeling of shocks, particle acceleration, and the Lagrangian propagation of microphysical plasma variables to characterize solar wind field and plasma fluctuations that impact planetary systems and magnetospheres.

The C-SWEPA project (Fig. 2) is carried out through five primary activities:

1. **Coupling of EPREM to the Next Generation Coronal, Solar Wind and Shock Model for the Modeling of Solar Energetic Particle Acceleration.** EPREM has been coupled to CME models previously [4,5; §A.3.1.2]. This work poses two main challenges: (1) the microphysics of diffusive

shock acceleration requires detailed treatment; (2) the 3-D time dependence of the Lagrangian EPREM grid and the intensive numerical requirements of calculations of focused and diffusive transport require sophisticated numerical treatments that harness the power of massively parallel computations [§A.3.1.3]. Acceleration of high energy SEPs occurs low in the corona [likely 2-3 R_s, 118, 119]. **Thus, it is critical that simulations are capable of describing the global evolution of CME-driven shocks and particle acceleration in the low corona.** The coupling of EPREM to CORHEL proposed here provides predictions of energetic particle intensities and time-histories from detailed 3-D shocks (Fig. 3) driven by CMEs. EMMREM modules are set up to calculate time-

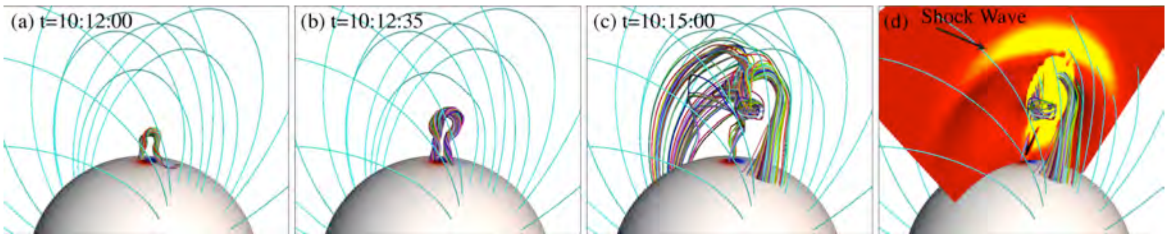

Fig. 3. C-SWEPA links SEP events to their physical origins in eruptive solar magnetic fields*. We show eruption of an idealized active region, developing into a 2500 km/s CME. 3(a-c): magnetic field evolution as the flux rope rises and then interacts with the background magnetic field (time in hr:min:sec). 3(d): same as (c) with a cut plane of radial speed (yellow - high, red - low) superimposed.*

dependent radiation exposure (Linear-Energy-Transfer, LET, spectra and dose-related quantities) based on well-established, working codes including the BRYNTRN and HZETRN code developed at NASA Langley [12] and the HETC-HEDS Monte Carlo code developed at Oak Ridge National Laboratory and the University of Tennessee [13].

2. **Incorporation of energetic particle seed populations and subscale processes involved in diffusive acceleration at shocks.** An EPREM shock finder and a module to describe diffusive shock acceleration at shocks have been implemented [§A.3.1.2]. The diffusive acceleration module specifies parallel and perpendicular diffusion coefficients near the shock to solve for the acceleration rate at the shock. The challenge to C-SWEPA is to build an appropriate self-consistent description of the diffusion coefficients using theories for particle acceleration [14]. Investments already made in incorporating a shock solver and a diffusive acceleration solver within EPREM position us to take the next steps of incorporating a detailed microphysical description of particle acceleration at shocks.

   The suprathermal seed population of energetic particles is key to understanding the fluxes of energetic particles [15]. C-SWEPA makes the links between energetic particles accelerated at CME shocks and suprathermal seed populations. Species dependence has been built in to EPREM [e.g., 6], which facilitates our composition studies.

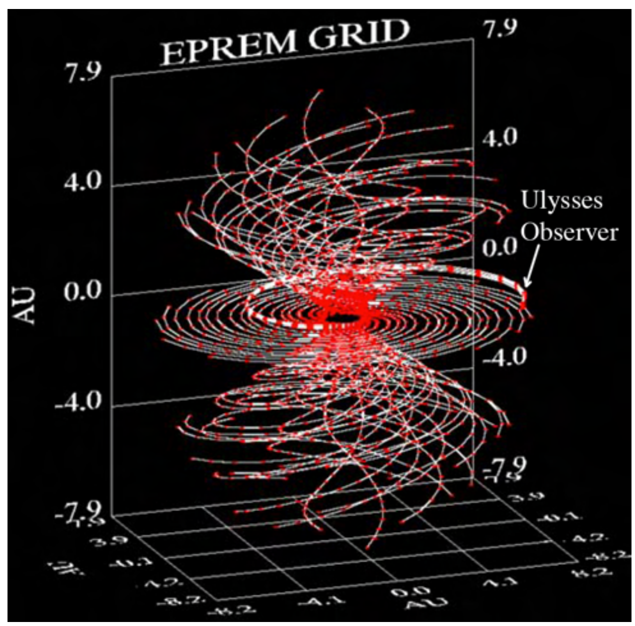

Fig. 4. *In EPREM a three-dimensional system node is followed out with the evolving solar wind to solve the particle transport and acceleration equations. In the node mesh used here, we focus on the ecliptic plane containing the Earth, the Moon, and Mars. The Ulysses spacecraft was also near the ecliptic plane during the observational period studied.*

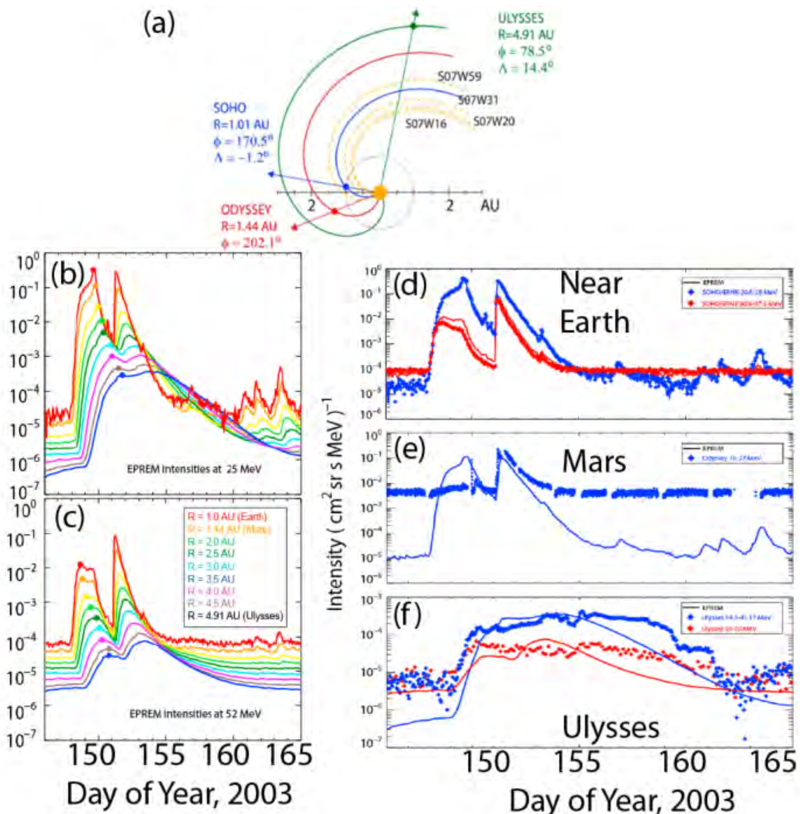

Fig. 5. *Location of Earth (SOHO), Mars (Odyssey), and Ulysses in heliographic coordinates on 28 May 0000 UT (DOY 148), looking down from the north pole at the ecliptic plane. Solid spirals represent the nominal magnetic field lines connecting each observer to the Sun, and the dashed lines represent the magnetic field lines connected to the active regions responsible for the four flares, whose X-ray-associated locations on the solar disc with respect to Earth are also shown.* ***As shown, EMMREM is in excellent agreement with observed data at the three different locations.***

3. **Validation at L1 and Heliospheric Observers.** EPREM incorporates observer histories and profiles. Fig. 4 shows an example of the EPREM grid at low resolution. Note the field lines that follow the Ulysses observer at all times. All spacecraft, satellites, planets, asteroids can be embedded as observers into EPREM with positional information described by SPICE kernels. Fig. 5 shows an example where we compare EPREM simulations near Earth (SoHO), Mars (Odyssey) and Ulysses. We have used EPREM in validation studies near Earth, Mars, Ulysses, and at other spacecraft including Helios, Messenger, SOHO, STEREO, New Horizons, and Cassini. We propose validation studies in C-SWEPA focusing on energetic particle composition and its relationship to flares, shocks and solar wind fluctuations at L1 observers (e.g., ACE, Wind, SoHO), STEREO, and other spacecraft.

4. **Simulated observer data at SPP and Solar Orbiter (SolO).** Probing the inner boundary of the solar wind with SPP and SolO are next steps in understanding our solar corona, its link to the solar wind, and the origin of CMEs, flares, shocks and SEPs. C-SWEPA uses simulated SPP and SolO hypothetical mission profiles and develops a series of event scenarios, observer histories (fields, solar wind, turbulence, suprathermal ions and SEPs including composition) to emulate data products, test modes of operation, and prepare for scientific analysis. Data sets are developed for a range of quiet, disturbed, CME and shock scenarios. Incorporation of mission profiles provides an important utility to maximize the science return from both missions.

5. **Inertial (radial) node lines, solar wind micro-states and RBSP.** The intensities of Earth's radiation belts are known to vary with solar wind conditions. During periods of high solar wind speed, which is also typically accompanied by enhanced variability in solar wind dynamic pressure, electron intensities in the outer zone radiation belt tend to be enhanced. When variations in the solar wind dynamic pressure cause the magnetosphere to contract and expand on time scales comparable to the third-invariant drift time of electrons trapped in the belts, then such resonant conditions can lead to particle diffusion in energy and in space. These effects have been quantified with simplified models of convected solar wind turbulence used to drive global magnetospheric MHD models [16,17]. *The RBSP mission will need to understand the external drivers of the magnetosphere, including the time history and spatial structuring of the solar wind that sweeps past and ultimately drives it.* In order to address this and other questions of solar wind microstructure, C-SWEPA

expands on the utility of node-connected field lines in EPREM by adding inertial lines of nodes along near-radial trajectories [§A.3.1.2]. These inertial nodes, following plasma parcels, will be used to investigate the sources and propagation of density structures on scales that resonate with the pumping of the magnetospheric radiation belt. This additional grid of plasma nodes enables C-SWEPA to develop stringent new tests of shear-generated solar wind turbulence models, as described in §A.3.2.4.

Relevance and Urgency. We are preparing for exploration beyond low-earth orbit, where accurate risk assessment due to the radiation environment is critical. As space becomes increasingly utilized for satellite technologies, the imperative for understanding and predicting the space environment becomes increasingly urgent. These realities reinforce incentives for the LWS and National Space Weather Program to develop predictive capabilities for radiation hazards that pose among the most significant risks to robotic and human exploration. C-SWEPA is urgently needed to develop tools to predict the hazards formed from flares, shocks and CMEs. C-SWEPA is broad and deeply relevant to National, NASA, NSF and LWS objectives (Blue Box). Further, the scientific depth of the project advances prediction, characterization, and NSF, NASA and HEOMD leveraged assessment capabilities while also advancing exploration and understanding of the detailed relationships between energetic particles, shocks, turbulence and evolving space plasmas.

C-SWEPA Relevant and Urgent for National, NASA, NSF and LWS Objectives

- The objectives of C-SWEPA directly address the primary goal of NASA's LWS TR&T program, stated as "the *development of first-principles-based models for the coupled Sun-Earth and Sun-Solar System"*. Such models act as tools for science investigations, as prototypes and test beds for prediction and specification capabilities, as *frameworks for linking disparate data sets at vantage points throughout the Sun-Solar System, and as strategic planning aids for enabling exploration of outer space and testing new mission concepts*." C-SWEPA brings together successful LWS TR&T projects and members of LWS focus teams, and CoIs on Solar Orbiter, Solar Probe Plus and the Radiation Belt Storm Probe Mission.
- C-SWEPA is a fundamental development of basic research that capitalizes on a variety of Geospace Sciences: "The Geospace Sciences Section … (NSF), in collaboration with the NSF Office of Polar Programs, … (AFOSR), and … (ONR), funds basic research in support of national space weather objectives. *This includes the development of space weather models for specification and forecast of conditions throughout the space environment. "*
- Major advances made over the last decade in physics-based numerical modeling of the coupled Sun-to-Earth system now provide meaningful opportunities to use models in a predictive sense. *Many agencies have prioritized predictive capabilities to serve their user communities [Spence et al., 2004], including NOAA's Space Weather Prediction Center and NASA's Space Radiation Analysis Group at Johnson Space Center*. An accurate warning system for SEP radiation hazards is critical in view of NASA's plans to send astronauts beyond low-Earth orbit. Demonstrating this commitment to the future of human exploration, NASA officially named the Multi-Purpose Crew Vehicle that could take its astronauts back to the moon, to Mars and to asteroids [see 20, NASA, 2011]. However, space radiation remains a major factor [11, *Cucinotta et al.,* 2010].
- C-SWEPA 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*".
- C-SWEPA makes the connection of LWS's advancing enterprise of scientific exploration and discovery to a practical module to understand the space environmental conditions experienced by human and robotic explorers. C-SWEPA is thus critical 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 …".*
- C-SWEPA is 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.

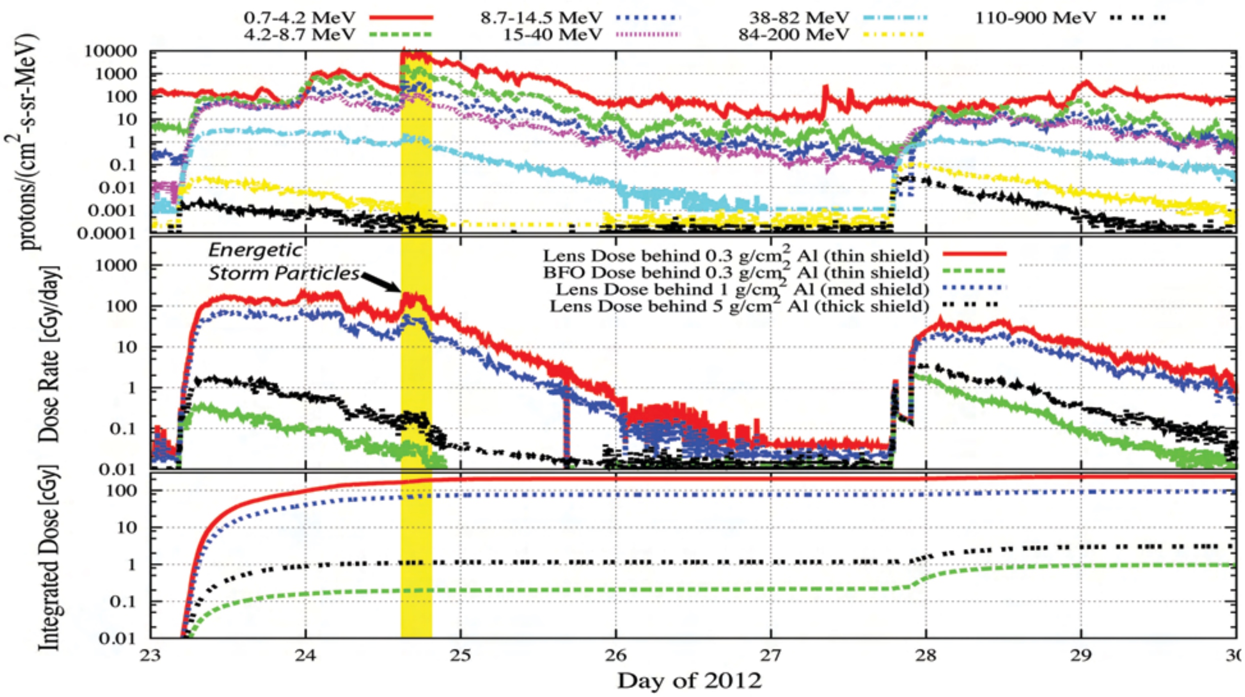

Fig. 6*. The Jan. 23 and Jan. 27 2012 SEP events demonstrate the clear need for C-SWEPA, which incorporates SEP acceleration within space weather frameworks that simulate CMEs and CME-driven shocks. The EMMREM-calculated doses for these events begin with a flare from an active region NW of central meridian. This provided both a magnetic connection near Earth and also a halo CME with a shock and energetic storm particles (ESP) that passed by Earth. The doses for the event were quite large (~200 rad behind thin shielding). The second event on Jan. 27 from the same active region occurred when it reached the NW limb, but only a flare was observed at Earth. An associated weak shock arrived at Earth, but the CME only glanced this region. Nevertheless, the seed populations and turbulence in the wake of the first event likely created conditions that led to the harder energy spectra and higher doses behind thick shielding during the 2nd event.*

Near real-time data products and the CCMC. Both the EMMREM and CORHEL teams have delivered their models to the CCMC where they can be run on demand. Both teams recognize the need to run models flexibly and to supply data products that serve space weather needs across the heliophysics community. To this end, the CORHEL team has delivered new scripts to the CCMC allowing a more intuitive interface to their model. The EMMREM team has recently developed the capability to run the model in near-real-time (Fig. 6 shows recent results of the near-real-time model). This work is currently supported in collaboration with CRaTER by the HEOMD. EMMREM has also linked to a real-time forecasting system called the Relativistic Electron Alert System for Exploration (REleASE), which after one year of operation at partner institutes at the University of Kiel and at NASA's CCMC, were yielding low false alarm rates and sensitivity to relatively small events [116,117]. REleASE provides the basis for a real-time operational SEP warning system. We are currently using CRaTER observations (SEP radiation dose) along with the REleASE model and COSTEP observations from SOHO (which measures relativistic electrons) to verify, validate, and refine the REleASE model [114]. The goal is to improve the reliability and thus value of the REleASE model toward realizing the up to 1-hour forecast of SEP events, a critical improvement over current forecasting. Results of the near-real-time data sets from EMMREM and the dose-rates based on REleASE energetic particle fluxes are currently available on the EMMREM website (http://emmrem.unh.edu/) and through the CCMC. **The C-SWEPA team is strongly committed to working with the CCMC to provide useful data products and model capabilities.**

Requirements. The major hurdle to C-SWEPA is creation of online resources allowing users to run event scenarios and rapidly estimate integrated event doses, which drives the following requirements:

1. Simulations must characterize the physical evolution of CME-driven shocks and related particle acceleration in the low corona.
2. The model must be available on-line and provide event scenarios from Sun-to-Earth.
3. These event runs will include the CME, its shock, energetic particle flux time series, and dose-rates, dose-equivalent rates and integrated doses behind various layers of shielding (see Fig. 6).
4. The forms for on-line input must be scripted with an intuitive user-interface.
5. Results of runs must be available to the public and not tied to individual users. In other words, during SEP events, users should be capable of seeing what simulations are running and what results look like. We anticipate that one or several users launch simulation runs that rapidly give many users a sense of the risks posed by the event.
6. The model must be capable of running at both the CCMC, at UNH, and at other facilities depending on the demand. As detailed in the section on deliverables, we plan to build several machines that include GPUs and deliver one of these machines to the CCMC along with documentation for running the coupled model.

Deliverables. The concept for C-SWEPA is the development of several computers that run C-SWEPA, documentation of the coupled tools, and an intuitive interface for the model. The C-SWEPA requirements place new stringent constraints on the deliverable.

EMMREM has been parallelized for GPU computing with increased efficiency by a factor of x120 with less than 4 months of development. This enormous increase in computational efficiency demonstrates the vast potential of GPU computing leveraged in the C-SWEPA project. However, GPU platforms are not traditionally supported by the CCMC. The procurement of the necessary hardware at the CCMC is detailed in negotiation with the CCMC in the first year of the project. Peter MacNeice, CCMC staff member and C-SWEPA CoI, facilitates transfer of hardware and serves as a liaison between the CCMC and the C-SWEPA team. Adequate funds have been allocated so that two identical GPU computing systems are procured: one at UNH and one at the CCMC. Therefore, the development of C-SWEPA on a GPU-enabled computer allows the increased computational efficiency required for sophisticated EMMREM simulations.

CORHEL simulations are currently supported at the CCMC and appropriate interfaces for these simulations are developed in the C-SWEPA project. Further, the C-SWEPA team explores implementation on GPU-enabled systems. Finally, the C-SWEPA team delivers CORHEL event data sets from supercomputer runs for integration with EMMREM on the CCMC and UNH GPU systems.

The deliverable is designed with straightforward interfaces so that simulations can be performed quickly based on well-described parameters for CME initiation, suprathermal seed populations in the low corona, and observational inputs such as synoptic maps. The effort is greatly simplified because C-SWEPA integrates routines that have already been developed and coupling between the EPREM and shock-capuring MHD routines has been achieved.

Transformational Aspects of C-SWEPA. C-SWEPA is an advanced computational tool that has dual transformational potential for scientific research and situational awareness:

- C-SWEPA integrates advanced computational tools for CME initiation, shock formation and energetic particle acceleration so that we may develop predictive understanding of the implications of solar events. C-SWEPA improves our awareness of the hazards posed by solar disturbances that are particularly important as the solar activity increases. *Scientifically, this work allows us to develop deeper understanding of the efficacy of shocks for particle acceleration, the accuracy of self-consistent descriptions of particle acceleration at shocks including the wave-particle interactions, and the 3-D and time-dependent aspects of particle acceleration and radiation hazards.*
- The EPREM code allows incorporation of multiple species of energetic particles, which is critical for discovering how different seed populations such as flare-accelerated ^{3}He are re-accelerated by shocks in the corona and inner heliosphere. This capability was exploited in the study of pickup ions [6,7,8] for comparing the acceleration of solar wind species (e.g., H^+ and He^{++}) versus interstellar

pickup ions (e.g., He^+) that are introduced into the solar wind beyond ~0.5 AU. This comparison demonstrated definitively that the pickup ion acceleration process is active well beyond 0.5 AU. In C-SWEPA, we utilize the capability of EPREM for description of many populations to explore how pre-existing seed populations from flares and other sources [e.g., 15, 21] are re-accelerated by CME shocks. *C-SWEPA thus delivers a wealth of information on seed populations that were never before modeled to discover the implications for shock acceleration in the low corona and inner heliosphere.*

- C-SWEPA makes a fundamental Sun-Earth connection by incorporating highly resolved Earth-connected (or "observer"-connected) inertial lines populated with nodes that cross the magnetosheath on short timescales (~ minute). The nodes along these inertial lines track the evolution of density and the microstate in the wind, thus connecting conditions in the low corona with the microstate of solar wind that pumps and disturbs the magnetospheres. C-SWEPA thus leverages the unique Lagrangian properties of the EPREM grid to deliver *new fundamental information that will be vital to studies of the magnetosphere, RBSP, of other planetary magnetospheres and the microstates and turbulence within the solar wind.*
- C-SWEPA incorporates a variety of observers based on the SPICE kernels of Spacecraft including the Earth, Moon and Mars, L1 observers (ACE, SoHO, Wind), STEREO, New Horizons, Cassini, Ulysses, LRO and other observers including planets, satellites, comets and asteroids. This capability has been used extensively in past studies involving EMMREM. *The existing capability will be heavily leveraged to compute sample histories of solar wind, CMEs, shocks, energetic particle and microstate and turbulence histories for the SPP and SolO missions. These histories provide a vital resource for the planning and data analyses of both missions.*
- *C-SWEPA leverages a new, powerful GPU computing capability and develops a new mode for the successful delivery of models and their operation at the CCMC and other modeling and data centers such as the Space Weather Prediction Center (SWPC) and the NASA, JSC Space Radiation Analysis Group (SRAG).* By delivering a platform specifically designed for C-SWEPA, we provide both a new computational resource and avoid platform-dependent issues that can cripple the implementation of complex models at modeling centers.

C-SWEPA's commitment to sharing resources and serving the Heliophysics and Space Physics community. In complex projects such as C-SWEPA, there is a balance between a model's flexibility and the development of specific operating frameworks that serve broad needs of the scientific community. It is critical that C-SWEPA remain open to collaborations across the community so that resources may be utilized in new and innovative ways. The C-SWEPA team is strongly committed to sharing its model and facilitating collaborations that explore wide-ranging scientific applications.

Connections to LWS TR&T Focused Science Topic (FST) Teams. In the first year, the C-SWEPA team arranges one or more joint meetings with relevant FSTs and creates strong modes of interaction and communication with these FSTs. Several members of our team have participated in LWS TR&T Focus Science Topic (FST) Teams over the past five years, and three members of our collaboration (Lee, Mikic, and Torok) are currently FST-Team members. Our connections to these FST Teams will help our project, and these FST teams, in a number of ways. For example, one of the 2011 FST Teams is led by Dr. Nat Gopalswamy of GSFC to investigate "Factors that Control the Highly Variable Intensity and Evolution of Solar Particle Events" during the next four years. Co-Investigator Martin Lee is a Grant-PI member of this Team, which consists primarily of solar energetic particle (SEP) observers and data analysts with access to decades of SEP measurements throughout the heliosphere. Although the emphasis of this particular FST is on the extreme variability of SEP events, this feature of SEP events cannot be isolated from a detailed investigation of all aspects of these complex events. The complexity of SEP events arises, for example, from the geometry of the heliosphere and its magnetic field, a possible superposition of particles accelerated at a solar flare and those accelerated by the associated CME-driven shock, the mechanism(s) controlling particle escape from the acceleration region or CME-driven shock, and injection rates of solar wind plasma at a shock wave. Understanding the variations and evolution of SEP events in the context of such complications will certainly be enhanced by the capabilities of EPREM, which can model global geometry, the interplanetary magnetic field, injection rates, and wave excitation and its effect on transport and acceleration timescales. Conversely, the analysis of SEP data within the FST Team leads to quantitative descriptions of SEP events, statistical studies of similar events, and insights into SEP acceleration and transport, which will all influence our implementation of EPREM and provide test cases for study.

The C-SWEPA Team. C-SWEPA builds a highly multidisciplinary team needed to attack a problem that spans and integrates solar and heliospheric science involving solar wind turbulence and acceleration, CME initiation, shock formation, energetic particle acceleration and associated hazards. *The proposed team covers all of the key elements in modeling and observations of solar eruptions, SEP acceleration and transport, and magnetospheric implications of solar wind disturbances and fluctuations.*

Table 1 lists key personnel, affiliations, roles and expertise to outline their contributions to the overall C-SWEPA team as described generically above. PI Nathan Schwadron (UNH) is responsible for the overall project and its scientific outcomes. The MHD lead Jon Linker (PSI), CoPI, will coordinate technical development and deliverables. The project is organized into four science subgroups representing the major areas linking the **Corona and Solar Wind (science lead Chandran), CME Initiation and Shocks (science lead Riley), SEP Acceleration and Propagation (science lead Lee), Solar Wind Waves and Turbulence (science lead Isenberg).** Each science subgroup draws on senior experts (see chart below), junior scientists, graduate students, and undergraduates at team institutions. Core team members already have significant experience working together successfully on similar, multi-institution projects such as CISM, EMMREM, and CORHEL. Many of the current C-SWEPA team members participate on the NSF Sun-to-Ice project. The related scientific investigations into extreme events are leveraged by C-SWEPA for developing a more complete end-to-end understanding of the effects of large SEP events.

Table 1: *The C-SWEPA team is ideal, covering all key elements in modeling and observations of solar eruptions, SEP acceleration and transport, and magnetospheric implications of solar wind disturbances and fluctuations.*

Key Investigators, Institutions, and Titles	**"C-SWEPA" Role(s) and Expertise**
Ben Chandran, UNH, Prof.	CoI: **Solar Wind Science Lead**
John Cooper, GSFC Space Scientist	CoI: Energetic Particle Modeling and Data Analysis
Mihir Desai, SwRI, Staff Scientist	CoI: SEP observations and analysis
Kai Germaschewski, UNH, Assoc. Prof.	CoI: GPU development, coupling
Joe Giacalone, UAz, Assoc. Professor	Collab: SEP modeling
Matt Gorby, UNH, Inf. Tech. III	Key Personnel: GPU & Code development
Phil Isenberg, UNH, Prof.	CoI: **Waves and Turbulence Science Lead**
Justin Kasper, SAO-CfA	CoI: Validation from Wind, SPP and SolO studies
Kelly Korreck, SAO-CfA	CoI: SEP Modeling, SDO Validation
Kamen Kozarev, SAO-CfA	Post-Doc, Key Personnel
Marty Lee, UNH, Prof.	CoI: **SEP Science Lead**
Noe Lugaz, UNH, Researcher	CoI: CME Initiation and Shock Formation
Jon Linker, PSI, Pres, Senior Scientist	CoPI: **CORHEL Lead**, CME initiation and evolution
Roberto Lionello, PSI	CoI: CORHEL, solar wind, CMEs, shocks
Zoran Mikic, PSI, Senior Scientist	CoI: CORHEL, solar wind, CMEs, shocks
Peter MacNeice, CCMC Staff	CoI: CCMC liason
Pete Riley, PredSci CFO, Senior Scientist	CoI: CORHEL, **CME Initiation Science Lead,** validation
Nathan Schwadron, UNH, Assoc. Prof.	PI: **EMMREM Lead, Integration Lead**
Harlan Spence, UNH, EOS Director & Prof.	CoI: Magnetosphere Connection; Solar Wind Structure
Sonya Smith, UNH, Project Manager	Key Personnel: C-SWEPA Project Manager
Mike Stevens, SAO-CfA	CoI: L1 Validation Studies (e.g., Shock Structure)
Vitcheslav Titov, PSI	CoI: CORHEL, Solar Wind, CMEs, Shocks
Tibor Torok, PSI	CoI: CORHEL, Solar Wind, CMEs, Shocks

A.3 Technical Approach

A.3.1 C-SWEPA Model.

A.3.1.1 CORHEL (Fig. 7) is a suite of coupled models and tools for describing the solar corona and solar wind developed by the team at Predictive Science, Inc. (PSI). Currently, CORHEL delivers solutions to the community via four customers at the present time: the CCMC, the NSF CISM project, the PSI modeling web site (www.predsci.com), and AFRL at Kirkland Air Force Base in Albuquerque. CORHEL is a series of Bash-shell scripts that link together different (primarily magnetohydrodynamic [MHD]) codes. The 3D MHD codes are written in Fortran and achieve parallelism using the Message Passing Interface (MPI). The Magnetohydrodynamic Algorithm outside a Sphere (MAS) code, in particular, has been shown to scale efficiently on thousands of processors.

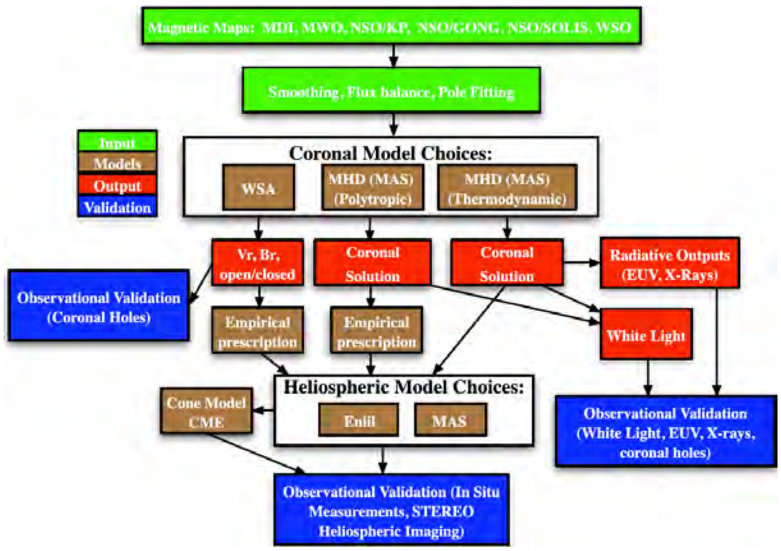

Fig. 7. CORHEL combines a complete set of MHD, field, and coronal solvers to describe solar wind, CMEs and associated shocks. Green boxes indicate the primary input: data from measured solar magnetic fields. The coronal module encompasses three choices: WSA runs for immediate answers from a baseline model, polytropic MHD for quick turnaround runs, and thermodynamic MHD for the most physically realistic description. Red indicates coronal model output, including simulated emission and white light images. Coronal model solutions are fed into the heliospheric model (two choices) using either empirical prescriptions for the velocity, density, and temperature or directly driven by outputs from the thermodynamic coronal model.

CORHEL develops MHD solutions from the low corona out through the heliosphere. CORHEL is divided into coronal and heliospheric domains, allowing different codes and approximations in each domain. The primary input data to CORHEL are synoptic maps of the photospheric magnetic field from observatories (e.g., SOHO MDI, NSO SOLIS, NSO Gong, and HMI aboard SDO).

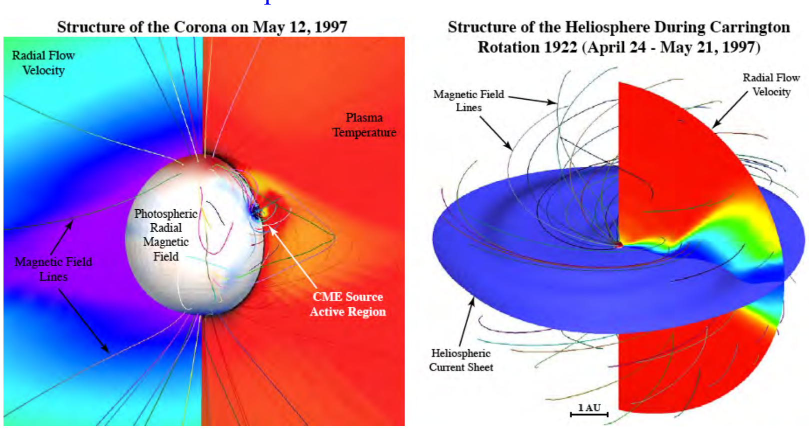

***Fig. 8.** CORHEL provides complete MHD models of the corona, shown here prior to the May 12, 1997 CME. (left) Magnetic field lines, plasma temperature, and velocity, together with the radial magnetic field at the photosphere. (right) Plasma velocity, heliospheric current sheet, and magnetic field lines in the heliospheric simulation.*

The team at Predictive Science has a long legacy of developing MHD models of the structure and dynamics of the solar corona and inner heliosphere [22-28]. The incorporation of a realistic energy equation that accounts for anisotropic thermal conduction, radiative losses, and coronal heating allows the plasma density and temperature to be computed with sufficient accuracy to simulate extreme ultraviolet (EUV) and X-ray emission observed from space. Fig. 8 shows the state of the solar corona and inner heliosphere for Carrington rotation (CR) 1922 (April 24, 1997 - May 21, 1997) and provided the background state into which the well-studied May 12, 1997 CME erupted [29-33]. The coronal solution on the left was computed with the MAS code. The heliospheric solution was generated using the MAS heliospheric model, with values from the coronal solution providing the boundary conditions. Accurate modeling of the plasma density is crucial for determining the Alfven speed (V_A) in the corona, which strongly influences where SEP acceleration begins. For example, Fig. 9 shows the simulated Alfven speed of the corona prior to ejection of a CME (May 13, 2005) with a speed of 1700 km/s was ejected from the active region, where the Alfven speed was large.

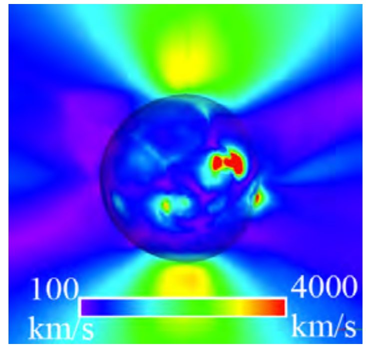

Fig. 9. *CORHEL accurately captures the Alfven speed (V_A) prior to the May 13, 2005 CME, which is critical for determining where shocks form and SEP acceleration begins. The region of high V_A > 10,000 km/s is the active region where the CME was launched.*

<u>*A.3.1.2 EMMREM*</u> (Fig. 10) is a numerical module for characterizing time-dependent radiation exposure in the Earth-Moon-Mars and interplanetary space environments [1]. A version of the code has been released to NASA's SRAG and the CCMC. The EMMREM framework is written in C, Bash and Perl. The primary modules of EMMREM are the Energetic Particle Radiation Environment Module (EPREM), the Baryon Transport Module (BRYNTRN), and High Z and Energy TRaNsport (HZETRN) code for radiation transport through planetary atmospheres. EPREM solves for the propagation and acceleration of energetic particles in the evolving magnetic fields of the inner heliosphere with input based on observations from satellites. It is written in C and parallelized with MPI. BRYNTRN 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. It is written in Fortran. EMMREM takes input based on solar energetic particle observations or simulations, propagates observed time series through the inner heliosphere, and derives the differential energy flux, dose-rate and Linear Energy Transfer time series at observers (satellites, planets, etc.) within the code. Figs. 5,6,11,13,15 show examples of the EMMREM system run to determine fluxes and dose rates in the inner heliosphere.

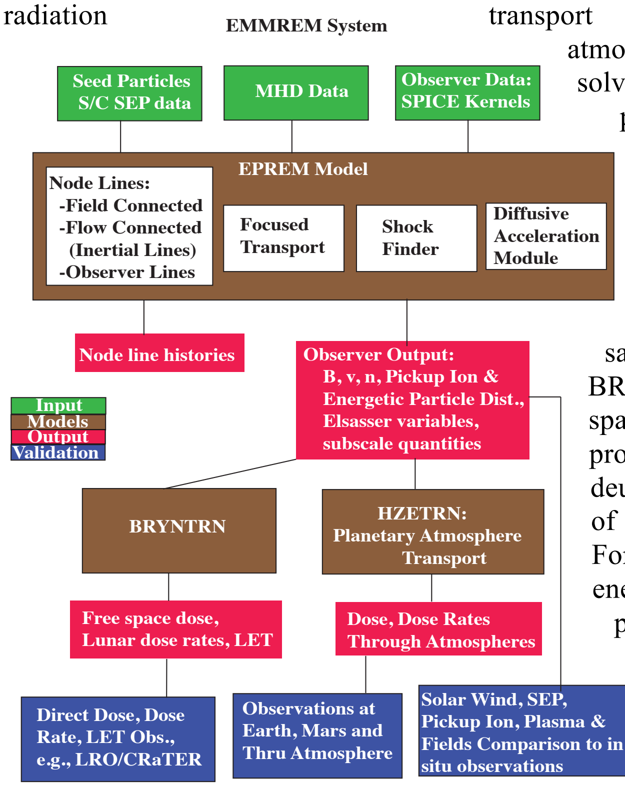

Fig. 10. *The EMMREM framework is designed to characterize time-dependent energetic particle differential energy fluxes, radiation doses, LET spectra and transport through planetary atmospheres. EMMREM couples with MHD models to solve diffusive acceleration at shocks and can compute time dependent subscale quantities on its propagating nodes to characterize subscale physics.*

The EPREM code builds up solutions through several key elements. (1) Nodes are propagated out through the inner heliosphere based on the local solar wind velocity [see Fig. 4]. These nodes are introduced on the inner boundary from fixed source locations (lat. and long.) that rotate with the Sun. Therefore, the lines of nodes that connect to a given source region trace out magnetic field lines in the inner heliosphere. (2) These Lagrangian node-lines that trace the magnetic field facilitate the solution of the focused transport equation [1]. Figs. 11 and 12 exemplify this approach to modeling SEP fluxes during the 2003 Halloween storms. Fig. 13 shows the EMMREM doses predicted from these events.

The details of the particle scattering process are controlled by a pitch-angle scattering term contained within an EPREM module. The module allows considerable flexibility in defining the analytical form for pitch-angle scattering, including energy dependence, time dependence, dependence on local conditions such as the anisotropy of the distribution function, and on composition (e.g., mass-per-charge). This flexibility is vital to developing self-consistent descriptions of particle acceleration and propagation.

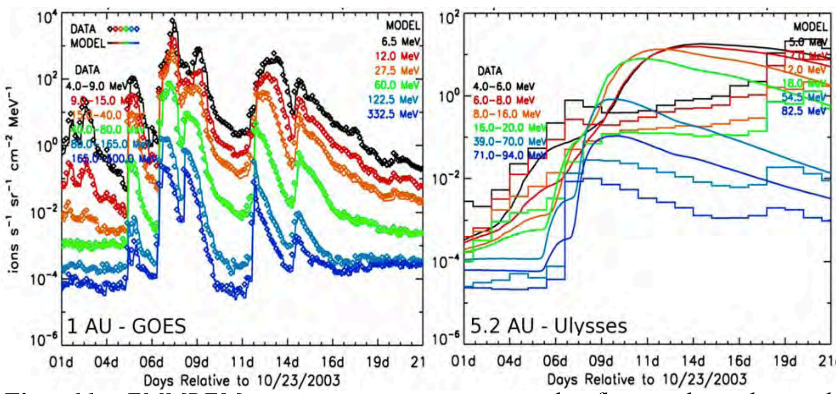

Fig. 11. EMMREM projects energetic particle fluxes throughout the heliosphere along node-connected field lines using the focused transport equation [1] (left). The 1 AU observed fluxes and (right) the particle fluxes integrated out to Ulysses are plotted with the observed daily averaged proton fluxes. In this complex event, the Ulysses connected field line is about 20° off of the Earth-connected field line. Nevertheless, the EMMREM-predicted event onset and integrated fluxes are comparable to those observed by Ulysses.

EPREM has been successfully coupled to 3D MHD simulations using interpolation of the MHD solution to the EPREM nodes [4,5]. This coupling offers unique opportunities for modeling particle acceleration from MHD shocks and propagation along the disturbed field lines in time-dependent 3-D solar wind models [5]. EPREM incorporates a shock finder that determines the upstream, downstream, shock location, and directionality at every timestep of a run by searching for large changes in the flow speeds along EPREM node-lines. EPREM also incorporates a particle acceleration solver that accurately models diffusive processes at the shock occurring on scales that may become smaller than the EPREM and MHD grids. The numerical particle acceleration solver develops a discrete, time-dependent solution to the Parker transport equation under the influence of the upstream and downstream solar wind conditions [a similar approach to 34]. The time-dependent solution has one free parameter, an integration length across the shock, δx, which we find to be related to the acceleration rate, $dp/dt = (p/3)\,[(u_1-u_2)/3]\,(1/\delta x)$. Here, p is he energetic particle relativistic momentum, and u_1 and u_2 are the normal components of the up- and down-stream solar wind speeds relative to the shock. The diffusive acceleration rate [e.g., 35] at the shock is given by $dp/dt = (p/3)\,[u_1^2\,(r-1)/r]\,(1/\kappa_{xx})$ where the compression ratio is $r= u_1/u_2$ and the diffusion coefficient is given by κ_{xx}. Therefore, diffusive shock acceleration theory requires that the integration length is $\delta x=\kappa_{xx}/u_1$. Detailed shock interactions including self-generated waves and cross-field diffusion [35,39,40] are captured by dependencies in the diffusion coefficient κ_{xx} on the distribution function, energy and distance.

Fig. 12. EMMREM's 3-D grid is critical for interpreting time histories and radiation exposure in large events. Shown here is the configuration of the 2003 Halloween events (left). Location of the largest 5 flares (dashed lines) associated with this series of events, the Earth-connected field line (blue), Mars connected field line (green), and Ulysses connected field line (red) (right). Overall field configuration out to Ulysses shows that Ulysses, Mars, and Earth are well aligned.

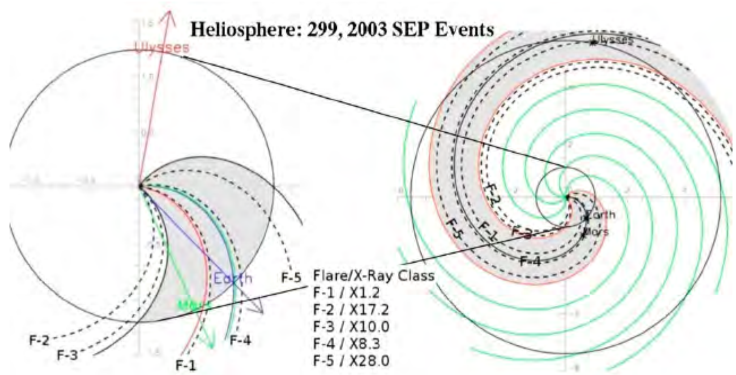

Fig. 14 shows an MHD-coupled EPREM run in which we simulated the May 13, 2005 CME event using results from BATS-R-US [42]. An MDI synoptic magnetogram for CR 2029 (April-May 2005) initialized the steady state solar wind based on an empirical flux expansion model [36]. An out of equilibrium flux rope was then inserted in an active region near the equator to simulate the CME initiation. Diffusive shock acceleration was modeled employing a constant parallel scattering mean free path of 0.01 AU. For every energy bin, the model calculates the injection speed [37]. If particle speeds are lower than the injection speeds, the model reverts to the usual case of focused transport. Pile-up in the sheath traps some particles with energies <10 MeV. We used quiet time ^{4}He ion (0.1-0.5 MeV/nuc) observations from ACE/ULEIS for the suprathermal pre-event spectrum [38]. We converted the spectrum to protons at 10 R_s assuming the flux is scaled to 1.6 R_s via an inverse-square dependence, and a He/H ratio of 10%. The simulation spans ~90 minutes. During the first 26 minutes, a steady state solar wind description was maintained, after which the time-dependent MHD solution was used. The result demonstrates the capabilities of EPREM for modeling diffusive shock acceleration when coupled with an MHD code. The abrupt rise-time is associated with shock acceleration low in the corona during the rapid lateral expansion of the CME. Both observers (on the CME's flank and nose) observe an impulsive signature associated with this expansion. Only the observer on the nose detects sheath passage near the end of the simulation where the highest fluxes of high-energy (10-50 MeV) ions are observed in association with the IP shock passage. By coupling the state-of-the-art MHD model (CORHEL) with EMMREM, C-SWEPA takes the next logical step needed by the Space Weather community to predict doses associated with intense SEP radiation.

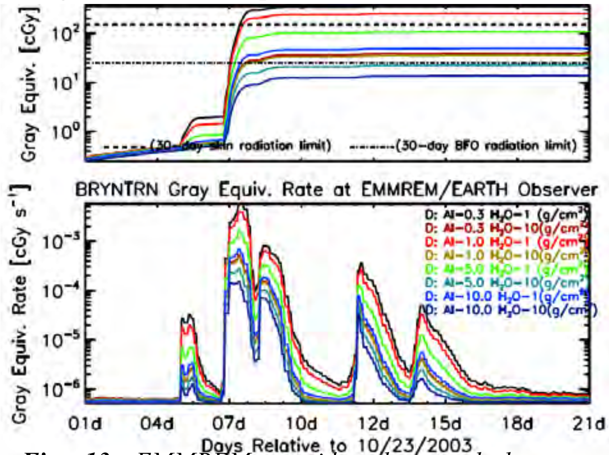

Fig. 13. EMMREM provides dose and dose rate calculations allowing detailed risk assessment from SEP radiation events (top). Accumulated doses and (bottom) dose rates near Earth during the 2003 Halloween events with proxies for skin/eye dose (1 g/cm^2 H_2O) and doses in BFO (10 g/cm^2 H2O) behind 0.3, 1, 5, and 10 g/cm^2 of shielding.

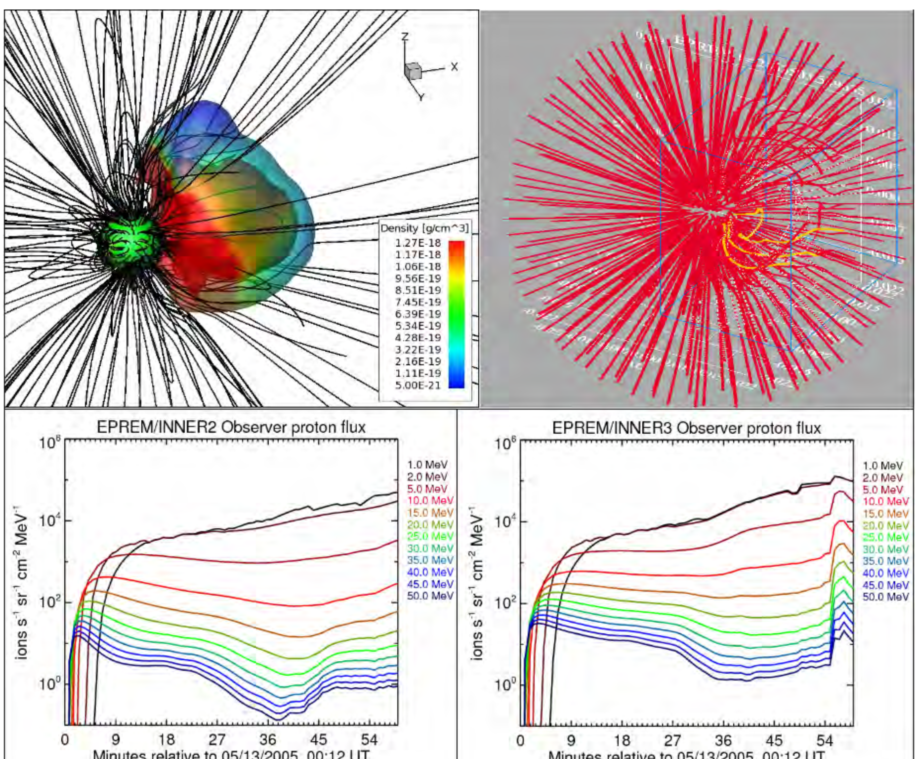

Fig. 14. Diffusive shock acceleration modeled with the MHD-coupled EPREM code. Magnetic field lines (top left) for the May 13, 2005 CME with density enhancements in the shock sheath (color contours). Nodes are shown (red, top right); MHD box in blue, and observer-connected field lines (yellow). Flux time series for two observers at 8 Rs (bottom) – near nose (right bottom) and E flank (bottom left) of the CME. Shock passage occurs near end of the simulation.

The EMMREM team has also applied its tools to other models (Fig. 15). Any modeled SEP event can be fed into the BRYNTRN code to calculate the Earth, Moon and Mars environmental radiation. Interestingly, the modeled doses investigated by EMMREM all represent extremely hazardous events. C-SWEPA performs investigations using a wide variety of events to understand the underlying physics of particle acceleration that creates the variability seen in SEP events.

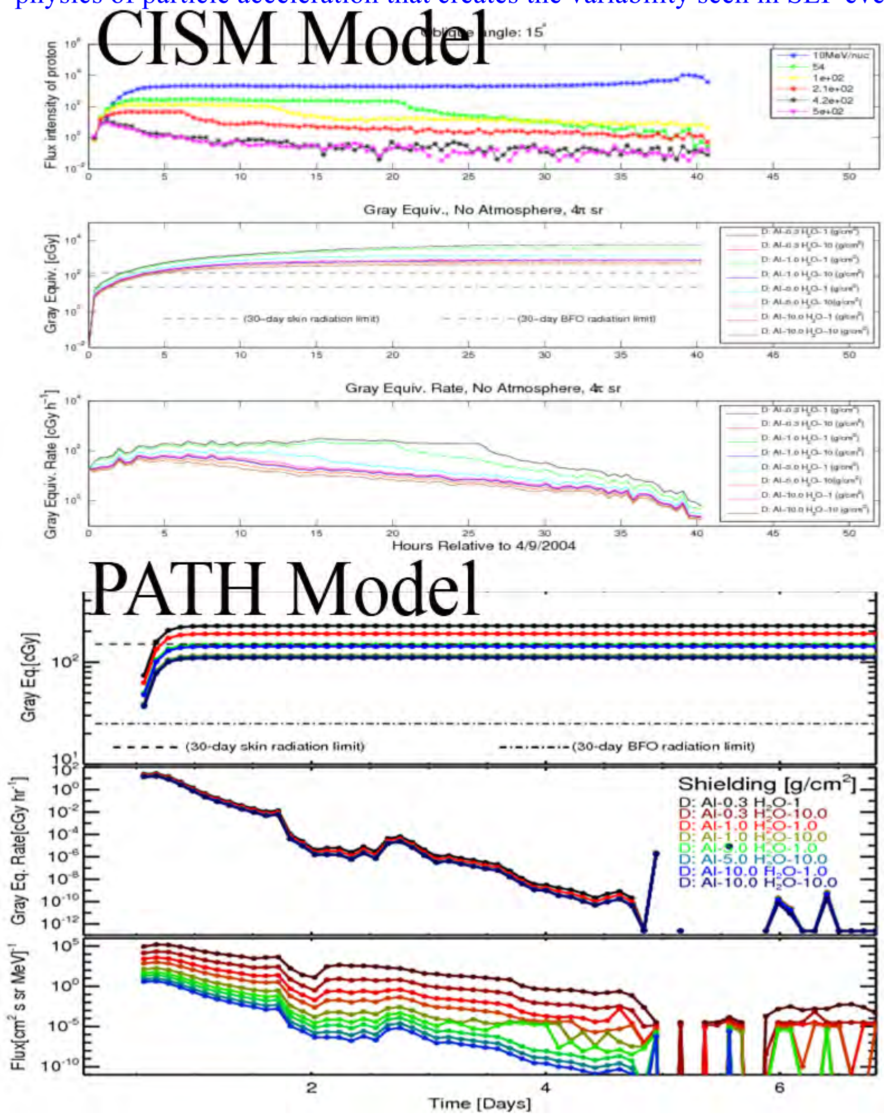

Fig. 15. C-SWEPA via EMMREM couples with models such as CISM and PATH to quantify radiation hazards. Modeled events generally create very large doses, and represent extremely hazardous events.

C-SWEPA incorporates a new mechanism for resolving substructures in the solar wind facilitated by EPREM's node data structures. Inertial node-lines allow us to resolve latitude and longitude regions of interest. The inertial node-line that connects to Earth is critical. A node is initiated every ~minute along an inertial node-line, creating ~10,000-20,000 nodes out to Earth. Each node contains information about advected densities and turbulence using recent innovations [§A.3.2.4]. Perturbations and turbulence initiated low in the corona are connected to the microstructures within solar wind that propagate to Earth and perturb the magnetosphere.

<u>A.3.1.3 Efficiency and Parallelization of EMMREM using GPUs</u>. Moore's Law states that the number of transistors on a chip roughly doubles every two years, which is holding true. But, starting in the mid-2000s clock speeds began topping out and the increased transistor density came in the form of more and more cores. To push to higher resolutions and performance, parallelization became a necessity and the concept of many core High Performance Computing (HPC) began taking center stage. The next step in HPC is coming through the use of heterogeneous architectures such as the Graphical Processing Unit (GPU). GPUs have not only revolutionized the world's fastest supercomputers (Tianhe-1A, Nebulae - Dawning TC3600, TSUBAME 2.0 - HP ProLiant SL390s), but also provided unprecedented computational opportunities all the way to small clusters and desk-side workstations. In terms of cost and performance, C-SWEPA requires a highly efficient computational system. To this end, the use of GPU's provides the critical leverage we need for this project (Fig. 16).

We have allowed the entire grid to "live" on the GPU, keeping costly communication between the host and device to a minimum. Our algorithm spawns one thread per grid-point, taking advantage of the ultra-lightweight threading capabilities of the GPU. The portion of the model re-written to utilize the GPU now represents a small fraction of the overall runtime, and the total time to complete a run has been substantially reduced. At high resolutions the new hybrid CPU/GPU code runs 12x faster for a total performance increase of 60x over the original code. We have costed 2 high-end GPU machines for use in C-SWEPA: one housed at UNH and one at the CCMC.

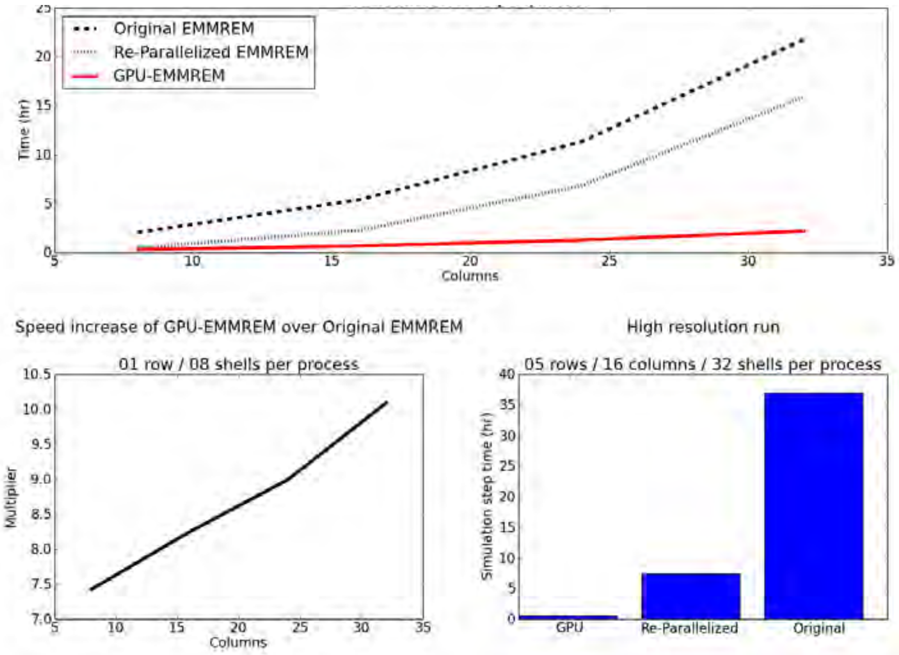

Fig. 16. *GPUs lead to critical performance advances for C-SWEPA: Difference in scaling between the three versions of EMMREM (top); Speed increase at low resolution (GPU vs. original; left bottom) and extreme efficiency of the GPU code at high resolution (bottom right).*

A.3.2 Science Subgroup structure. At the core of the C-SWEPA program is a focus on fundamental questions. C-SWEPA encompasses broad scientific investigations that attack problems related to (1) the corona and solar wind, (2) CME initiation and shock evolution, (3) SEP composition and propagation, and (4) solar wind waves and turbulence. In each of these four areas, a science subgroup is lead by a C-SWEPA investigator who liaises with the LWS FSTs and develops high-impact studies that leverage C-SWEPA tools. These investigations are documented in the scientific literature, and associated simulation and observational datasets are made available to the scientific community. We document here the studies undertaken by these subgroups.

A.3.2.1 Corona and Solar Wind Science Subgroup. One of the problems at the forefront of solar-wind modeling is inclusion of Alfven waves (AWs) and AW turbulence, which may carry the bulk of the energy that powers the solar wind [54]. A key property of turbulent AWs is that only counter-propagating AWs interact. As a result, the turbulent heating rate, which is determined by the strength of wave-wave interactions, depends upon the amplitude of both outward-propagating AWs and inward-propagating AWs (where the propagation direction is defined in the local plasma frame, and "outward" means away from the Sun). In the limit of no inward-propagating AWs, the turbulent heating rate vanishes, regardless of how much energy is present in outward-propagating AWs. In the solar wind, most of the outward-propagating AWs originate from the Sun [54,55]. On the other hand, inward-propagating AWs are produced primarily by wave reflection [56-60] and velocity-shear instabilities [61,62]. A number of previous numerical solar wind models included AW turbulence without separately accounting for inward- and outward-propagating AWs [63-67]. The only previous numerical solar wind models that separately accounted for inward- and outward-propagating AWs were 1D [68-70]. C-SWEPA utilizes physics-based treatments in CORHEL of inward/outward-propagating AWs to study the effects of AW turbulence.

A.3.2.2 CME Initiation and Shocks Science Subgroup. CMEs occur most frequently during solar maximum but are present throughout the ~11-year solar sunspot cycle. In a small fraction of these events, unusually high-energy eruptions occur. While the picture of how SEPs are energized to MeV and higher energies is far from complete, shocks associated with CMEs clearly play an important role. It is believed that these shock waves must form low in the corona to achieve the required particle energization; however, signatures of shock waves are difficult to find in coronagraph images [72]. The evolution of the shock and its interaction with the ambient solar wind are critical to SEP acceleration and transport.

While the subject of CMEs has been well studied [73-87], fundamental questions remain. How are extreme CMEs initiated? Where do the shocks form? How do CMEs and associated shocks evolve in the solar wind? Why do some fast CMEs yield strong radiation storms, while others do not? What sets the limit on the energy release in a CME? In order to provide crucial information for SEP acceleration and transport models, we must model the ambient corona and solar wind with high fidelity. In particular, to correctly identify where shocks form in the interaction of the CME with the surrounding medium, the Alfvén speed in the corona must be accurately represented.

The next key milestone for understanding CMEs in general is to model an eruption in realistic coronal magnetic fields with candidate CME initiation mechanisms. It is important to model the initiation mechanism itself, as opposed to ad hoc CME initiation models, in which an unstable configuration is contrived (such as inserting a flux rope into an ambient structure). Ad hoc CME studies are useful for understanding the propagation of shock waves in the corona. However, they cannot reveal the underlying cause of the CME, or provide insights into which active regions are likely to produce an event.

3-D CME simulations based on observed photospheric magnetic fields have produced eruptions with speeds of ~1000 km/s [e.g., 88]. Fig. 3 illustrates an example of such a simulation. In spite of some notable idealizations, studies like these are important in that they demonstrate that fast CMEs can be produced self-consistently (for these cases flux cancellation was used).

A critical component in understanding shock formation that results from fast CMEs is to more accurately model the coronal plasma, especially in active regions. Polytropic models using an artificially low ratio of specific heats [as in 88] can result in densities that are off by orders of magnitude in active regions. It is well known from coronal loop models that an accurate calculation requires consideration of energy transport processes (anisotropic thermal conduction, radiative losses, and coronal heating). In earlier studies, we could only include these processes in 2D [89,90] or 3D localized models of active regions [91,92]. Recently, we successfully incorporated this physics in 3D global coronal models to perform an event study of the May 12, 1997 CME [32], and simulated emission in EUV and X-rays from the solutions. We used MDI (Michelson Doppler Imager) magnetograms for the boundary conditions. The model shows features of the real event, such as dimming regions, postflare loops, and EIT waves. We have analyzed the simulated EIT waves in our model [93] and found that they agree well with the waves observed in the real event, indicating that the MHD wave speeds are similar to those in the actual corona. In C-SWEPA, we develop physics-based models of CME ejection using a variety of events and compare the results with observations with the goal of understanding the key elements for shock accelerated ions.

A.3.2.3 SEP Acceleration and Propagation Science Subgroup. SEP events occur primarily during periods of maximum solar activity. They divide into two classes: "Gradual" events last for days, are ion-rich, generally extend to higher energies, extend over a wide range of longitude, and are usually associated with CMEs. "Impulsive" events last for hours, are electron-rich, rarely extend in energy above ~30 MeV/nucleon, are released over a narrow longitude range centered on the magnetic connection to the flare site, and are enriched in heavy ions and ^{3}He. Impulsive events are more frequent: over the 11-yr solar cycle ~1000 impulsive events occur compared with ~10 gradual events.

Impulsive events are accelerated in flares at sites of magnetic reconnection, an origin that accounts for their shorter timescale and narrow range in longitude. Their composition presumably arises from stochastic acceleration by plasma turbulence. Gradual events are accelerated by CME-driven coronal/interplanetary shocks, an origin that immediately accounts for their CME association, composition, broad range in longitude, and extended time profiles. The SEP phase of a gradual event occurs early in the event when the shock is able to accelerate particles to the higher energies. When the shock passes Earth the gradual event appears as an energetic storm particle (ESP) event. An event that is magnetically well-connected to the flare site at early times produces a strong SEP event at Earth but produces a weak ESP event on the shock flank. A central meridian flare/CME that produces a strong ESP event at Earth is not magnetically well-connected to Earth early in the event and cannot produce a strong SEP event at Earth. Impulsive and gradual components in a large event with both acceleration mechanisms operative may be superposed and/or mixed. In addition, particles produced in one event may serve as "seed" particles for a subsequent gradual event so that SEP events can be very complex.

Our SEP effort builds on successes of existing models for particle acceleration and transport associated with CME-driven shocks — including flare-accelerated particles. In extreme events, high-energy particles may arrive at Earth within hours of the preceding X-ray and/or gamma-ray signals. The observed timing suggests that particle acceleration to very high energies occurs on a short time scale, with the CME-driven shock well inside of 10 R_s. At this distance, shock parameters vary with longitude, during propagation, and from one event to another. Many strong shocks do not cause large SEP events. A successful acceleration model must identify what leads to extremely efficient acceleration. It is also important to model acceleration at low energies, which leads to formation and injection of seed particles. The coupled solar/heliospheric MHD model proposed here provides the much-needed global description of the plasma and magnetic field parameters at and surrounding the shock, as it evolves.

Impulsive and gradual events depend on accurate description of electron and ion diffusion in turbulent magnetic fields, including resonant scattering parallel and perpendicular to the average field, and the effect of field-line random walk. Gradual events require calculation of the evolution of the shock including compression ratio, shock normal orientation, and magnetic obliquity. Also critical for gradual events is wave excitation in the foreshock by the accelerating protons; these waves control the acceleration timescale, the form and rigidity dependence of the spectral rollover in energy, and the escape rate of particles ahead of the shock in the SEP phase of the gradual event. This upstream particle escape is self-consistently modeled by the spatially variable pitch-angle scattering in the focused transport calculations. Finally, we must specify the remnant particle population, which is directly accelerated at the shock, and the injection rate of the upstream solar wind plasma at the shock front into diffusive shock acceleration. C-SWEPA utilizes detailed 3-D coupling between MHD shocks, energetic particle acceleration and propagation, seed populations and composition, and detailed subscale descriptions of diffusive shock acceleration to discover the broad implications of coronal structure, solar wind, CMEs and shocks, thereby leveraging scientific investigations to develop predictive understanding of SEPs.

A.3.2.4. Solar Wind Waves and Turbulence Science Subgroup. Our ability to follow local plasma parcels with Lagrangian nodes at high spatial resolution enables detailed investigations into the microscale physics of the solar wind that would not be feasible by other means. The principal application is to test and refine models for the evolution and transport of MHD turbulence in the expanding wind. Phenomenological models of increasing scope and sophistication have been developed to treat the radial evolution of turbulent intensities, cross-helicity, residual energy, and interaction between the turbulence and slab waves [19, 94-98]. Comparisons of these models with observations have been favorable, but they were limited to reproducing general trends in the average solar wind. The most detailed comparisons have been in the outer heliosphere, where solar-rotation averaged data at 1 AU was used to predict similarly averaged proton temperatures seen at Voyager 2 [99]. Considerably more information was obtained than was available from the behavior of an idealized, steady-state treatment [100,101]. The obvious difficulty with posing similar time-dependent tests in the inner heliosphere is the lack of reliable conditions to impose at the inner boundary of the system, where *in-situ* observations are not (yet) available. The primary driver of turbulence between the Alfvén critical point (~15 R_s) and the interstellar pickup protons beyond 5-20 AU is the plasma stream shear [102,103].

The phenomenological turbulence models consist of coupled first-order differential equations, whose solutions we advance through straightforward subsidiary calculations at each propagating Lagrangian node. We envision time periods when the CORHEL code, its standard observational inputs near the Sun, provides reliable fluid solar wind inputs at ~ 0.1 AU. Choosing periods when evolving streams (or the heliospheric current sheet) will impact a spacecraft near 1 AU, we then have a reliable handle on the variable background flows throughout the region, including the evolving shears in both velocity and magnetic field. We still will not know the exact turbulent input values at the inner boundary, but the detailed information on the fluid allows us to explore the range of plausible choices. Direct comparison between the simulated output turbulent properties and the time-dependent observations (averaged over a suitable correlation time) yield strong tests of the turbulence models on time scales of hours, greatly improving our understanding and generating increasingly dependable models.

A.3.3: Validation through Comparison to spacecraft observations. C-SWEPA enables the necessary transition from developing, coupling, and validating physics-based modules such as those discussed in §A.3.1-§A.3.2 so that we can utilize the integrated system and make reliable end-to-end predictions and forecasts. C-SWEPA predicts whether CMEs and their interplanetary shocks traveling through coronal and solar wind conditions are strong enough to generate SEPs with sufficient fluences and energy content to cause hazardous radiation storms at Earth. We use remote sensing (coronal and white light) observations and *in-situ* solar wind, magnetic and electric fields, and SEP observations obtained by Heliophysics missions as well as other key data sources (e.g., MESSENGER and NOAA's GOES satellites) as inputs to test and validate outputs of each module. Our main task is to validate the physics-based models and determine the radial distribution and evolution of solar wind turbulence, CMEs, shocks, suprathermal seed particles, and their effects on SEP intensities and energy spectra throughout the inner heliosphere out to 1 AU. In addition, we create modeling toolkits along with a large volume of synthetic datasets consisting of the properties of CMEs, shocks and their associated suprathermal and energetic particles to aid and support the analyses of new observations from upcoming LWS missions such as SPP and SolO. Table 2 lists the data sources for C-SWEPA validation.

Table 2: *Spacecraft, instruments, measurements, data availability periods for use by the C-SWEPA team.*

Spacecraft	Instruments	Measurements	Time Period	S/C Orbit
ACE	SWEPAM, MAG, EPAM, ULEIS, SIS	In-situ solar wind, magnetic field, suprathermal (ST) and EPs	1997 – present	L1
SAMPEX	LICA, PET	In-situ suprathermal, EPs	1992 – 2004	LEO –Polar Orbit
IMP-8	Plasma, Mag, EP ions and electrons	In-situ solar wind, magnetic field, ST and EPs	1973 - 2006	Near-circular, 35 R_E, 12-day orbit.
Wind	SWE, MFI, STICS, STEP, EPACT, Waves	In-situ solar wind, magnetic and electric fields, suprathermal and energetic particles	1994 – present	Complex orbits until 2004, L1 thereafter
SoHO	MDI, LASCO, EPHIN, COSTEP	Vector magnetograms, White light images, in-situ suprathermal, EPs	1995 – present	L1
GOES	SXI, EPS	White light images, EPs	1990 –pres.	Geosynchronous
STEREO	SECCHI, PLASTIC, IMPACT, SWAVES	White light, *in-situ* solar wind, B&E fields, suprathermal and EPs	2006 – present	2 S/C at 1 AU; Separation ~30°/year
ULYSSES	SWOOPS, MAG, Hi-SCALE, COSPIN	In-situ solar wind, magnetic field, suprathermal and EPs	1990-2009	High lat. (80 deg) heliocentric orbit
HELIOS 1, HELIOS 2	MAG, Rad,Plasma, EP el. & Ions	In-situ solar wind, magnetic field, Suprathermal and EPs	H1: 1975-85 H2: 1976-79	Hel. Orbits, perihelion, 0.29 AU
LRO	CRaTER	Energetic articles and dose	2010 – pres.	Lunar orbit
MESSENGER	EPPS	Thermal, suprathemal, and energetic particles	2004 – present	In Mercury orbit
Solar Probe Plus	SWEAP, Fields, WISPR, and ISIS	White light hel. images, in-situ solar wind, B&E fields, suprathermal and EPs	Launch ~2018	3 Passes with Perihelion <10 R_S
Solar Orbiter	PHI, METIS, SolOHI, STIX, MAG, RPW, SWA, EPD	Vector mag., White light sol. and hel. images, thermal and non-thermal x-ray, in-situ solar wind, B&E fields, suprathermal and EPs	Launch in 2017/2018, 7 year mission	Elliptical orbit w. per. ~0.28 AU & incr incl. >25° wrt solar equator.
RBSP	ECT, RBSPICE, RPS	Thermal, suprathemal, and energetic particles	Launch ~2012	Two s/c study Van Allen rad. belts

A.3.3.1 Solar Orbiter (SolO) and Solar Probe Plus (SPP). SolO approaches the Sun to 0.28 AU and SPP moves to ~9 R_s. They measure *in-situ* properties of CMEs, shocks, waves and turbulence, the ambient solar wind and interplanetary magnetic field while these phenomena are still relatively pristine and link them back to their solar source regions with the aid of simultaneous, high-resolution remote sensing measurements. C-SWEPA generates a database of synthetic CMEs, shocks, and SEP events as a function of heliocentric distance, longitude, and latitude along the SolO and SPP trajectories. C-SWEPA creates user-friendly modeling toolkits that provide the SolO, SPP and LWS communities with well-tested, mature, physics-based modules to link the remote sensing and *in-situ* measurements, provide physical context, and facilitate the interpretation of complex solar and heliospheric phenomena.

A.3.3.2 ACE, SoHO, Wind, STEREO, GOES and L1 spacecraft. 1 AU spacecraft data provide vital validation sources for solar wind, CMEs, and SEP properties including composition. The 3D, time-dependent nature of the C-SWEPA modules make them ideal for comparing simulations with contemporaneous measurements in multiple locations. For example, the varying locations of STEREO and L1 spacecraft relate longitudinal dependence of SEPs to shock and CME structure.

A.3.3.3 Transformational Historic Observations by Helios and Ulysses. Spacecraft and mission designers use SEP intensity gradients to estimate the radiation environment. From 0.3-1 AU, peak proton intensities decline more slowly than beyond 1 AU [104]. Poorly understood physical processes determine the inner-heliospheric SEP properties. Proton intensities in large SEP events have upper "streaming" limits [105,106] that are sometimes exceeded [107] resulting in large uncertainties in radiation risk assessments. In such cases, proton-generated Alfvén waves may have dissipated more rapidly, allowing particles to escape the acceleration region. Ulysses showed that large-scale transient structures, more prevalent near solar max., can act as barriers for suprathermal and energetic particles, creating particle reservoirs inside Jupiter's orbit. CME shocks launched in such reservoirs have immediate access to pre-energized seed populations [e.g., 109]. C-SWEPA CME shock acceleration and transport modules are validated using historical observations of CMEs and SEP events from the Helios and Ulysses eras [e.g., 110] to advance reliable forecasts and accurate radiation risk assessments.

A.3.3.4 RBSP and Magnetosphere. We apply powerful techniques to micro- and meso-scale processes in the solar wind, particularly those known to generate space weather in Earth's magnetosphere. For example, we characterize magnetospheric boundary conditions driven by periodic solar wind density enhancements at several mHz (in Earth's rest frame) that produce global oscillations of Earth's magnetic field [111-113] (see §A.3.2.4). These coherent magnetospheric oscillations, in addition to broader band excitations from the modeled turbulent solar wind, provide important information on resultant electromagnetic fields in the magnetosphere. C-SWEPA provides the complex, global solar wind conditions at the magnetopause boundary, both the monochromatic and broadband solar wind dynamic pressure components. These drivers create electromagnetic waves in the magnetosphere leading to diffusion and energization of radiation belt particles. By predicting these boundary conditions, C-SWEPA provides a missing link in RBSP science.

A.3.3.6 LRO/CRaTER Observations. Schwadron et al. [114] show detailed comparisons between space radiation conditions including SEP events and results of EMMREM modeling. Similar comparisons for the Jan 23rd, 27th 2012 events (Fig. 17) show the accuracy of EMMREM dose rate predictions. CRaTER thus provides direct validation of the biological impact of C-SWEPA predictions.

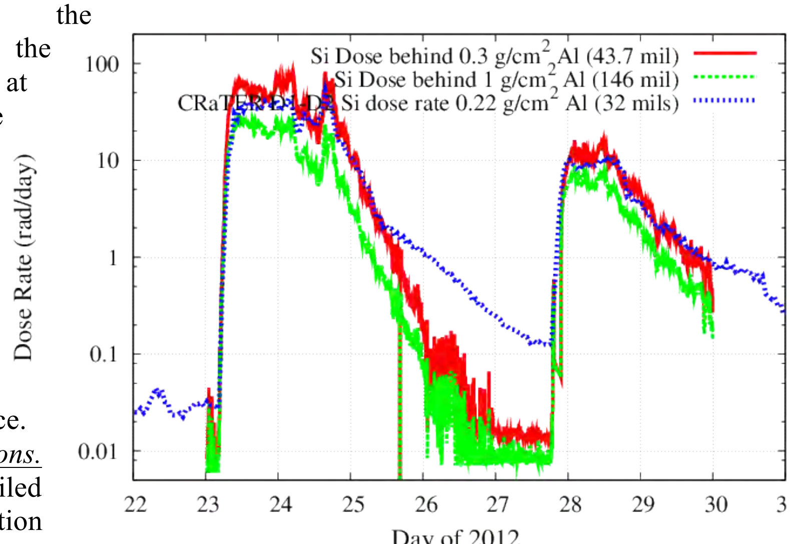

Fig. 17: *EMMREM predicts highly accurate dose rates (red & green) compared to CRaTER measurements (blue) during the Jan 23 and 27 2012 SEP events.*

A.4 Timeline, Management and Impacts

A.4.1 Work Plan and Timeline. The C-SWEPA work plan (Fig. 18) is ordered around 5 yearly project-level milestones:

- **Milestone 1,** procure hardware and model single event Sun-to-Earth.
- **Milestone 2,** deliver coupled model to CCMC along with benchmarks, examples and documentation.
- **Milestone 3,** develop two semi-autonomous runs of model using solar inputs.
- **Milestone 4,** run coupled model autonomously.
- **Milestone 5,** final coupled model runs, timing analyses, and benchmarking. Final updates to CCMC.

A.4.2 Development and Management Plan. The development and management plan begins with formulation during the first year. C-SWEPA team members meet with CCMC team members to discuss procurement of the appropriate GPU systems. Integration of EPREM and CORHEL has already begun, and the work during the first and second year focuses on optimizing performance and developing an intuitive script for running the system. In the first 2 years, the science subgroups meet to formulate desired modes of the system including coronal heating functions, CME initiation methods, SEP seed populations, wave and turbulence models, wave-particle interactions near shocks and in the inner heliosphere that affect dependence of the scattering mean free paths, forms of scattering operator on distribution functions, and statistical acceleration operators. Discussions are organized by science subgroup leads who interact directly with EMMREM (Schwadron) and CORHEL (Linker) leads to update modules. Science subgroups review model interfaces and system-control scripts. In the final two years, development leads provide updates to modules and deliver the final system. Two separate C-SWEPA GPU machines operate at the CCMC and UNH. We have allocated adequate funds (~$40K) for procuring both systems.

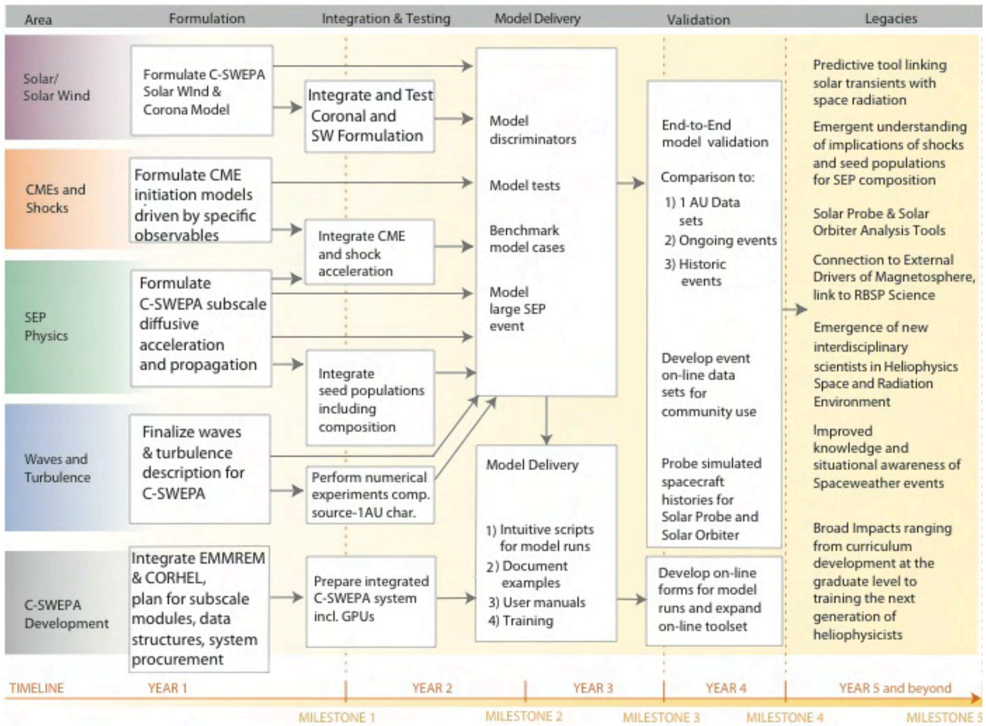

Fig. 18: *The work plan for C-SWEPA links areas conducting core and linked research guided by annual outcomes. Over the 5-year project, a progression from formulation to integration & testing, model delivery, and validation leaves valuable legacies.*

A.4.3 Broader Impacts. C-SWEPA advances discovery and understanding while promoting teaching (curriculum development at UNH and the hispanic-serving University of Texas San Antonio), graduate student training, and undergraduate involvement. Prof. Schwadron is active in recruiting under-represented groups for graduate studies at UNH and participates with diversity programs at UNH to broaden the participation of underrepresented groups (e.g., gender, ethnicity, disability, geographic, etc). C-SWEPA enhances the infrastructure for research and education through development of computing systems for use by the science community. C-SWEPA results are disseminated broadly to enhance scientific and technological understanding. By advancing tools for understanding and predicting spaceweather, C-SWEPA provides important societal benefits enabling expansion of space technologies.

A.4.4 Mentoring Plans and Activities. K. Kozarev is currently finishing his PhD at Boston University and was recently awarded the LWS Jack Eddy Fellowship. Mr. Kozarev will spend the next several years at the SAO-CfA hosted by Dr. J. Raymond to study coronal shocks and how they accelerate particles through observations [e.g., SDO-AIA, 115]. Mr. Kozarev has played a pivotal role in EMMREM. His continued work with C-SWEPA will both aid in his fellowship work and greatly benefit the project. Dr. M. Stevens is also a postdoc at SAO-CfA under the supervision of Dr. J. Kasper. For C-SWEPA, Dr. Stevens performs validation studies using data from Wind and other satellites to determine *in situ* shock structure and its influences or relationships to particle acceleration.

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