Living With a Star Strategic Capabilities (LWSSC21)
Abstracts of Selected Proposals
(NNH21ZDA001N-LWSSC)

Below are the abstracts of proposals selected for funding for the Living With a Star Strategic Capabilities (LWSSC21). Principal Investigator (PI) name, institution, and proposal title are also included. Thirteen (13) proposals were received in response to this opportunity. On March 28, 2022, four (4) proposals were selected for funding.

Spiro Antiochos/University Of Michigan, Ann Arbor
A Capability for Community Modeling of Solar Eruption Propagation and Particle Radiation

The University of Michigan in close partnership with NASA/GSFC and NWRA proposes to build and deliver to the CCMC the Strategic Capability SCEPTER (Solar Coronal Eruption Propagation to Earth with particle Radiation). SCEPTER will be built on four cornerstone models that the proposing team has developed and delivered to the CCMC over the past two decades: AWSoM a model for the background corona and heliosphere, EEGGL a model for solar eruption (CME/flare) onset and evolution, M-FLAMPA a toolkit for calculating energetic particle acceleration and transport along dynamic field lines, and AMPS a complete modeling suite for calculating either single particle or particle distribution evolution in time-varying E-M fields. SCEPTER will also be built on the unmatched record of success by the proposing team in delivering on schedule and as promised Capabilities to the CCMC, in full partnership with CCMC staff, and in making the models available to the community both through the CCMC and via a non-commercial open-source license for the source code on GitHub.

SCEPTER will meld these foundational models into one powerful capability with a single set of interfaces so that the user can select an eruptive event and study its complete life cycle including impact at Earth. To achieve this ambitious goal, we will make major upgrades to both the background and eruption models. We will add to AWSoM an innovative method that we have developed for aligning the magnetic field line and the fluid flow in the wind, so that the connectivity from the heliosphere to the Sun can be determined, thereby, enabling rigorous calculation of SEP fluxes along those lines. We will add to EEGGL options for initiating the eruption: by a TD fluxrope and by shearing flows and/or helicity condensation. The most dramatic upgrade for SCEPTER is that we will couple our widely-used model for flux emergence/cancellation with EEGGL. With this new model, EEG-2, SCEPTER will be truly transformational. It will allow the general community to study, for the first time, the pre-eruption energy buildup as determined by the physically self-consistent interaction of the photosphere/convection region with the corona. This new capability is also very timely, because the increased computational resources needed by the inclusion of emergence/cancellation match up well with the new dedicated allocations that the CCMC has received on NASA HEC

architectures. In partnership with the CCMC we will develop interfaces and user manuals for running SCEPTER both at the CCMC's in-house resources and at the HEC Centers. To validate user results and achieve closure with NASA mission observations, SCEPTER will provide the tools to output from the simulations, synthetic data for all the relevant missions in NASA's Heliophysics System Observatory, including SOHO, STEREO, SDO, WIND, and ACE, as well as for PSP and SO when that mission data becomes accessible to the external community. To schedule and focus the model development we have selected four science investigations that we will perform and that will define the timing of the milestones and model delivery to the CCMC.

The SCEPTER program is clearly bold and ambitious, but the proposing team has all the science expertise and development experience for successfully carrying out this program. The PI Antiochos and Co-PI Gombosi have decades of proven leadership in both science and modeling advances. The Institutional PIs Karpen and Leka are leaders in observations and simulations of solar eruptions. SCEPTER build on the long-standing partnership between the three participating institutions and the CCMC in delivering major capability advances to NASA and the Heliophysics community.

Gian Luca Delzanno/Triad National Security, LLC
Beyond MHD: Flexible fluid-kinetic global geospace model

The objective of the proposed work is to develop a new capability that will enable new investigations aimed at answering a fundamental and yet so far unanswered question: What is the role of microscopic/kinetic effects on the large-scale dynamics of the Earth's magnetosphere?

In general, the new capability will enable investigations of many pressing questions in magnetospheric science. Specifically, we target questions centered around the physics of magnetic reconnection onset in the magnetotail, which is essential for better understanding and modeling of magnetospheric substorms, some of the most energetic phenomena that are key to space weather science. With minimal modifications, our new capability will also enable significant progress on understanding the processes controlling dayside solar wind/magnetosphere coupling.

The Earth's magnetosphere is a complex system comprising diverse particle populations interacting via processes characterized by several orders of magnitudes in scale separation between the kinetic and system scales. Despite remarkable progress over the past decade, all existing methods that attempt to go beyond a magnetohydrodynamics (MHD) description of the magnetosphere have significant limitations. The method proposed here promises to overcome the limitations of existing approaches by coupling a highly-accurate modeling framework built on MHD and leveraging decades of development, GAMERA, with a unique approach to solve the kinetic equations, called SPS, by means of a spectral expansion. The project involves including anisotropic pressure and Hall MHD physics in GAMERA, developing improved preconditioning and

adaptive capabilities in SPS, and developing a coupled GAMERA-SPS framework that will be delivered to the Community Coordinated Modeling Center. Several verification and validation efforts will document the accuracy and efficiency of the new algorithm and its ability to reproduce observational data.

The proposal is strongly aligned with the solicitation and incorporates many of the requested Targeted Objectives. It achieves 'Improved modeling of reconnection and electron scale physics in general' by embedding the SPS kinetic solver into the large-scale global MHD model GAMERA. It develops 'Inclusion of Hall MHD physics' in GAMERA. It uses 'New approaches to solving the Vlasov-Maxwell equations such as moment expansion or spectral transform methods' and achieves 'Improvements to computational stability and efficiency, novel approaches to reduce computation demand without impacting the physics' through the SPS spectral approach that allows one to dial-up kinetic physics as necessary and hence reduce the computational load relative to a fully kinetic approach. It also performs 'Extensive validation of codes metrics on code diffusivity, energy and momentum conservation, accuracy in solving equations, deviation from pure MHD, etc'. The proposal is also strongly aligned with the overall NASA Heliophysics Science Objectives. By developing new capabilities that include kinetic/microscopic physics in large-scale magnetospheric modeling, we enable investigations that 'Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe', 'Advance our understanding of the connections between solar variability and Earth and planetary space environments' and support 'Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth'.

John Dorelli/NASA Goddard Space Flight Center
Magnetosphere Aurora Reconnection Boundary Layer Emulator (MARBLE): Magnetosphere-Ionosphere Coupling on Multiple Scales

Understanding the connection between magnetospheric dynamics and the aurora has remained one of the most challenging problems in magnetospheric physics for the last fifty years. One of the more exciting developments in the last two decades was the discovery that dispersive Alfvén waves (DAW) play a significant role (comparable to quasi-static potentials) in accelerating magnetospheric electrons to energies capable of generating auroral arcs during periods of high auroral activity. DAW have also been invoked to directly connect collisionless reconnection physics to the aurora, with important implications for the relative timing between magnetotail reconnection onset and auroral substorm onset. Unfortunately, there does not exist a global magnetosphere code capable of modeling the physics of reconnection generated DAW and their coupling to the ionosphere. We propose to address this significant gap in our modeling capability by developing a new "collisionless Hall MHD" model in which frozen-in perpendicular ExB electron motion is self-consistently coupled to non-local electron and ion transport parallel to the magnetic field. The new computational model, MARBLE (Magnetosphere

Aurora Reconnection Boundary Layer Emulator), will be designed to couple to an existing global Hall MHD code for the magnetosphere as well as a Fokker-Planck model for electron precipitation into the ionosphere. The new model will be capable of addressing the following science questions:

Q1. How does three-dimensional collisionless magnetic reconnection project to Earth's ionosphere?
Q2. How do reconnection generated field-aligned currents propagate to the ionosphere?
Q3. How is reconnection generated energy flux transported to the ionosphere?

MARBLE will be designed to run on clusters of Graphics Processing Units (GPUs) to enable reasonable simulation times for large magnetospheres with 5-10 cells per ion inertial length. Most of the development will occur on a dedicated 8 NVIDIA A100 cluster at NASA-GSFC. The same development environment will be available through an AWS cloud based interface provided by the Community Coordinated Modeling Center (CCMC) at NASA-GSFC. Our long term strategy will be to scale MARBLE up to larger clusters with thousands of GPUs.

Our proposed program will support two full time postdoctoral researchers with expertise in computational methods and machine learning to focus on: 1) the development of efficient numerical approaches for solving the electron and ion drift kinetic equations, 2) the use of deep learning to develop surrogate models for the propagation of input parameter uncertainties to quantities of interest.

MARBLE will be released under the NASA Open Source Agreement v1.3 and distributed in a NASA public github repository. In parallel, we will work with the CCMC to make MARBLE available to users through their Runs on Request web based interface. We will coordinate with the CCMC to ensure that we are meeting computational, storage, I/O, visualization and post-processing requirements at all stages in MARBLE's development. We will also work closely with the CCMC to establish a community driven model validation approach using both standard computational benchmarks as well as spacecraft and ground observations. This validation plan will promote an open science approach, with collaboration, transparency and reproducibility as core values. Several MARBLE community workshops will be organized during the course of the program.

Jon Linker/Predictive Science Inc.
DYNAMCS: A DYNAmically evolving Model of CMEs and SEPs

Coronal mass ejections (CMEs) are remarkable displays of solar variability, and are the leading cause of space weather effects at Earth. Major solar energetic particle (SEP) events are closely associated with CMEs. Measurements of the Heliophysics System Observatory (HSO) provide us with an unprecedented view of CMEs and SEPs. Exploiting these data to further our quantitative understanding of these fundamental phenomena requires advanced physics-based models. Such models can also become

prototypes for eventual operational space weather models. We propose a four-year program to create a DYNAmically evolving Model of CMEs and SEPs (DYNAMCS) and deliver it to the CCMC for runs-on-demand. Our proposed program strongly leverages and builds on our present modeling capabilities from MAS/CORHEL and EPREM/EMMREM.

Our first major goal and delivery milestone is to seamlessly link ambient corona/solar wind, CME initiation, and SEP acceleration/transport models to produce comprehensive simulations of CME-SPE events for runs-on-demand.
Recognizing that the notion of a quasi-steady background corona that is perturbed by an event is too simplistic for many real-world situations, our second major goal and milestone is to deliver an evolving background coronal and solar wind magnetohydrodynamic (MHD) model, capable of running continuously, to the CCMC. This model will be driven by magnetic maps that assimilate available magnetograms and farside data to continuously update the ambient structure of the solar corona and inner heliosphere.

Finally, as the effects of multiple flares/CMEs are poorly understood, yet may have important space weather consequences, our third goal/milestone is to allow multiple eruptions to be introduced into the continuously-running model, providing a near-real time description of the solar corona and inner heliosphere.

When completed, DYNAMCS will address key target objectives, including:
(1) Combining data assimilation and simulations
to successfully span multiple spatial scales and improve the understanding of CME evolution in the corona and inner heliosphere;
(2) Incorporating new capabilities to study the evolution, magnetic properties, and substructure of CMEs as they transit the corona and inner heliosphere and interact with the solar wind;
(3) Incorporating new techniques or simulation capabilities that can eventually lead to improved forecasts of the space weather impact on the Earth system as a result of improved understanding of CMEs and their evolution through the corona and inner heliosphere; and
(4) Providing a broad combination of models and observations for detailed understanding of the propagation of CME/flare-generated particles from the Sun to 1 AU.

DYNAMCS will provide post-processing of the results for innovative diagnostics and validation, so that fundamental science questions can be addressed, including:
(1) How does evolution of the ambient corona and solar wind affect CME evolution, propagation, magnetic-field properties, and geo-effectiveness?
(2) How does this evolution affect magnetic connectivity in the inner heliosphere and the subsequent propagation of SEPs?
(3) How do multiple eruptions affect CME evolution, propagation, magnetic-field properties, and geo-effectiveness?
(4) How do multiple eruptions affect SEP acceleration and transport?

These questions are relevant to the three Heliophysics Science Objectives: (1) Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe; (2) Advance our understanding of the Sun's activity, and the connections between solar variability and Earth and planetary space environments, the outer reaches of our solar system, and the interstellar medium; and (3) Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.
