5.0 Theory and Modeling Introduction

In SEC research, the systems under study are typically of great complexity. Furthermore, they can be sparsely sampled or have good sampling only over a narrow spatial, temporal, or spectral range. Using these observations of complex systems, the SEC researchers seek to develop the capability to predict the behavior of the combined system under well-defined conditions and verify this development using new observations. Such an endeavor requires well-tailored development of abstractions of the system, in the form of theories or models. Thus, the intrinsic nature of SEC research necessitates a strong theory and modeling program.

Currently, SEC study of the Sun-heliosphere-planet system is undergoing three substantial changes. One of these changes lies in the markedly increased complexity of present and planned future missions, especially those based on clusters of spacecraft. The second and perhaps more fundamental change involves an evolution from a discovery-driven investigative mode to one motivated by quantification and the desire to verify concepts of understanding. This paradigm shift is especially evident in the goal to understand the coupling between elements in the Sun-heliosphere-planet system. Finally, the Space Weather element of the Living With a Star program requires the development of physics-based models that provide predictive capability. These transformations result in a much closer and much more essential tie between scientific flight missions and accompanying activities in theory and modeling of space plasmas. Thus the role of theory and modeling emerges in a new, prominent light within the SEC Division and has become central to the SEC strategic science objectives. Sections 5.1, 5.2, and 5.3, discuss the tie between theory and modeling and the three primary SEC science objectives. Section 5.4 presents a brief summary.

5.1 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

The transport of matter and energy, together with magnetic flux and momentum, over huge distances, poses a grand challenge problem to Sun-Earth Connection research. Theory and Modeling forms an essential element of this research. The analysis and description of the vast and complex Sun-heliosphere-geospace system mandate tools for integration between missions addressing different aspects of the transport problem. Due to the sheer size of the domain, such a glue can only be provided by large-scale models.

Large-scale models, such as those developed for the solar corona or ionosphere-thermosphere, fulfill a set of needs in SEC research. Traditionally, such models have been utilized to provide the overall context for the interpretation of spacecraft measurements. This highly useful function will continue in the future. In addition, large-scale models now can also provide high-quality estimates of the connection between individual measurements, separated in space or in time. As an example, the overall structure of the solar wind, involving currents sheets separating different magnetic fields, determines whether coronal ejecta or energetic particles arrive at the Earth or not. Comparisons like this example are essential to extend the value of measurements beyond the local environment, and to develop better, model-based manifestations which reflect the level of understanding. The interplay between model predictions and spacecraft measurements thus provides a new avenue of space research, combining new windows into the workings of the SEC system through direct feedback between mission data analysis and modeling.

Beyond this overarching role, large-scale models directly support specific missions. For example, global models of the corona and solar wind are used to interpret and predict, co-rotating interaction regions, propagation of cosmic rays in the heliosphere, and the propagation characteristics of CMEs. These models are important for STEREO and Solar-B, and, in the absence of true global measurements, are important for Telemachus. Other examples of mission support through modeling are GEC and MagCon, where data assimilation techniques into large-scale models provide, for the first time, a comprehensive map of properties, dynamics, and transport in geospace and in the ionosphere.

5.2. Explore the fundamental physical processes of space plasma systems.

In a growing area of space research, investigations are moving away from the basic morphological studies of the discovery period to more detailed and targeted probing of the inner workings of key physical processes. Better understanding of the overall morphology generates the need to understand key physical processes, which determine the overall system state and dynamics. Accordingly, mission-based research often aims at distinguishing between different candidate mechanisms, or at least understanding of a single process, which fundamentally determines system behavior. Often, these processes are driven by micro-scale instabilities. Understanding of the processes on the micro-scale typically requires basic theory supported and enhanced by kinetic and hybrid modeling.

This basic theory and modeling is playing an increasing role in SEC missions. Typically, plans for missions are based on prior knowledge, obtained from prior missions. In the future, mission conception, tailoring, and execution will focus increasingly on the verification or falsification of understanding. In particular, many future missions will have as their goal to test the veracity of a prediction of fundamental plasma system behavior, obtained from theories and models. The conception of such flight missions, their execution, and the enhancement of understanding require the establishment and maintenance of strong theory and modeling activities.

Following the prediction phase, fundamental plasma models will be intricately involved in the preparation and execution of missions. An example of the interplay between theory and observations is the study of magnetic reconnection. MMS will study this process at microscopic levels of detail heretofore only accessible by modeling. Thus the concept underlying MMS, as well as its design relied heavily on results from modern models and theory. During the flight phase, MMS will involve a close interaction between observations and models to bring closure to the operation of reconnection in geospace. Reconnection in the solar coronal environment has been, to date, even less accessible to direct measurements. Therefore, Theory and Modeling will play a similarly fundamental role in the conception and execution of RAM. Modeling will also play an important role in understanding cross-scale coupling such as turbulent transport. Here, kinetic and/or hybrid models must be developed for large-scale systems approaching the global magnetohydrodynamic models.

5.3 Define the origins and societal impacts of variability in the Sun-Earth connection.

The Space Weather element of the Living With a Star program requires research and development targeted at the basic physics needed to create space weather forecasting capabilities. With the exception of very few simple causal relationships, forecasting is based on modeling the future behavior of the space environment based on known present conditions. Such models are necessarily physics-based in that the underlying physics, developed from theory and guided by observations, provides the key ingredient for forecasting capability. Finally, the testing of candidate models against new measurements takes on an additional and very important role of validating progress. These models will combine global modeling and local modeling approaches such that the physics included in the global model will be derived from local models and theory, which is in turn driven by targeted LWS observations.

The close-knit relation between model development and observations will benefit all LWS missions. Specifically, SDO will provide scientific insight, inputs to models, as well as the data against which solar interior, coronal, and heliospheric models can be evaluated. The close linkage between observations and models will also answer one of the most pressing questions underlying space weather modeling; the question of which information has to be provided to models for precision forecasts of the future space environment. Modeling plays a similar role within the geospace segment of LWS, consisting of Radiation Belt Storm Probes, and Ionosphere Thermosphere Storm Probes and Inner Heliospheric Sentinels. Here models and theory will, through mapping techniques and data assimilation, extend a set of multi-point measurements to large-scale specification. Subsequent comparisons between predicted and actual futures will lead to the scientific understanding and forecasting capabilities.

5.4 Summary of Theory and Modeling in the SEC Division.

This discussion elucidates the growing importance of theory and modeling for the SEC Division. Theory and modeling is suitably implemented in four forms. First, the success and value of basic scientific research renders the SEC Theory Program highly valuable. In order to address national needs in the space weather area, a targeted and well-planned research activity is required, which also needs to be integrated with LWS missions. This activity should also include a plan for the transitioning of research results and models to the operational agencies. The needs of other missions also mandate that suitably sized theory and modeling activities be established alongside instrument and spacecraft subsystem development. The roles of supporting innovative ideas and approaches have been successfully filled by a strong supporting research and technology program.