APPENDIX B

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION LIVING WITH A STAR

B.1 Introduction

Sun-Earth Connections is one of four major themes of emphasis within the National Aeronautics and Space Administration programs. One of the four key questions to be addressed under Sun-Earth Connections is how solar variability affects life and society. At the end of 1999, NASA put forward its Living With a Star (LWS) Program to advance scientific understanding of solar variability and its effects. LWS has four main objectives:

- Identify and understand variable sources of mass and energy coming from the sun that cause changes in our environment with societal consequences, including the habitability of Earth, use of technology, and the exploration of space.
- Identify and understand the reactions of geospace regions whose variability has societal consequences (impacts).
- Quantitatively connect and model variations in the energy sources and reactions to enable an ultimate US forecasting capability on multiple time scales.
- Extend the knowledge and understanding gained in this program to explore extreme solar terrestrial environments and implications for life and habitability beyond Earth.

Although the objectives of LWS are broader in scope than the National Space Weather Program, many of the planned activities support space weather goals. LWS will provide the scientific context and understanding that will lead to a capability to accurately predict solar activity and its effect on the space environment. Initially the main application of such knowledge is to geospace, but as mankind starts to explore the solar system, the requirement is extended to interplanetary space and other planets, specifically Mars.

LWS seeks solutions to a broad class of problems associated with the dynamic effects of solar, interplanetary, magnetospheric, and upper atmospheric phenomena that have an impact on humans. In particular, it is focused on the impact of these phenomena on modern technology and on the safety of humans as they travel beyond the Earth.

LWS is a cross-cutting initiative whose goals and objectives have the following links to each of the four NASA Strategic Enterprises:

- **Space Science** - LWS quantifies the physics, dynamics, and behavior of the Sun-Earth system over the 11-year solar cycle.
- **Earth Science** - LWS improves understanding of the effects of solar variability and disturbances on terrestrial climate change.
- **Human Exploration and Development** - LWS provides advanced warning of solar energetic particle showers that affect the safety of humans in space.

- **Aeronautics and Space Transportation** - LWS provides detailed characterization of radiation environments useful in the design of more reliable electronic components for air and space transportation systems.

B.2 LWS Program Elements

The following subsections describe the LWS strategy for studying the effects of solar variability.

B.2.1 Accelerate Solar Terrestrial Probes

Studying the Sun-Earth connected system requires simultaneous observation of interacting regions. In the current budget, missions have two-year design life and are launched at 2.5-year intervals. This limits synergism between missions studying different regions of the Sun-Earth system. The LWS goal is an interval of 1.5 years between missions to enable simultaneous study of key linked regions in the Sun-Earth system.

In addition to currently planned missions, LWS adds observational and modeling capabilities to fill gaps in coverage of key regions of the Sun-Earth system. The gaps and the planned solutions are listed below.

Missing: Detailed information on dynamics of the solar interior and the dynamo that generate and control solar variability *(including both short and long term variations).*

Solution: A Solar Dynamics Observatory providing high time and spatial resolution data to probe the:

- Solar interior and the subsurface structures underlying regions generating solar disturbances.
- Dynamics of magnetic structures in the solar atmosphere where these disturbances occur.

Missing: Continuous observations of solar regions generating solar disturbances; measurements of the solar interior from the other side of Sun.

Solution: Solar Sentinels:

- To observe the entire solar surface, *including the far side from Earth.*
- To observe, globally and in stereo, solar wind disturbances from the Sun into interplanetary space.
- To obtain "missing" seismology data from the solar far side.

Missing: Detailed information on the dynamics of the terrestrial space environment during geospace disturbances.

Solution: Geospace Dynamics Network: A network of spacecraft to provide data with sufficient spatial and temporal coverage to specify the dynamics of disturbances affecting geospace and the neutral atmosphere.

Missing: Detailed information on long term effects/relation to global change of variable solar inputs on upper terrestrial atmosphere.
Solution: Geospace Dynamics Network

Missing: Theoretical understanding and end-to-end modeling capability ranging from solar sources to effects in geospace and the upper atmosphere.
Solution: Dedicated theory and modeling program

- To understand the physical connection between the solar source, geospace and the upper atmosphere.
- To specify space environment parameters of relevance to humans and human assets.
- To enable a predictive capability of the impact of solar disturbances on humans and human assets.

B.2.2 Establish a Space Weather Research Network

The program proposes a Space Weather Research Network (SWRN) comprising a distributed network of spacecraft providing continuous observations of the Sun-Earth system. The network would contain two key components:

- The *Solar Dynamics Network* would observe the Sun and track disturbances from the Sun to the Earth.
- The *Geospace Dynamics Network* would comprise constellations of small satellites in key regions of geospace to specify the dynamics of disturbances affecting geospace and the neutral atmosphere.

The SWRN is shown in Figure B-1 and described in more detail below.

B.2.3 Establish Targeted Data Analysis and Modeling

LWS can exploit data from present and past missions:

- To improve knowledge of space environmental conditions and variations over the solar cycle.
  - Obtain reliable environmental specifications for cost-effective design of spacecraft and subsystems to minimize space environmental effects and damage.
  - Important for commercial satellites and military space systems which must have "all weather" capability.
- To develop new techniques and models for predicting solar/geospace disturbances which affect human technology. For example, recent research has revealed a connection between sigmoidal x-ray signatures and regions with high probabilities for producing CMEs.
- To develop cost-effective techniques for assimilating data from networks of spacecraft.

B.2.4 Establish Orbital Technology Testbeds

LWS provides the opportunity for low cost validation of radiation-hard and radiation-tolerant systems in high radiation orbits. This opportunity can be exploited through NASA, industry, DOD, and other agency partnering.

B.2.5 Establish and Expand Partnerships

- Major contribution to the National Space Weather Program (NSWP).
- Establish/expand collaborative research efforts with DOD, DOE, NOAA, NSF.
- Coordinated research and development on the space environment and space weather.
- Launch of LWS missions as secondary payloads on Evolved Expendable Launch Vehicles (EELVs).
- Use of LWS real-time/near real-time data for operational purposes.
- Establish partnerships for flight of NASA- provided and/or designed space environmental sensors on commercial and other government agency spacecraft.

B.3 The Space Weather Research Network

The Space Weather Research Network (SWRN) would provide crucial measurements from a series of critical vantage points distributed around the Sun and Earth. See Figure B-1. The results would then be brought together and analyzed in a coordinated fashion to discover the essential knowledge, to provide warning of specific events that will affect our space assets, and to relieve effects on our increasingly technology-reliant society.

The SWRN draws heavily upon other NASA missions, although their implementation may be modified if they are applied solely to space weather investigations. The ultimate output of the program would be the scientific knowledge and observational specifications to improve operational space weather systems, and the models to apply to the data to produce accurate and reliable forecasts over the time-scales required to be beneficial to humanity’s space endeavors.

B.3.1 A Global View of the Sun

The first part of SWRN is to obtain the required measurements of the Sun, the driver of the system. The output of particles and fields in the form of the solar wind and radiation across the whole electromagnetic spectrum can affect our environment in many different and specific ways.

It is vital to observe the entire Sun, including the far side, which is not visible from Earth. For example, from a medium-term (days) prediction point of view, it is important to know whether an active region about to rotate onto the solar disk has grown or decayed while on the far side of the Sun. It is then possible to better assess its likelihood of producing a major flare or CME. Events, such as coronal mass ejections, on the far side of the Sun can affect space weather.

From a longer-term prediction (weeks) point of view, it is important to be able to “see” how the sub-surface magnetic field is evolving before it erupts into new sunspot groups. This is now possible with the new science of helioseismology.

Predictions of the next solar cycle (years) would require continuous observations of the solar polar regions where the reversal of the global solar dipole first becomes evident. Also precise measurements of the solar irradiance as a function of wavelength is required to determine the solar input to the Earth and planets. Similarly, measuring the amount of energy lost by the Earth across the spectrum is equally vital.

The specific measurements we need to obtain a high-fidelity view of the Sun are:

- Remote sensing of the internal dynamics of the Sun from a geosynchronous vantage point (Solar Dynamics Platform) which provides a capability of high data rate. This mission could be combined with the irradiance measurements of the Sun and Earth (i.e., an extended version of SONAR).
- Remote sensing of solar activity from key vantage points around the ecliptic (i.e., a next generation STEREO mission including a Solar Farside Observer component).
- Remote sensing of the solar polar regions (i.e., a version of the Solar Polar Imager mission)

Such a group of “Sentinel” missions would produce the data we require individually, but operating together they would provide us with a powerful predictive tool for space weather. Assuming they were designed in a coordinated way, they could also make true tomographic (3D) images of solar events.

While such measurements would characterize solar activity on all the required time-scales in a coordinated fashion for the first time, we also need to know the effects that our ever changing Sun has on the inner heliosphere and understand how those perturbations propagate out from the Sun towards the Earth.

B.3.2 Transit of the Solar Wind

The second stage of the SWRN program is to see how solar disturbances propagate towards the Earth. Their passage through the interplanetary medium dominated by the solar wind changes their nature and effect on the planets they encounter. It is vital that we use both in situ and remote sensing techniques to sample their progress and evolution.

Such measurements also give us a short-term alert (hours) to the approach of a solar disturbance, such as a CME. The required measurements consist typically of particle, fields and plasma wave instruments that characterize the composition, velocity and density of the solar wind as well as the strength and direction of the imbedded magnetic field. This vector information determines the geoeffectiveness of a given event. The transit of CME mass will be tracked with remote sensing techniques (e.g., Stereo CME imaging).

Such measurements should be made from the solar "Sentinel" missions discussed above. There needs to be a small group of such sensors "upwind" from the Earth, within the solar wind stream that will impact the Earth. The L1 point has been ideal for such a group of instruments to characterize the global as well as the local properties of the solar wind disturbances that may cause strong geomagnetic storms.

B.3.3 The Global Properties of Geospace

The previous two parts of the SWRN program provide warning and characterization of the events as they approach the Earth. The last and most complex part of the puzzle is determining how a given event will impact geospace.

To do this we must understand how the energy "leaks" through our magnetospheric shield, how it is redistributed and dissipated. These are global phenomena that are often controlled by local microphysical processes. Hence we have to use a combination of remote sensing to sample a broad range of the macroscale phenomena and widely distributed in situ measurement techniques similar to those used in the heliosphere to understand the microscale processes.

Hence the measurements we need to make are:

- Remote sensing of the Earth's polar regions and night side to see auroral development (i.e., an extension of the Pole Sitter concept to include both poles and the Lagrangian location.)
- In situ plasma and field measurements of the Earth's radiation belts (Radiation Belt Mappers) to see how they are affected by such events (i.e., a version of IMC)
- A combination of remote sensing and in situ sampling of the Earth's upper atmospheric layers (Ionospheric Platforms) to see how these effects propagate down into inner geospace and how they affect the Earth itself

B.4 A Coordinated Approach

This exciting program would be the first step to creating a comprehensive space weather forecasting capability. However it also requires that the data be brought together in a systematic and coordinated fashion, and that LWS missions are supported by a solid theory and modeling program. Only in this way can we study the Sun-Earth connection as a system. A new breed of interdisciplinary scientist must be encouraged to approach the space weather problem in much the same way as we solved the problem of inaccurate short-term meteorological forecasts 25 years ago.

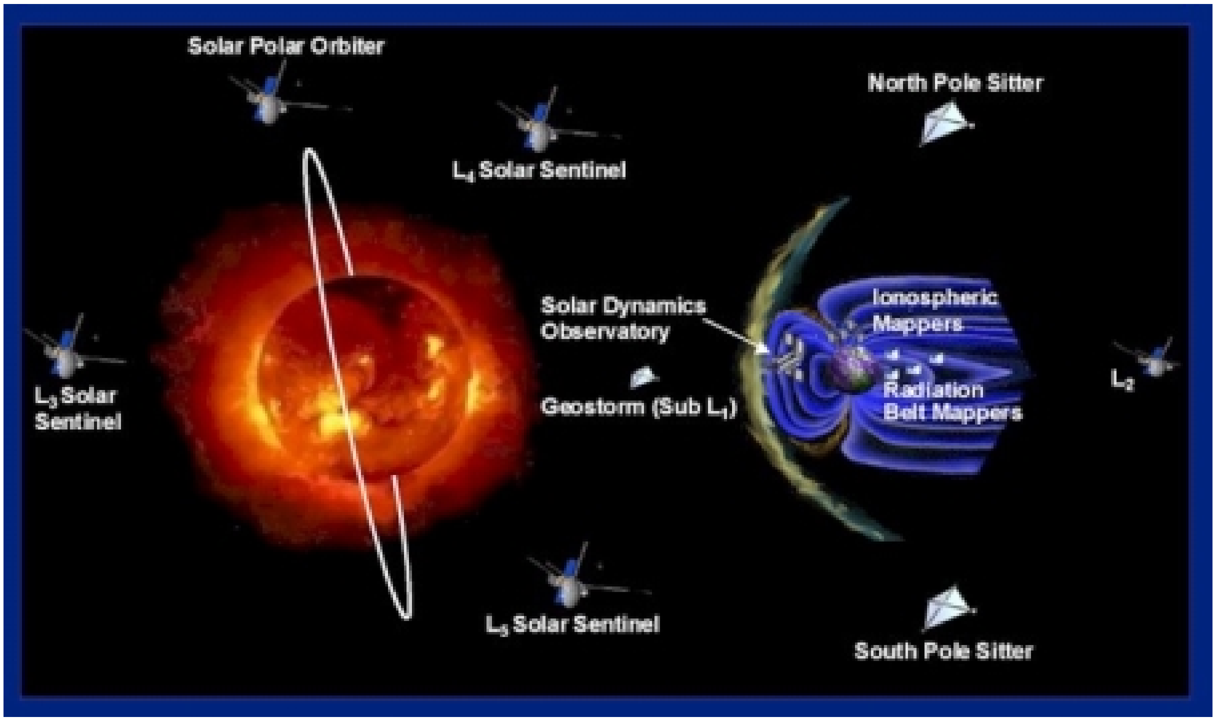

Figure B-1. Space Weather Research Network