Living With a Star

George L. Withbroe

Office of Space Science, NASA Headquarters, Washington DC

The goal of the Living With a Star (LWS) program is to develop scientific knowledge and understanding of those aspects of the connected Sun-Earth system that directly affect life and society. The NASA LWS initiative includes four major elements: (1) a Space Weather Research Network of solar-terrestrial spacecraft, (2) a theory, modeling, and data analysis program, (3) Space Environment Testbeds for flight testing radiation-hardened and radiation-tolerant systems in the Earth's space environment, and (4) development of partnerships with national and international agencies and industry. This paper provides a brief overview of the LWS program.

1. INTRODUCTION

The Living With a Star (LWS) program seeks to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. It is the study of the physics of solar variability and its effects.

Why do we care? We have increased dependence on space-based systems, a permanent presence of humans in Earth orbit, and eventually human voyages beyond Earth. Solar variability can affect space systems, human space flight, electric power grids, GPS signals, high frequency radio communications, long range radar, microelectronics and humans in high altitude spacecraft, and terrestrial climate. Prudence demands that we fully understand the space environment affecting these systems. In addition, given the massive economic impact of even small changes in climate, we should fully understand both natural and anthropogenic causes of global climate change. Solar variability is a primary natural driver and may be responsible for as much as 30% of the global warming in the past century. The scientific community has demonstrated its strong interest in the scientific challenges implicit in the LWS goal. The LWS program serves multiple national interests such as those discussed in interagency reports by the National Space Weather Program (1995, 2000) and the National Security Space Architect (1999), and the National Research Council report *Solar Influences on Global Change* (Lean *et al., 1995).*

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The strategy for NASA's program for understanding the connected Sun-Earth system is organized around three fundamental quests or questions:

- Why does the Sun vary?
- How do the planets respond to solar variability?
- How does solar variability affect life and society?

These three interlinked quests can be restated as objectives for LWS: To determine

- How a star works.
- How it affects humanity's home.
- How to live with a star.

2. NASA SOLAR-TERRESTRIAL RESEARCH PROGRAM

Since the early 1960's NASA has supported the scientific study of the phenomena and fundamental physical processes involved in solar-terrestrial physics. In the late 1980's this research program was consolidated under the NASA Space Physics program. In the mid-1990's the name of the program was changed to the Sun-Earth Connection program to convey better the primary objective, the study of the Sun-Earth connected system, a system driven by a variable star, our Sun. During the 1990's NASA and its international partners launched a powerful set of spacecraft under the International Solar Terrestrial Physics (ISTP) program. These missions, and complementary smaller international and Explorer-class missions, make up the extensive fleet now studying solar-terrestrial events and physics during the current solar maximum. For information on ISTP and other solar-terrestrial missions see the NASA websites given in the references.

Several missions in this research fleet also provide real-time or near real-time data for support of space weather activities. Data from the Advanced Composition Explorer (ACE), Solar and Heliospheric Observatory (SOHO), Yohkoh, and soon Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), are routinely used for space weather purposes by operational agencies (*e.g.*, NOAA, USAF), including the only real-time solar wind monitor providing 30-60 min space weather warnings (ACE). The real-time capability of ACE stems from a NOAA/NASA partnership established when ACE was under development. In order to provide a backup/replacement for ACE, the NASA Sun-Earth Connection program is funding development of a real time solar wind instrument that was added to the Earth Science mission Triana currently scheduled for launch in 2002. The ACE and Triana instruments also will provide two-point measurements of the solar wind at the L1 position approximately 1.5 million km from Earth between the Sun and Earth. EUV and coronagraphic images from SOHO are proving to be very useful tools for detecting coronal mass ejections (CME's) headed toward Earth. Earth-directed CME's appear as "halo" events in the coronagraphic images. The Solar Terrestrial Relations Observatory (STEREO) currently under development, and planned for launch in 2004, will provide the next step via stereo imaging of the Sun and a capability to track solar mass ejections from Sun to Earth using optical and radio instruments.

Many of the new tools for space weather forecasting stem from NASA-sponsored solar-terrestrial research, from imaging coronal mass ejections, discovering x-ray signatures of active regions likely to produce CME's, to detecting solar active regions on the far side of the Sun via helioseismology. These advances and the steady flow of new knowledge from the ISTP and complementary missions, coupled with a renewed interest in the effects and potential importance of solar influences on terrestrial climate, led to the development of the Living With a Star (LWS) Initiative.

3. LIVING WITH A STAR INITIATIVE

3.1 Introduction

LWS is built on the heritage of the past and current international solar-terrestrial physics research effort, the Sun-Earth Connection (SEC) Roadmaps (Burch *et al.* 1997, Strong *et al.* 2000) developed in conjunction with the NASA Space Science strategic planning process, recent reports of the National Research Council/National Academy of Sciences (Lean *et al.* 1995, Neugebauer *et al.* 1995, Siscoe *et al.* 2000), and reports by the interagency National Space Weather Program (1995, 2000) and the National Security Space Architect (1999). The goal of LWS is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. LWS differs from the other programs in the NASA Sun-Earth Connection program in that contribution to the LWS goal is a primary criteria in the selection of the research problems and missions to be undertaken within the program. The LWS program is not limited to space weather. Equally important are solar influences on global change.

Relevant issues involving impacts of solar variability on life and society include:

- Human radiation exposure in space flight and high altitude aircraft,
- Impacts on technology related to space systems, communications, navigation and terrestrial systems, and
- Terrestrial climate change, both short and long term.

LWS, a NASA research program, directly benefits the National Space Weather Program, aerospace industry, satellite operations, air transport industry, communications and navigation. LWS also has links to each of the NASA Enterprises. For Space Science, LWS quantifies the physics, dynamics, and behavior of the Sun-Earth system over the 11-year solar cycle and is the detailed study of the only star and space environment directly accessible by a wide range of remote sensing and *in situ* measurements. For Earth Science, LWS improves the understanding of the effects of solar variability and disturbances on terrestrial climate change. For Human Exploration and Development, LWS provides data and scientific understanding required for advanced warning of energetic particle events that affect the safety of astronauts. Finally, for 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.

3.2 Science Questions

A flowdown of science questions directed at space weather hazards for human radiation exposure, impacts on technology, and the relationship to terrestrial climate are summarized below. This summary was prepared by the NASA Sun-Earth Connection Advisory Subcommittee chaired by Andrew Christensen.

Human Radiation Exposure: The systems affected are the International Space Station, space exploration, high altitude aircraft, space utilization and colonization. The space weather hazards are:

- Solar energetic particles (SEP) events.
- Relativistic electron events (REE).

The relevant science questions are:

- What determines when SEP or REE will occur?
- What determines their spatial, temporal, and spectral development?
- What are the mitigation strategies?

Mission definition issues include:

- What are the required predictive capabilities?
- What parameters should be monitored?
- Where is the best place to monitor them?
- What models are needed?

Impact on Technology: The systems affected are satellites (Earth orbiting), spacecraft (non-Earth orbiting), human space flight (International Space Station, Space Shuttle), communications and navigation, and some ground systems (e.g. the electric power grid).

The relevant space weather hazards are:

- Variable atmospheric drag.
- Enhanced ionospheric ionization.
- Solar x-ray and solar energetic particle events (SEP).
- Relativistic electron events (REE).
- Magnetospheric particles and fields.

The relevant science questions are:

- What determines the heliospheric, magnetospheric, atmospheric, and ionospheric responses to solar variability?
- What causes onset and development of ionospheric scintillations?
- What determines when solar generated particle and radiation events, magnetospheric storms and substorms occur?
- What determines the spatial, temporal, and spectral development of all these phenomena?
- What drives these phenomena and how much warning can reliably be obtained?
- How do the mean space environmental conditions (relevant to spacecraft design) at a given spatial location vary through the solar cycle and what are the probabilities of different levels of deviations from the mean?

Mission definition issues include:

- What are the required predictive capabilities?
- What variables should be monitored?
- How and where should it be done?
- What models and theory are needed?

Terrestrial Climate: The terrestrial phenomena that are affected are climate change (past and future), surface warming, and ozone depletion and recovery. The relevant solar-terrestrial sources are:

- Solar electromagnetic radiation.
- Solar and galactic cosmic rays.
- Upper atmospheric/ionosphere boundary region.

The related science question is:

- What is the role of the sun and heliosphere in global climate change on multiple time scales (seasonal, decadal, centennial)?

Relating this science question to missions requires addressing the following issues:

- What long-term studies of sources of energy from the Sun should be undertaken to advance understanding of solar effects on climate change?
- What long-term studies are needed to understand the role of the heliosphere, magnetosphere and the upper atmosphere/ionosphere on climate?
- How should development of quantitative models proceed?
- What predictive capabilities will be needed?

These issues have been, and continue to be addressed, through meetings and workshops involving stakeholders who are interested in and/or affected by solar variability and its effects on life and society. These interactions provide the basis for a requirements flowdown for the LWS program.

3.3 LWS Elements

LWS has four elements: (1) a Space Weather Research Network, (2) a Theory, Modeling & Data Analysis Program, (3) Space Environment Testbeds, and (4) Partnerships.

Space Weather Research Network: There are two groups of missions proposed in the LWS Initiative to form a Space Weather Research Network. (a) solar dynamics element (Solar Dynamics Observatory and Solar Sentinels) that observe the Sun and track space disturbances originating there and (b) geospace dynamics elements (Radiation Belt Mappers and Ionospheric Mappers) consisting of constellations of small satellites located in key regions around the Earth to measure effects of solar variability on the geospace environment. Further in the future are missions that depend on development of solar sail propulsion, the Solar Polar Orbiter/Imager and Earth Pole Sitters. The location of the LWS missions in the Sun-Earth environment are depicted schematically in Plate 1.

The Solar Dynamics Observatory (SDO) will observe the Sun's dynamics and help us understand the nature and source of variations, from the solar interior into the solar atmosphere. The Solar Sentinels will provide a global view of the Sun and inner heliosphere and describe the origin and evolution of eruptions and flares from the Sun to Earth. The Radiation Belt Mappers will study the origin and dynamics of the radiation belts and determine the evolution of penetrating radiation during magnetic storms. The Ionospheric Mappers will gather knowledge on how the ionosphere behaves as a system that responds directly to solar photons and energetic particles, as well as solar

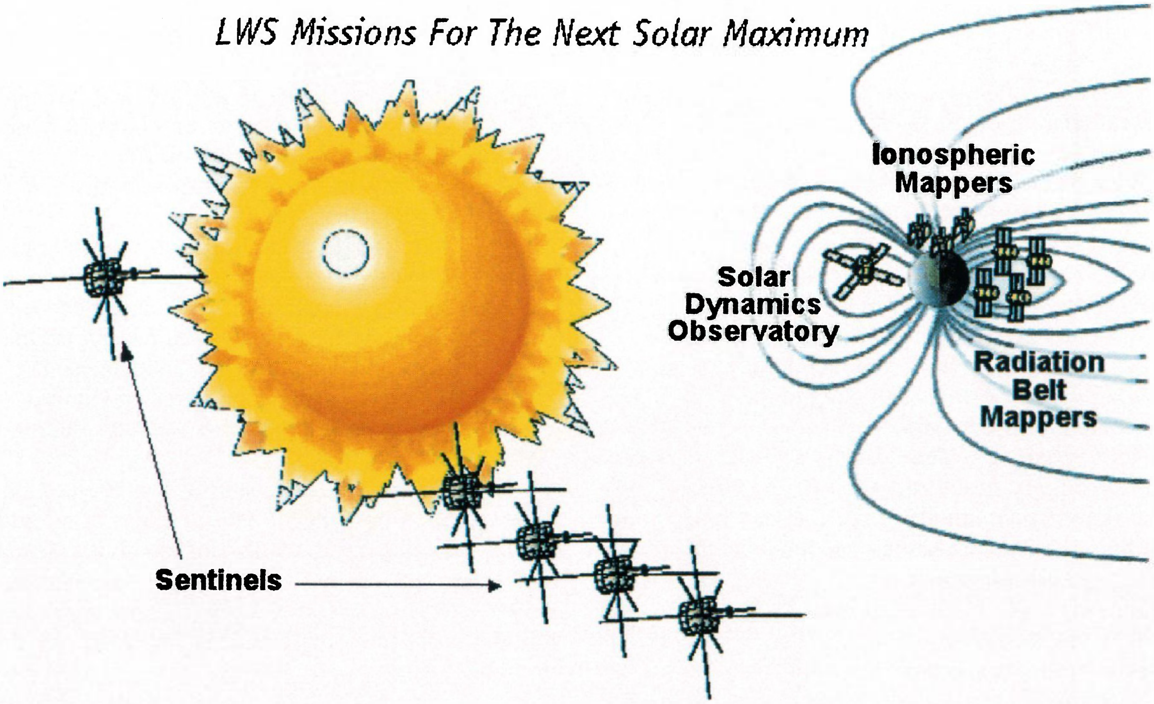

Plate 1. LWS Space Weather Research Network. The four types of missions planned for launch by the next solar maximum are illustrated schematically.

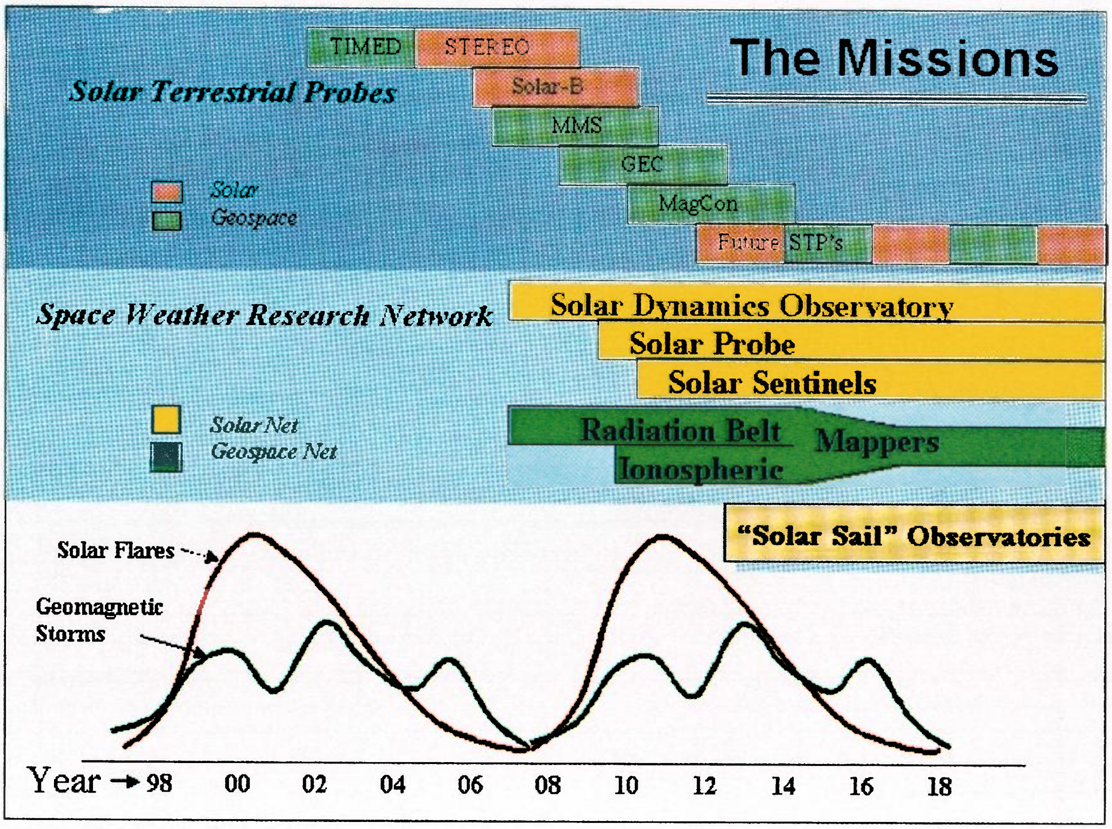

Plate 2. LWS and the Solar Cycle. The approximate times when various Solar Terrestrial Probes and Living With a Star missions are expected to be operating are illustrated schematically.

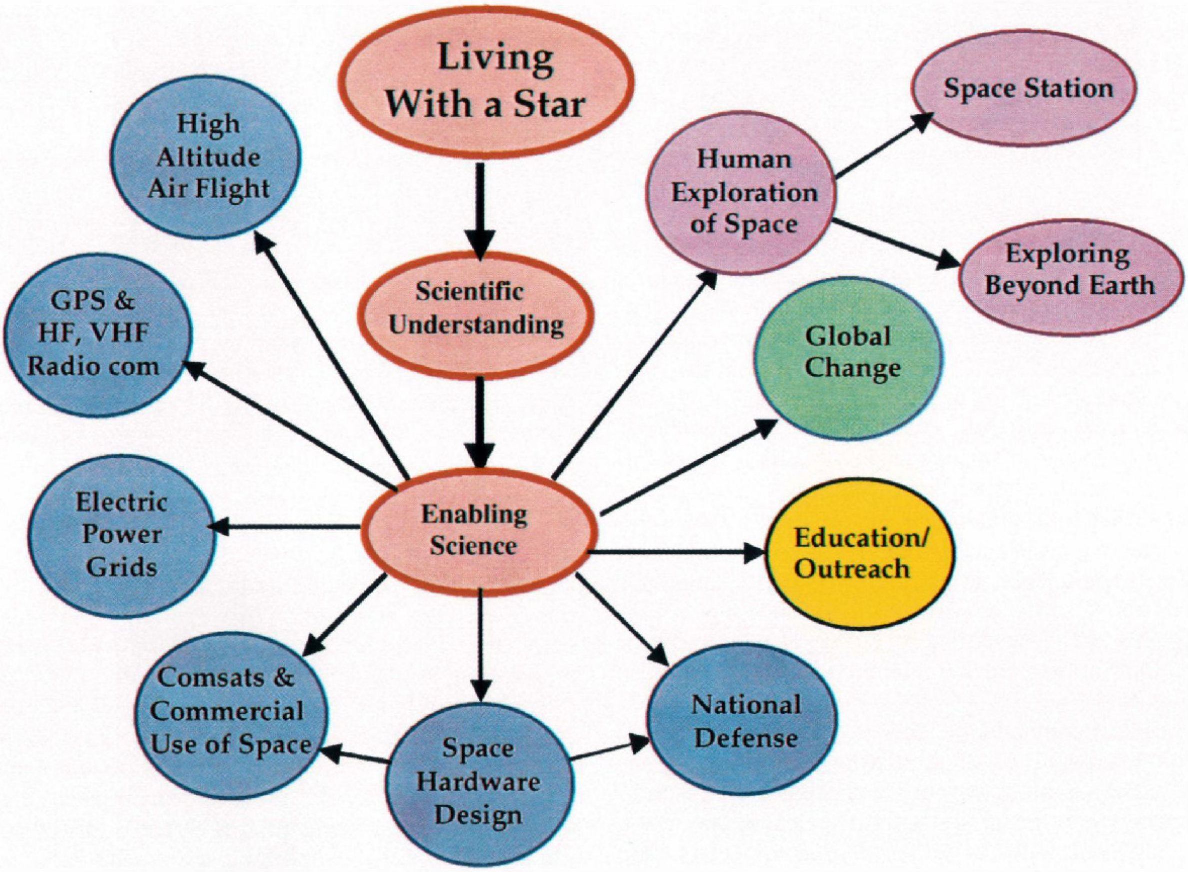

Plate 3. Sun-Earth Connections.

wind energy stored and then suddenly discharged by the magnetosphere during geomagnetic storms and substorms.

The schedule for the launch of these missions is planned so that the basic mission set (SDO, Solar Sentinels, and Magnetospheric and Ionospheric Mappers) will be operational by the next solar maximum, as illustrated in Plate 2. The upper part of the plate shows the Solar Terrestrial Probe (STP) missions currently under development or planned. The LWS and STP missions are intended to operate synergistically. The presently planned STP missions include Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) mission, Solar-B, STEREO, Magnetospheric Multiscale (MMS), Geospace Electrodynamic Connections (GEC), and Magnetospheric Constellation (MagCon). Additional information about these missions can be found at the NASA Space Science Mission and Solar Terrestrial Probe websites given in the references.

Theory, Modeling and Data Analysis: The LWS research and data analysis program will exploit data from present and past missions to (1) improve the scientific knowledge and understanding of those aspects of the Sun-Earth connected system relevant to space weather and terrestrial climate change, (2) develop new techniques and models for predicting solar/geospace disturbances that affect human technology (e.g. the "S marks the spot" signature of solar regions with enhanced probability of generating coronal mass ejections), and (3) improve knowledge of space environmental conditions and variations for design of cost-effective systems to minimize or eliminate impact of space environmental effects. The first solicitation for proposals for data analysis, theory, and modeling in support of LWS goals was issued by NASA Headquarters for investigations to begin in 2001. Future solicitations will are planned yearly.

An important component of this effort will be the newly initiated Community Coordinated Modeling Center (CCMC). The CCMC's purpose is to take new research-grade space environment simulations codes, modify them to run on Department of Defense supercomputers, and transition the results to operational agencies such as NOAA. Additional information about the CCMC may be found at the CCMC website given in the references.

Space Environment Testbeds: The use of environment-tolerant systems in place of environment-hard systems shifts the focus from risk avoidance to risk management. This requires a better understanding of on-orbit performance for risk assessment analyses. The goals of the Space Environment Testbeds element of LWS are to:

- Understand space environment effects on current and emerging technologies and biosystems.
- Understand application of space weather predictions for risk management of new technologies.
- Establish ground test protocols for new technologies.
- Validate models.
- Demonstrate instrumentation for LWS missions.
- Improve environmental guidance for spacecraft design and operations.

Partnerships: The LWS Initiative is developing partnerships with other federal and international agencies to augment existing capabilities and provide new systems. To this end, LWS will:

- Work with partners to define national needs.
- Prototype new observing capabilities to prove or disprove their usefulness. Useful technologies will be made available to other agencies for monitoring and predictive purposes.
- Make data from research missions available for use by other federal agencies and the scientific and applications communities.
- Work with national and international partners to develop a coherent, synergistic program in studying solar effects on space weather and climate.

3.4 Complementary Missions

LWS will be complemented by data from other missions. These include currently operational or soon to be launched space research missions of NASA and its international partners. The relevant solar missions are Yohkoh (91), SOHO (95), TRACE (98), and HESSI (01) where the number in parentheses is the launch year. The relevant geospace missions are: Geotail (92), SAMPEX (92), WIND (94), POLAR (96), FAST (96), IMAGE (00), Cluster (00), TIMED (01), and TWINS (03,04). In addition, the GOES series of NOAA operational missions will continue to be a source of data at geostationary orbit. The relevant heliospheric missions are IMP-8 (73), Ulysses (90), ACE (97), and TRIANA (02), and Solar Probe (08). As indicated earlier (*cf.* Plate 2), the Solar Terrestrial Probes (STP) are particularly relevant to LWS because they will be operational in the same time frame as the LWS missions, whereas many of the currently operating missions will be well beyond their design lifetimes. See the NASA Space Science Mission website for more information on the above missions.

4. SUMMARY

The NASA LWS Initiative is a scientific research program that will provide the scientific context and understanding necessary to characterize, understand, and predict those aspects of solar variability and its effects that affect life and society. Plate 3 depicts the communities that will benefit from the scientific understanding resulting from the LWS program. The SEC and LWS websites (see references), which are periodically updated, provide additional information about the NASA Sun-Earth Connection program and its LWS component.

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George L. Withbroe, Code SA, NASA Headquarters, Washington DC 20546