Living With a Star
Science Architecture Team

report to SECAS

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LWS Science Architecture Team

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INTRODUCTION

This document is a summary of the work of the LWS Science Architecture Team (SAT) from November 2000 to July 2001, prepared at the request of the Sun-Earth Connections Advisory Subcommittee (SECAS). The main findings of the SAT are as follows:

Observational Requirements:
The global observations required to meet LWS goals can only be met by a combination of new spacecraft and instruments carefully chosen to fill key gaps not covered by other NASA and other agency spacecraft. The initial set of missions to be defined in detail by Mission Definition Teams are:

- **Solar Dynamics Observatory(SDO) --** Solar seismology and magnetic field studies; EUV radiation; radiation belt studies (Science Definition Team study completed in mid-2001)
- **Radiation Belts --** Radiation belt studies over a range of L shells; two launches in order to cover full solar cycle
- **Low Earth Orbit --** *in-situ* measurement of ionosphere and thermosphere dynamics and structure; solar energetic particles & polar cap size; SAA
- **Eccentric Polar Orbit --** global auroral imaging and O/N_2 perturbations; energetic neutral atom imaging for ring current dynamics
- **Inner Heliospheric Mappers --** 4 identical spacecraft in inner heliosphere orbits; structure, dynamics, & radial evolution of CMEs, solar particles, and geo-effective disturbances

Data Systems Team
This team will define a Comprehensive Data System from which LWS researchers can easily access the multiple observations required to develop, refine, and test theory and modeling of the Sun-Earth system. The system, which may be a virtual system, will include data from other NASA and other agency programs as appropriate, and plays a critical role in the program.

Theory, Modeling & Data Analysis Definition Team
This team will design a coordinated and comprehensive theory, modeling and data analysis program. Activities in this area not only allow development of new theories and improvements of models, but also will form the basis for new observational initiatives to be undertaken later in the program.

The SAT identifies the Comprehensive Data System and Theory, Modeling, and Data Analysis as *critical management challenges* for the LWS program, since it is much more complex and comprehensive than any prior undertaking by the community.

BACKGROUND AND GUIDANCE

The LWS Science Architecture Team (SAT) was organized by NASA Headquarters in the fall of 2000 to carry out a broad number of tasks in the definition of the LWS program. The main role of the SAT from its Charter is to "examine the LWS program requirements and architecture from an overall systems point of view." Since LWS is a major leap forward in systems approach to studies of Sun-Earth Connections, the SAT focused primarily on broad requirements (the SAT Charter is in Appendix 1).

In addition to the Charter, the SAT received additional guidance from the Sun-Earth Connections Subcommittee, which articulated the program goal and objectives that are listed in Table 1. A key portion of the SECAS guidance was the inclusion of societal consequences as a requirement for assessing the relevance of phenomena to the program. The SECAS material went on to list a number of specific areas appropriate for LWS (e.g., radiation exposure at Space Station; see Appendix 2 for the complete text).

Priorities among the broad objectives for LWS were provided to the SAT by George Withbroe, SEC program director. They are summarized in Table 2 (see Appendix 3 for the complete text). Although the LWS priorities rated some areas as higher priority than others, out initial guidance from NASA Headquarters was to consider all areas in our work.

Prior Studies

The SAT's work on these issues benefited tremendously from a number of recent publications, in particular:

- NASA Workshop on Sun-Climate Connections Summary Report, University of Arizona, March 6-8, 2000
- National Space Weather Program Implementation Plan, 2nd Edition, July 2000
- NASA LWS Pre-Formulation Study, Volume 1, Program Architecture, August 22, 2000
- Space Weather Architecture Study, National Security Space Architect, December 1997 - June 2000

The Workshop on Sun-Climate Connections was a critical resource for the SAT, and the measurement requirements identified in it were used extensively for the climate related recommendations in this report. The LWS Pre-Formulation Study was used extensively in the SAT's consideration of nominal missions for obtaining measurements required by the program. Even though the “notional” missions defined in the Study were set-aside under guidance from SECAS, the eventual missions considered here have

Table 1 -- LWS Goals and Objectives from SECAS

LWS Goal
Develop the scientific understanding necessary to enable the US to effectively address those aspects of the Connected Sun-Earth system that directly affect life and society.
LWS Objectives
• Identify and understand variable sources of mass and energy coming from our Star 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 our knowledge and understanding gained in this program to explore extreme solar-terrestrial environments and implications for life and habitability beyond Earth. March 2000 SECAS meeting

many features in common with the Pre-Formulation missions. The studies and costing research carried out by the LWS project at GSFC was critical for the SAT's ability to make estimates of the capability and costs of recommended missions. The National Space Weather Program document was particularly useful for its view of comprehensive modeling, and for its survey of existing models and goals for future, comprehensive models.

Table 2 -- LWS Priorities

Priority	Area
1	Solar Influences on Global Change
2	Space Environmental “climate” data (e.g., specification models)
2	Nowcasting Space Environment
3	Prediction of: a) Solar Proton Events (astronaut safety, especially for deep space) b) Geomagnetic Storms for applications where effective mitigation is possible (e.g. electric power grid). c) Space Environment for operation and utilization of space systems.

SAT Workshop

Discussions at the first meeting of the SAT in November 2000 made it clear that the small membership of the SAT did not cover all the scientific and technical areas encompassed by the program. On the other hand, the SEC community had been considering many of these issues for years, and a great deal of thought had been given to many aspects of the problem. As a way of systematically tapping into this expertise, the SAT decided to hold a one day workshop where scientists from the all segments of the community could come together and discuss these issues from the point of view of the LWS program. The overall goals of the workshop were to

- Identify all phenomena relevant to LWS for three subprogram areas (Space Explosions, Space Storms, and Space Environment)
- Identify predictive requirements and goals
- Identify required observations and theory / modeling

About 50 members of the community were invited and the acceptance rate was extremely high (>90%) given the short notice between the invitation and workshop (6 weeks). A great deal of information was collected at the workshop, and organized afterwards by the SAT subgroup leaders. The notes from the workshop formed the basis for the subsequent work of the SAT in both the identification of areas of relevance, and in the required observations and models. Attendees at the workshop are given below in Appendix 4. The SAT’s notes from the workshop can be downloaded from the following URL: http://lws.gsfc.nasa.gov/lws_sat_workshop0601.pdf

Practical considerations

Some additional practical considerations should be mentioned to clarify the scope of the SAT's work.

The SDO mission: When the LWS program started, the flagship Solar Dynamics Observatory (SDO) mission was far ahead of other missions in the program. SDO had already been part of the SEC strategic plan (as the SONAR mission) and a Mission Definition Team (MDT) had been formed and begun meeting prior to the formation of the SAT. Linkage between the SAT activities and the SDO MDT was achieved by having joint membership on the SAT and SDO MDT from both the outside science community, and the LWS project scientist. Although briefed on the SDO Science Definition Team effort and status, the SAT considered the SDO science measurements as a "given" in the future program, and did not attempt any redefinition of the SDO mission.

Sequence of Geospace vs. Heliospheric Missions: Beyond the SDO mission, which will be the first new spacecraft launched under LWS, there is an additional issue regarding missions that are focused on phenomena in the space near Earth (Geospace missions) and those in the heliosphere between the Sun and Earth Orbit (Heliospheric missions). Due to launch considerations, Heliospheric missions require dedicated launches, while in Geospace there are many more possibilities due to the number of spacecraft being launched into similar orbits. Based on a number of considerations including the cost, timing, and the sequence of missions in the Solar Terrestrial Probes program, NASA Headquarters determined that the sequence of missions following SDO would be the initial Geospace missions first, followed by Heliospheric missions (these missions are described in Appendix 7). For this reason, the SAT did not consider alternate sequencing scenarios for the recommended LWS missions.

Rate of progress: although LWS is a research program addressing scientific questions in the SEC area, it has the unique feature that the questions to be addressed must be relevant to societal consequences. The SAT concluded that the LWS program must therefore show clear progress in at least some areas in a 5-10 year time scale. This has important implications for the scientific strategy of the program, since near-term progress must necessarily be based largely on theories, models, and observations of the type available today. Therefore, the near-term strategy for achieving progress is to improve on our current understanding and theories, as well as the observations. The SAT therefore focused primarily on near-term activities (5-10 year time scale).

While the SAT emphasized the near-term activities, the ultimate goals of LWS will undoubtedly require a sustained, long-term effort, and such a long-term program is anticipated by the SEC community. The SAT recognized that a portion of the initial resources should be used for risky, but potentially high pay-back research thrusts that may form the basis of an ultimate program. This type of basic research was seen as a key part of the program, but less so in the initial few years. The LWS program will certainly support such fundamentally new approaches, but the SAT noted that in addition there are other areas of the SEC program where this can be carried out, namely the Research and Analysis program for theory, modeling, and data analysis, and the STP and Explorer programs for new space observations.

SAT APPROACH

The Sun-Earth system includes a wide variety of spatial regions and processes connected by complex linkages such as those sketched in Figure 1. Many of these regions and processes have been traditionally the focus of separate disciplines. The SAT recognized, as given in its charter, that a key defining aspect of the LWS program is the development and implementation of "systems science" capability in order to gain a global understanding. In order to achieve a systems approach to phenomena of interest to LWS, the SAT organized research areas in terms of linked sequences of events in order to

- follow physical processes from start to finish (e.g. sun to upper atmosphere)
- ensure that *all* significant links in the chain are identified
- enable a global theory, modeling and data analysis effort to achieve predictive goals

As an example, consider a CME whose origin is in solar magnetic fields, followed by an eruption and propagation through the corona and inner heliosphere, then impacting the magnetosphere, and finally depositing energy in the upper atmosphere, ultimately impacting communication, navigation, and radar (e.g., Figure 2). Understanding this sequence of events requires expertise from all segments of the SEC community. By following the problem from a start-to-finish perspective, it is ensured that all the critical linkages (e.g. corona to inner heliosphere, magnetosphere to ionosphere/thermosphere) are identified and their role addressed.

As another example, consider the possible role of solar variations (in electromagnetic radiation and energetic particles) in causing changes in the global ozone distribution and subsequent climactic impact. Progress in assessing this role requires solar observations of UV and X-ray emissions, and emissions of energetic particles. While the photons impact the upper and middle atmosphere directly, energetic particles have both direct (over the polar cap) and indirect (through magnetospheric precipitation) links to the upper atmosphere (e.g., Figure 3). Finally, to assess the results of the radiation inputs, it is necessary to have validated global atmospheric circulation models that can calculate the ultimate results from specified solar inputs and to connect to general circulation models of the space environment.

Space Storms and Space Environment: in considering the array of phenomena relevant to LWS, and the observations, theory, data analysis, and modeling relevant to treating them, the issue of *time scales* arises immediately. This provides a useful way to view aspects of the coupled space system without reverting to classical SEC sub-disciplines. Going back to the

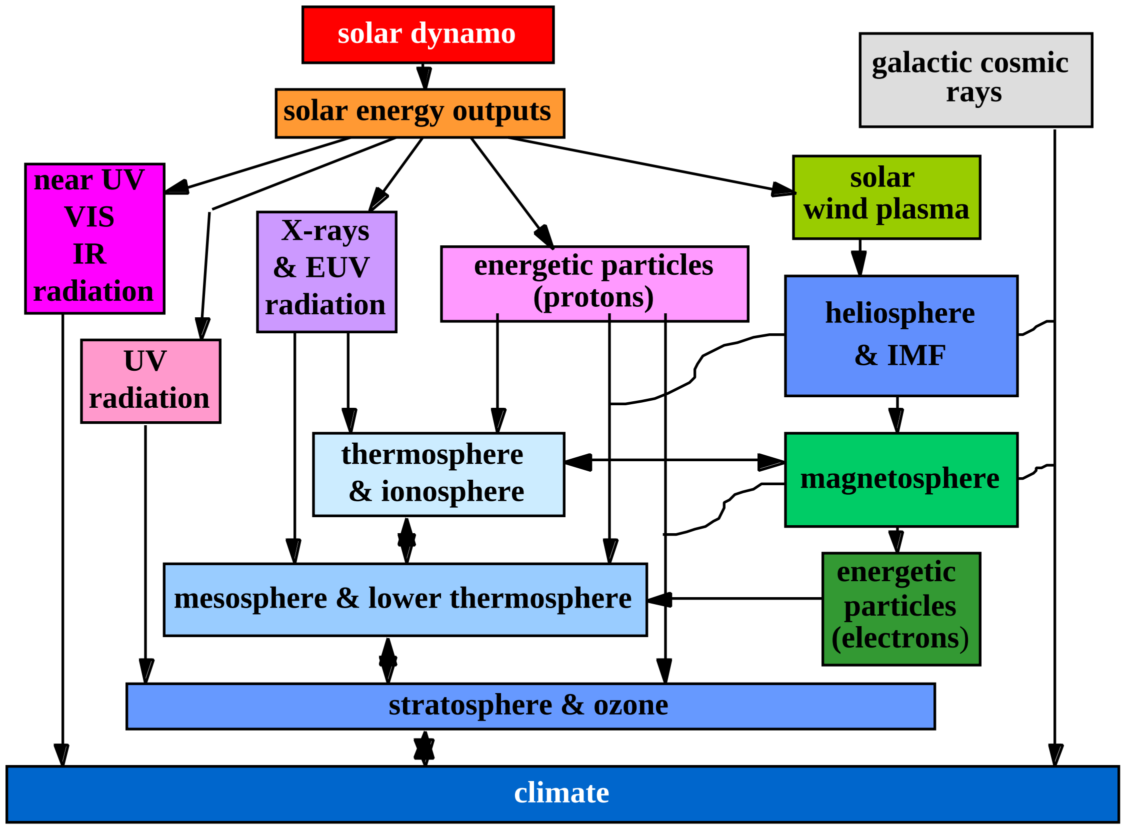


Figure 1: diagram illustrating linkages between different regions of the Sun-Earth system. Figure courtesy of Judith Lean.

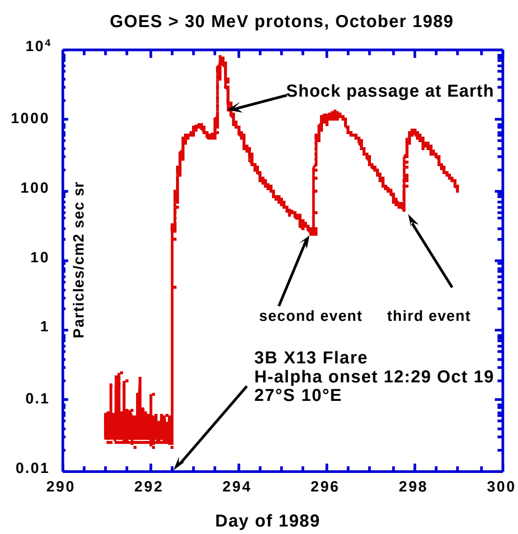
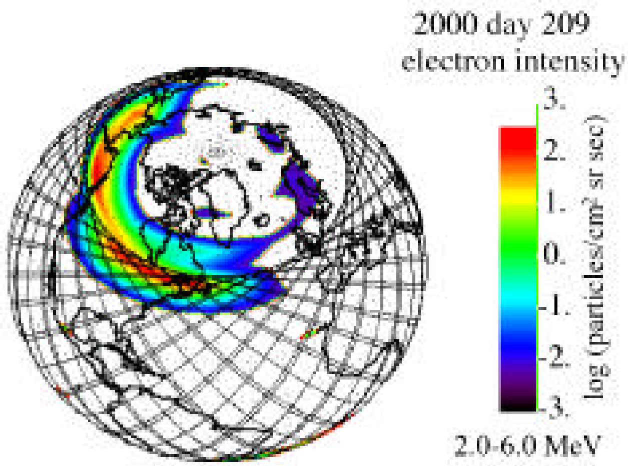


Figure 2: this large SPE originated in solar magnetic fields which erupted, causing a flare and a subsequent CME that propagated to Earth, impacting the magnetosphere and affecting the ionosphere/thermosphere. Two more events from the same magnetic region took place a few days later.



SAMPEX data courtesy of S. Kanekal

Figure 3: high speed solar wind streams energize the magnetosphere, followed by precipitation of energetic electrons into the upper atmosphere. This can affect the Space Station (whose orbital ground track is shown) and the chemistry of the upper atmosphere with possible implications for global ozone.

Prioritized areas (Table 2), note that Global Climate Change and Space-Environment specification models generally involve phenomena that have time scales of months, years, or even centuries. Archival data may be the only way possible to address some of the questions, and the specifications that result are not dependent on day-to-day events, but rather on longer scales such as solar cycles. In addition, issues of “nowcasting” or short-term prediction are not meaningful, and this has implications on observational requirements and the types of modeling and data analysis than can be employed. Such phenomena were grouped by the SAT under the heading **Space Environment.**

The other two entries in Table 2, Nowcasting Space Environment and Predictions of SPEs and storms, involve research that could lead to near-real time modeling of the Sun-Earth system. Both observational and theory, modeling, and data analysis for nowcasting and predictions require near-real time data, and models that can operate on a broad range of near real-time inputs. Although there is some overlap with areas of the space environment, the SAT treated this group separately as **Space Storms,** in order to ensure identifying the unique requirements of this part of LWS.

Table 3 -- LWS Science Architecture

Implementation Group / (Pre) Science Definition Teams (SAT subgroups)	Theory and Modeling / Data Analysis	Sun	Heliosphere	Geospace	Space Environment Testbeds
Space Environment • Climate forcing • Specification models	Specification modeling	Irradiance	Secular solar wind model	Solar cycle radiation specification	Radiation tolerance (degradation)
Space Storms • Nowcasting/anomaly • Prediction (events, environment)	Dynamic Models, Analysis	Flares CMEs SPEs	Solar/storm warning CME propagation	Shocks Storm process	Mitigation (SEUs, charging)

table courtesy of Larry Zanetti

These groupings are indicated schematically in Table 3, which shows the SAT organization on the horizontal column, with the vertical columns indicating the mapping into traditional segments of the SEC research agenda.

Problem areas

The SAT subgroups, Space Storms and Space Environment, each identified a set of "problem areas" -- areas of SEC basic research where improved understanding would have societal applications. The list of topics compiled by each group is intended to touch on all areas of significant interest to LWS. Tables 4 and 5 list the topics in each case. Examination of the tables shows that some topics might fit under more than one heading in the table (e.g., in Table 4 item 7 might be also listed under "Dynamics of the Near-Earth Radiation Environment").

Table 4 -- Space Storms Problem Areas

Solar Impacts on Communications, Navigation and Radar

1) Forecast the effects of variations in the electron density distribution in the ionosphere
2) Discover the cause of plasma density irregularities that cause radio scintillation

Tracking and Identification of Objects in Space

3) Understand and predict solar influences on satellite drag

Geomagnetic Induced Currents

4) Develop the capability to forecast induced currents due to ionospheric-geomagnetic current systems

Dynamics of the Near-Earth Radiation Environment

5) Discover the processes that accelerate, transport, and distribute energetic particles during geomagnetic storms
6) Understand and predict the intensity of outer-zone electrons due to high-speed solar wind streams

Particle Radiation Associated with Explosive Events on the Sun

7) Develop the capability to forecast solar particles accelerated by flares and CMEs
8) Predict the intensity of particles accelerated by traveling interplanetary shocks
9) Understand how solar/interplanetary variability governs the entry of energetic particles into the magnetosphere

Table 5 -- Space Environment Problem Areas

Solar Impacts on Communications, Navigation and Radar

1) Determine the effects of long and short term variability of the Sun on the global-scale behavior of the ionospheric density from 100 to 1000 km.
2) Discover the influence of solar variability on the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.

Tracking and Identification of Objects in Space

3) Determine the effects of long and short term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe them with accuracy better than 5%.

Dynamics of the Near-Earth Particle Radiation Environment

4) Understand the processes responsible for the acceleration, loss, and transport of radiation belt electrons and ions responsible for radiation dose and bulk charging effects.
5) Understand the geospace response to geomagnetic storms such as the development and trapping of the ring current, Joule heating of the ionosphere, ground induced currents, severe spacecraft surface charging environments, etc.
6) Reveal and characterize the effects of solar energetic particles at low Earth orbit and in the atmosphere/ionosphere

Climate variability due to solar variations

7) Identify and quantify the Earth's near-surface temperature changes attributable to solar variability (from both direct and indirect solar energy forcings).
8) Identify and quantify the changes in ozone distribution attributable to solar variability (in the form of electromagnetic radiation and energetic particles).

Deep space probe / Astronaut safety on Mars mission

9) Develop the capability to specify and predict solar activity (on time scales of active regions to the solar cycle) and heliospheric modulation of energy inflow from the Sun and the galaxies to the Earth’s space environment.

Sample problem area treatment

Given that the observational sampling of the Sun, heliosphere, and geospace is extremely sparse, the SAT adopted the view that the ultimate product of the program would be in physics-based models of the various regions of importance. In this approach, the role of observations is to understand the physical processes so that theory and models can be developed, and, eventually, to drive the models so that nowcasting and predictions can be made. In the words of one attendee at the SAT workshop, "the observations should be made to feed the models." Several very important implications follow from this approach, including

- The LWS program will need to develop large scale global models well beyond the scale undertaken by individual Principal Investigators, and involving interfaces among traditional SEC regimes that are not the focus of existing research.
- A broad community of researchers will need to have ready access to data sets from many spacecraft covering broad areas of the Sun-Earth system.
- It will be necessary to have a multi-year period of simultaneous observations of the whole system in order to understand, and convincingly demonstrate that we understand all the linkages.
- The importance of observations in the program can be quantitatively linked to their role in improving models, and/or reducing the uncertainties in nowcasting or forecasting.

The first three bullets above have a critical role in the management and organization of the LWS program. The last bullet provides a clear mechanism for evaluating and prioritizing measurement objectives.

With this model-centered approach, the SAT then approached the problem areas listed in Tables 4 and 5, with a view to defining the ultimate evolution of scientific knowledge and modeling that would be required for a meaningful LWS contribution to environment specification and/or nowcasting/forecasting in each case. As an example of the method used, we illustrate the case of producing a model that can specify and predict the mass density of the atmosphere between 120 and 600 km altitude with accuracy better than 5%. (problem #3 in Table 5).

Figure 4 shows the first sheet of the template, which lists

- Societal impact of problems that could be addressed with this improved model
- the primary current limitations on this model
- the LWS improvement goal in the 5-10 year period
- the LWS goal for the >10 year period

The first of the bullets gives an idea of the societal impacts and thus can be used to evaluate the importance of this problem compared with other LWS

Produce the capability to specify and predict the mass density of the atmosphere between 120 and 600 km altitude with accuracy better than 5%.

- **Societal impact:**
  - **Satellite orbits are perturbed by atmospheric drag.**
  - **Atmospheric conductivity is critical parameter for determination of induced ground-currents, and ionospheric radio scintillation.**
- **Primary Current Limitations:**
  - **Empirical model with 20% long term accuracy.**
  - **Poor altitude specification below 350 km.**
  - **Computational models driven by proxies for solar EUV radiation and electromagnetic drivers.**
  - **Sensitive to poorly specified small scale motions at lower boundary.**
- **5-10 yr LWS goal:**
  - **Refine empirical model of winds and density with new data & inputs.**
  - **Validation of physics-based models with variations in measured input drivers.**
  - **Establish data assimilation processes to accommodate sparse data sets**
- **> 10 yr LWS goal:**
  - **Validated physics-based assimilation model.**

Example of LWS problem area

Figure 4. Sample of LWS SAT template for improving knowledge of mass density of the upper atmosphere.

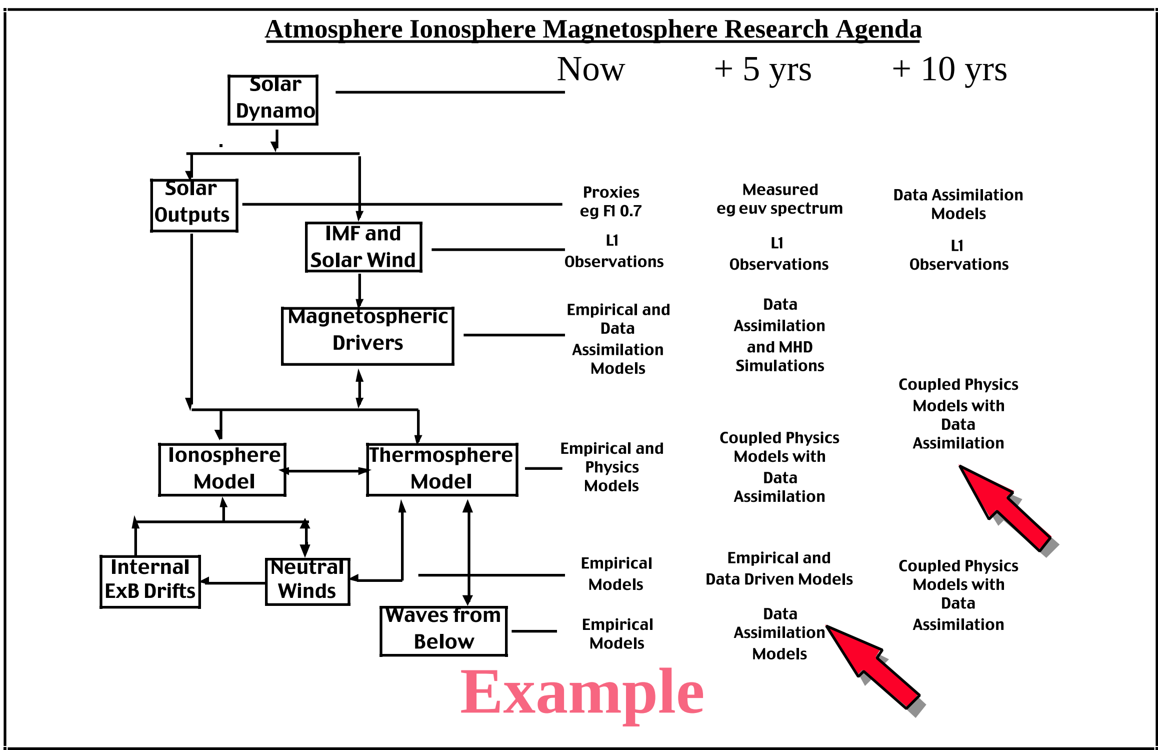


Figure 5. Present status of model elements and 5 and 10 year goals; arrows highlight some of the research agenda modeling goals.

problem areas. The second bullet inventories the current status. The third identifies the prospects for actually making progress on this problem in the near-term, and can form a basis for metrics. The fourth states the ultimate long-term goal in this area. The experience of the SAT members working on these charts was that they required expertise of researches from more than one area.

Figure 5 shows the research agenda for this problem area, with all the boxes on the left eventually leading to the required, improved theories and models, highlighted with arrows. The left of the figure shows linkages of different regions relevant to the problem. The presence of these different regions in the figure does not imply they are all equally important to making progress in this particular research area. SAT members noted that often, the more remote the linkage between a region and the area of interest, the less impact improvements in the remote area will have on actual improvements in model at hand. In this particular figure, this can be exemplified in the case of the solar dynamo box. By one path, the solar dynamo impacts the thermosphere, via coupling through the corona / IMF / solar wind / magnetosphere. Given the large number of couplings in this case, it is highly unlikely that improvements in a dynamo model could actually result in near-term improvements in the thermospheric model accuracy. However, by another path, the dynamo drives solar outputs (e.g. EUV) that link directly to the thermosphere. Improvements in this area may be of great importance to improved specification models of the thermosphere and ionosphere.

Considerations such as these can be used to evaluate the importance of measurements to a given problem. This can be important not only in addressing the question of whether or not a particular measurement should be made, but also on the question of whether it needs to be done simultaneously with other measurements and/or model developments. In the above example, it is essential to have simultaneous knowledge of the EUV irradiance and thermosphere/ionosphere response, whereas studies of the solar dynamo may proceed separately.

Figure 6 shows the next template for this problem, which is similar to Figure 5, but in this case shows the measurement requirements to meet the research goals. The column labeled NOW shows the current measurements used by the models. The location of the measurement in the column indicates the region that is being sampled or the instruments or spacecraft whose data is or would be used. The column labeled +5 years shows the needs at in the early phase of LWS, with measurements from the SDO spacecraft added to the column supplanting the F10.7 proxy with the EUV spectrum. Other planned missions are shown in these later columns, e.g. TIMED (2001 launch) and STEREO (2005 launch).

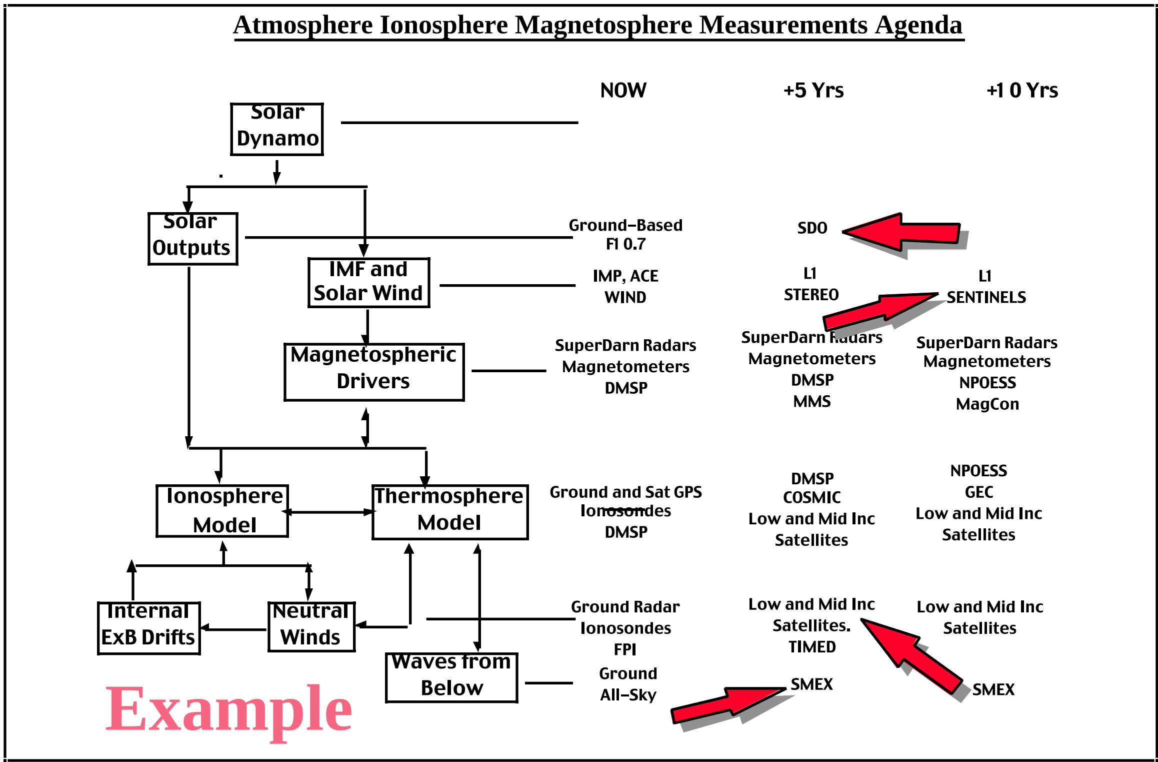


Figure 6. Sample of LWS SAT template for measurement requirements.

In this figure, it becomes clear that certain measurements required by LWS will not be available from existing or planned missions. *Such gaps identify "holes" in the observational picture that were used by the SAT to target the most important areas for new LWS measurements.* In the figure, some of the needed measurements are indicated by arrows, including SDO, sentinels, and spacecraft at low and medium inclination.

In addition to LWS missions, a "SMEX" satellite is indicated for some low altitude measurements -- this designation indicates the SAT's estimation of the mission size and <u>*not*</u> that the Explorer program selections would have prior assignment to LWS. (The SAT recognizes that SMEX payloads are chosen by a different process, but also notes that SMEX payloads can and have played a critical, cost-efficient role in meeting SEC strategic objectives).

LWS Mission Definition Team activities

The complete set of templates developed by the SAT is attached in Appendices 9 and 10. These templates are clearly at top level, and much more detail will be required in order to actually define specific programs. The SAT believes that this would best be accomplished by the various Mission Definition Teams (e.g. the Geospace Mission Definition Team), which must necessarily bring together experts in measurements as well as theory, modeling and data analysis. Following this procedure, the Mission Definition Team's activities would be to:

- Identify the LWS problem areas best addressed by a mission or missions,
- Determine significant model improvements achievable in the 5-10 year time frame,
- Enumerate existing or planned missions whose measurements can be employed to support the model development and theory improvements, and identify critical missing measurements,
- Identify targeted new measurements (partnerships or individual S/C) required to fill in the missing pieces,
- Iterate the process to achieve closure with resources, the level of science understanding, and societal impact.

This process will keep intact the systems approach required by LWS, and maintain a traceabilty of missions, measurements, and data analysis to the required specification, nowcasting, and forecasting goals of LWS.

SAT FINDINGS

The SAT charter directs the team to produce findings on aspects of the LWS program (see Appendix 1). In the May 2001 and July 2001 meeting there were several findings produced, summarized in Table 6.

Table 6 -- SAT findings

	May 2001 SAT meeting
Finding Number	
1	Overall guiding principles
2	SDO Science Payload
3	SDO Geospace Instrumentation
4	Theory Modeling & Data Analysis
5	Instrument Development
	July 2001 SAT meeting
1	Geospace Mission Definition Team to include Modelers
2	Theory, Modeling and Data Analysis Program Management
3	Comprehensive Data System Management

Findings #2, #3 of the May 2001 meeting and #1 of the July 2001 meeting concern the SDO payload and Geospace Mission Definition Team, and can be found in the complete text of findings in Appendices 5 and 6. The other findings are of a general nature and much of their content has is reflected elsewhere in this summary. The main points can be summarized as follows:

Overall guiding principles (May 2001, #1)
For LWS to successfully develop as an end-to-end system concerned with linkages responsible for the influence of the Sun on Earth,
- there must be an interval of time (a period of years) when all elements are observed concurrently
- emphasis must be placed on quantitative measurements so ensure that inputs from one component of the system to the next can be properly linked
- modeling and theoretical efforts need to emphasize the coupled nature of the system.

Theory Modeling & Data Analysis (May 2001, #4)
In addition to traditional focused grants, an additional component of the Theory, Modeling, & Data analysis is needed: development of end-to-end models for selected Sun-Earth linkages. The efforts envisioned here are well

beyond the scope of typical existing grants, and could require resources of $0.5-$1.0 M/year for initial periods of ~3 years, with evaluation by NASA to see if the project should be continued.

Instrument Development (May 2001, #5)
Since innovative, compact, and cost-effective instrumentation that maximizes access to space is crucial for achieving goals of LWS, it would be highly desirable to include instrument development in support of LWS needs.

Two of the findings from the July 2001 meeting, namely

- **Theory, Modeling and Data Analysis Program Management**
- **Comprehensive Data System Management**

are specifically relevant to the basic LWS architecture envisioned by the SAT and are therefore discussed in detail below.

The overall SAT vision for LWS activities is summarized in Figure 7. The systems approach required for successfully achieving program goals requires careful coordination among multiple elements of an extremely complex undertaking. At the top of the figure are the *Observations*. These use existing

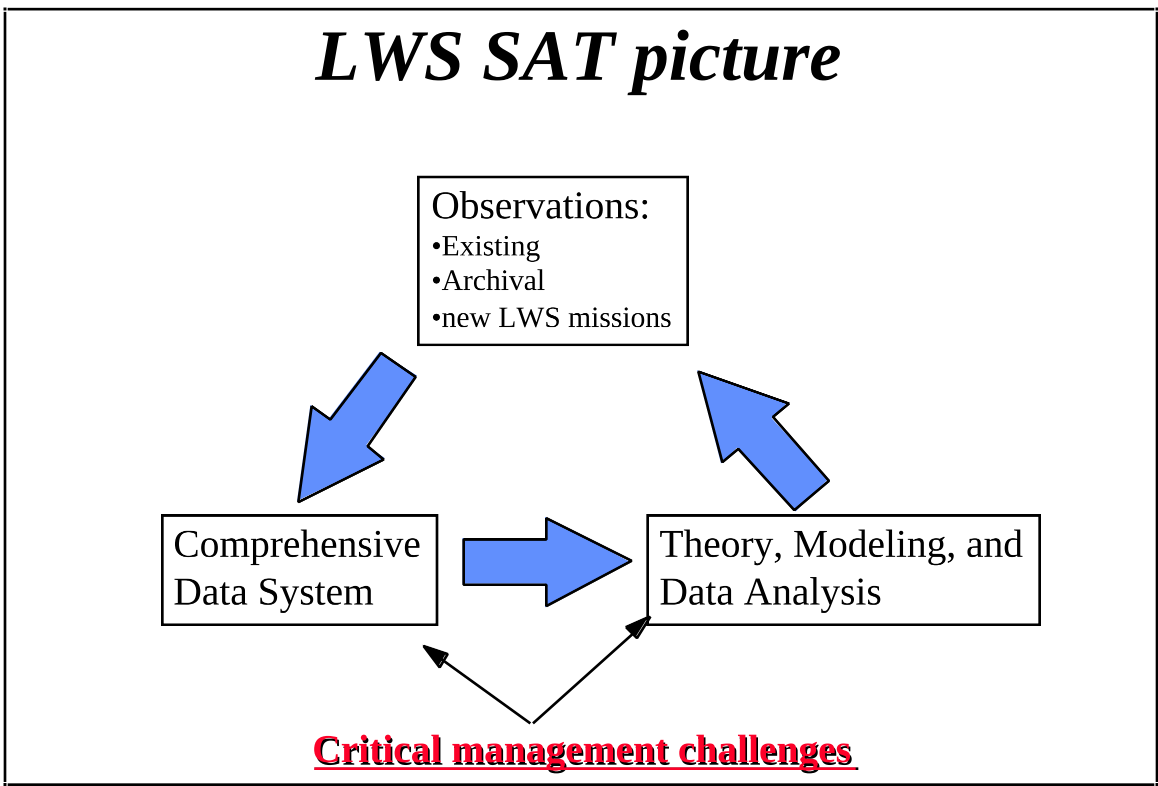


Figure 7. The integrated nature of LWS, and associated management challenges

resources, archival data, and carefully targeted new LWS missions on either separate spacecraft or in partnership with others. These observations must be placed in a *Comprehensive Data System* where they can be easily and inexpensively accessed by researchers who are attacking either small, focused problems, or developing large, global models. This data system in turn is the foundation for the *Theory, Modeling, and Data Analysis* activities which embody the scientific knowledge gained from the program. Activities in this area not only allow development of new theories and improvements of models, but also will form the basis for new observational initiatives to be undertaken later in the program. The SAT identifies the Comprehensive Data System and Theory, Modeling, and Data Analysis as *Critical management challenges* for the LWS program, since it is much more complex and comprehensive than any prior undertaking by the community.

Observational requirements

New LWS missions

The SAT identified a number of areas where required measurements would not be available from existing or planned spacecraft but that are necessary for the addressing LWS goals. The initial set of missions identified to secure these measurements for LWS are listed in Table 7, along with a general description of their goals. *Note that measurements from multiple disciplines are sometimes mixed on LWS spacecraft, e.g., radiation belt studies on SDO, particle precipitation and polar cap access along with ITM studies on LWS-GEO, etc.* The rationale for this choice of missions can be summarized briefly as follows:

Solar Dynamics Observatory

Advances in our understanding of solar dynamics require new nearly continuous observations of the Sun at greatly increased cadence compared to prior studies. These requirements can be met from, e.g., Geosynchronous orbit. Measurements include full-disk dopplergrams, magnetograms, precise photometric images, filtergrams recorded simultaneously in a variety of visible and EUV band-passes, EUV spectral irradiance, restricted field of view UV/EUV slit spectra, and white-light polarization brightness images of the solar corona. The SDO mission will be designed for a 5-year baseline with expendables to last an additional five years of an extended mission. A complete rationale and mission description has been generated by the Solar Dynamics Observatory Science Definition Team, and is available on the web at: http://lws.gsfc.nasa.gov/lws_sdo_sdt_report.pdf

Geospace -- Radiation Belt Missions
LWS geospace measurements targeted to understanding and modeling the magnetospheric energetic particle populations are (1) ions and electrons over a broad range of energies, (2) magnetic fields, (3) electric fields, and (4) ULF-VLF waves. These measurements need to be made in a variety of regions of geospace, including:

- near-equatorial elliptical orbits with multiple, simultaneous measurements at different radii; geosynchronous transfer orbits (GTO). are a likely candidate, with excellent partnering possibilities.
- geosynchronous orbits to avoid spatial/temporal aliasing inherent in elliptical orbits. The SDO is an excellent candidate platform.
- low earth orbiting (LEO - see below) component for directly measuring precipitating radiation belt particles *in situ*, geomagnetic cutoffs and inputs of solar energetic and SAA particles, and inputs to ionospheric and atmospheric models.

Geospace -- Ionosphere / Thermosphere
These missions address global specification and prediction of neutral upper atmospheric density and dynamics, ionosphere density, structure, and irregularities; dynamics, latitude, longitude, and local time variations in thermospheric winds and other parameters; global auroral energy deposition; global neutral density perturbations; and ring current dynamics.
LEO mission: the orbit is selected to maximize the longitude and latitude coverage within season variations, and also radiation belt polar cap goals (see Radiation Belt Missions)
Elliptical Polar Orbit (EPO) mission: has its inclination and eccentricity chosen to maximize efficiency of global aurora imaging and O/N_2 perturbations, etc., plus energetic neutral atom imaging for global view of ring current.

Inner Heliospheric Mappers
In order to understand the evolution of CMEs, shocks, and fast solar wind streams impacting Earth, and to develop the scientific understanding needed to predict the effects of events on the Earth system, LWS requires a global view of the inner heliosphere using multiple spacecraft. Magnetic fields, solar wind, energetic particles, and radio waves need to be measured. The nominal missions have 4 spacecraft with a single launch followed by Venus gravity assist to cover distances of 0.5-0.95 x 0.72 AU.

Cost issues: Using material from the pre-formulation study at GSFC, the SAT has estimated the overall costs of these missions, and finds that they can be accommodated within the Administration's LWS budget request for FY2001, assuming some partnerships and low-cost launches. We note that LWS cuts in the FY2002 budget request, including the removal of funding for Solar Probe, would have significant impacts on the pace of the program. Figure 8 shows the launch and operations timing for this mission set under the FY001 budget assumption and some partnership assumptions. Note that the critical period of simultaneous observations begins in late 2009 after the Inner Heliospheric Mapper missions become well separated from Earth. Additional details of these missions are given in Appendix 7; however, fully developed concepts will require the work of suitable Mission Definition Teams. Figure 9 shows the initial LWS system in place along with some key supporting spacecraft.

Table 7 -- SAT recommended initial mission set

Name	Launch	Description
SDO	2006	Solar seismology and magnetic field studies; EUV radiation; radiation belt studies
Geospace -Radiation Belt 1/2 and 3/4	2008 & ~2013	Radiation belts over a range of L shells; two launches in order to cover full solar cycle
Geospace-LEO	2009	*in-situ* measurement of ionosphere and thermosphere dynamics and structure; solar energetic particles & polar cap size; SAA
Geospace-EPO	2009	global auroral imaging and O/N2 perturbations; energetic neutral atom imaging for ring current dynamics
Inner Heliosphere Mappers	2009	~4 identical spacecraft in inner heliosphere orbits; structure, dynamics, & radial evolution of CMEs, solar particles, and geo-effective disturbances

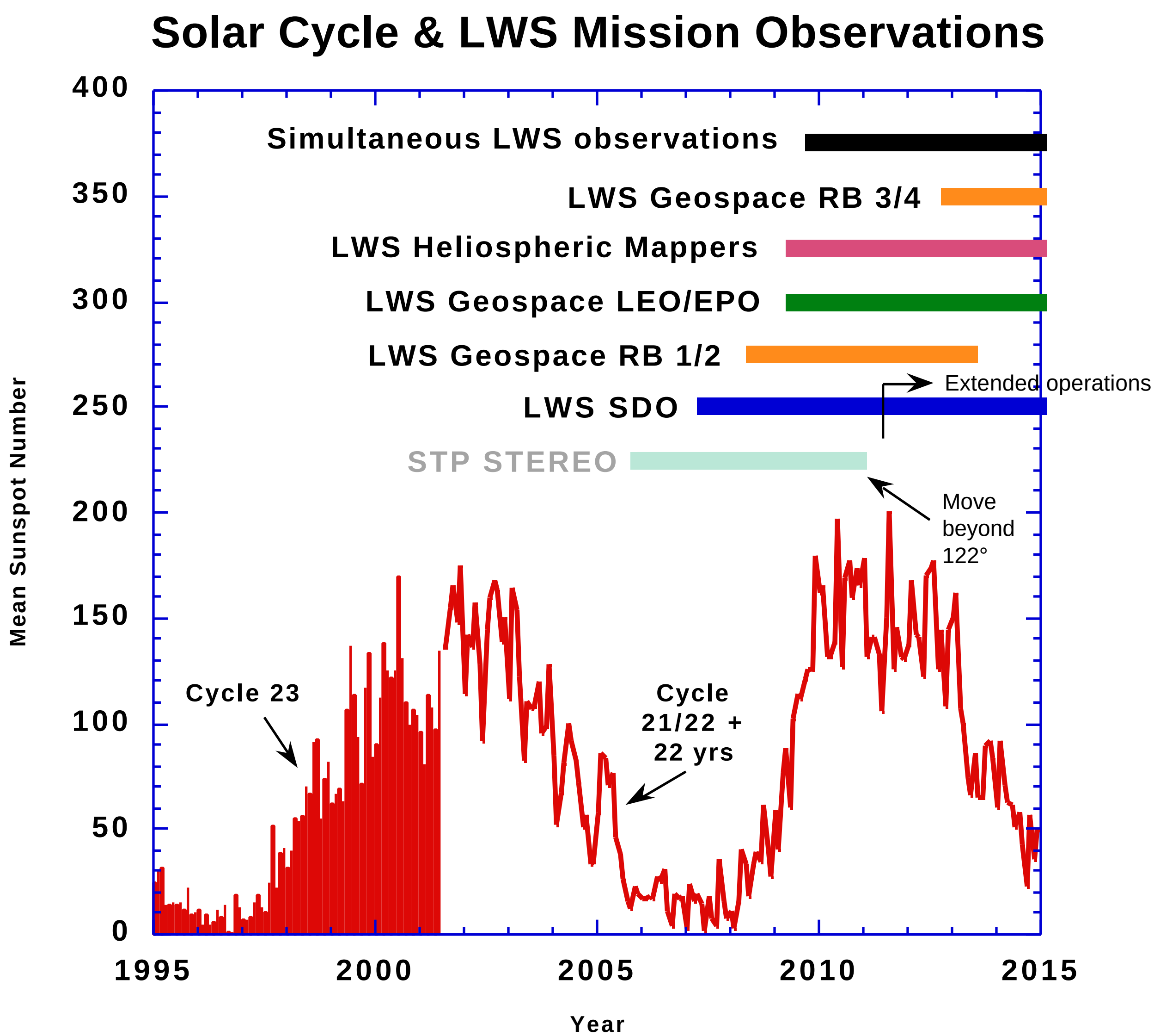
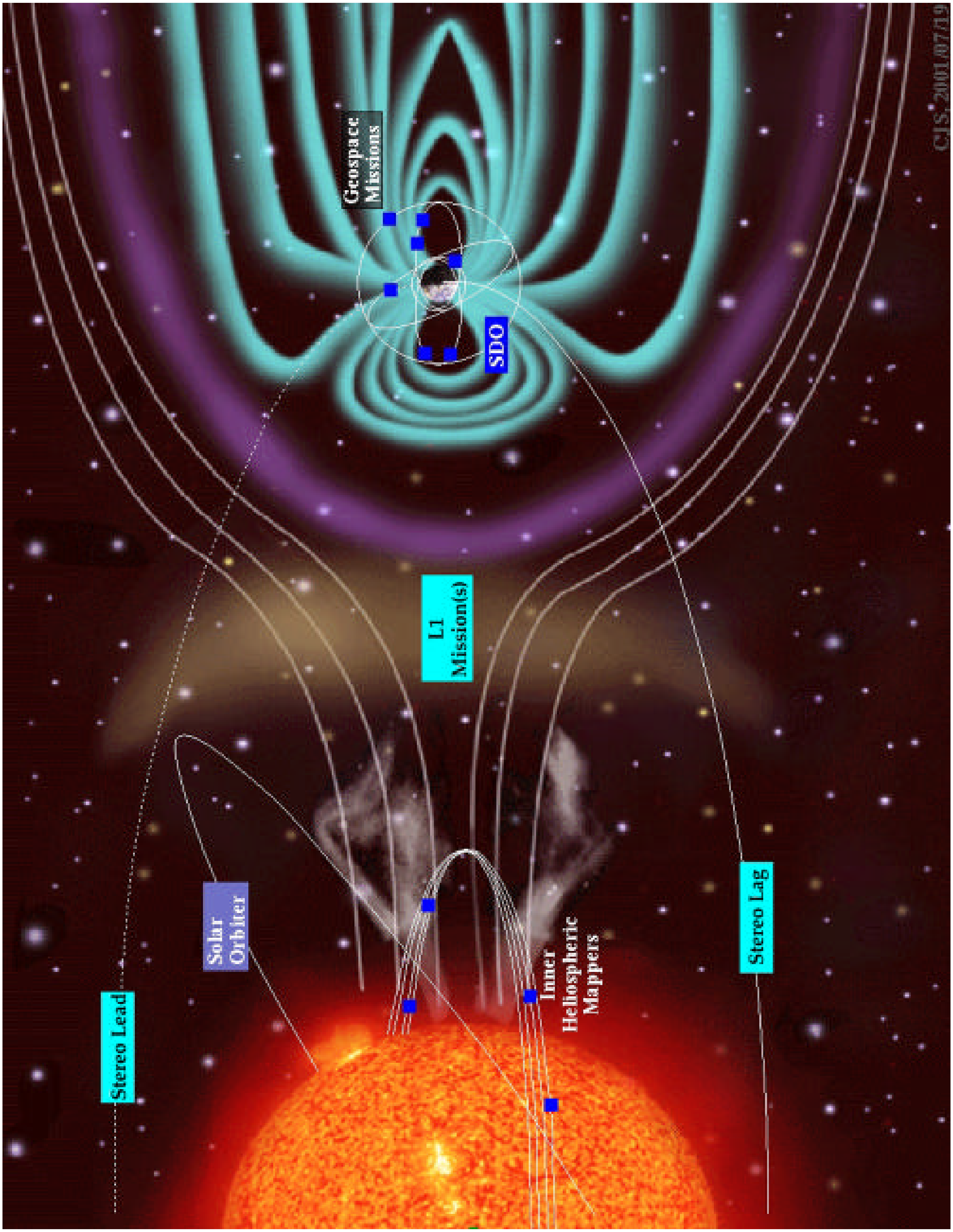


Figure 8. LWS mission set showing timing and the solar cycle. Notice that the STP STEREO mission spacecraft move beyond an Earth-Sun-S/C angle of 122° relatively early in the period of simultaneous LWS observations.

Figure 9. *(next page)* The LWS missions in place (dark blue), along with some of the required supporting missions (light blue boxes). Figure courtesy of K. Schrijver.


Geospace Missions
SDO
L1 Mission(s)
Solar Orbiter
Stereo Lead
Inner Heliospheric Mappers
Stereo Lag
CJS, 2001/07/19

Other required measurements

Each of the missions in Table 7 requires data from other, non-LWS spacecraft, to form a coherent picture from which the required LWS global analysis and understanding can be undertaken. Each of the mission descriptions in Appendix 7 lists some of these other missions, and Table 8 collects them together. It is not required that all missions listed in Table 8 be operating for LWS to be a success; however, in each problem area there are subsets of measurements that will form an irreducible set. Even in this case, there may be multiple ways of obtaining the measurement; for example, at L1, many needs could be met by ACE or Wind or Triana; and many magnetospheric needs met from L1 could also be met for a portion of the time by IMP-8.

Table 8 -- LWS Supporting Missions

Spatial Region	LWS Supporting Missions
Outer Heliosphere	Voyager, Ulysses
Solar (remote)	SOHO, HESSI, TRACE, Solar-B
Inner Heliosphere	SOLO, Messenger, Beppi-Columbo, Solar Probe
Heliosphere at 1 AU	STEREO, IMP, Geostorm,
L1	ACE, Wind, Triana
Magnetosphere	MagCon, GEC, TWINS, Polar, Cluster, GOES, LANL-GEO, GPS, IMP-8
Low Earth Orbit	SORCE, TIMED, DMSP, TIROS, NPOESS, SAMPEX, C / NOFS

Data Systems Team (DST)

The LWS program goal is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. In order to build the required comprehensive observational picture, the LWS program needs to create a data system from which researchers can easily access the multiple observations required to develop, refine, and test theory and modeling of the Sun-Earth system.

The SAT strongly believes that a Data Systems Team should be formed to examine these issues and make specific recommendations to LWS management. Issues to be examined by the DST include

- identification of NASA and non-NASA spacecraft and ground observations that play important, or critical, roles in acquiring the data required to carry out the theory and modeling advances required to achieve the goals of LWS, including mission extension and scientific productivity of existing NASA assets. This assessment might be carried out by the DST in coordination with the Theory, Modeling, and Data Analysis Definition Team (TMDADT - see below).
- partnering or other arrangements with non-NASA agencies to help ensure the availability of observations from non-NASA missions that are important or critical to LWS
- creation a system from which individual researchers can easily access the multiple observations required to develop, refine, and test theory and modeling of the Sun-Earth system. This effort could build on existing archives such as those from the ISTP program, or might be a distributed, virtual system.
- Examination of the costs of the data system, and in particular the benefits of adding a particular data set(s) to the system compared with the associated cost. The SAT and/or TMDADT (see below) should be consulted on the scientific importance of data sets to be added to the system.

The SAT points out that in the multi-year period before the first LWS mission is launched, many important LWS problems could be addressed using this system, thus yielding payback from the LWS investments early in the program. Such investigations could include not only topics addressed by current observations, but perhaps more importantly, topics that require investigation of solar-cycle dependences. Improved models of the radiation belts is an obvious example.

It is essential that LWS management and its Data Systems Team initiate this effort in the near future, so that the required system will formed early in the LWS program.

Theory, Modeling, and Data Analysis Team (TMDADT)

The Living With a Star program will be considered a success if and only if there are substantial improvements in theoretical understanding and modeling of each component of the Sun-heliosphere-geospace system, and in particular of the linkages among these components. Theory and modeling is the embodiment of knowledge acquired by the LWS program. It is a product and an output -- a deliverable that will provide lasting benefits and permit the eventual transition to an operational program. Data analysis will provide one of the key means by which improvements in theory and modeling will occur.

It would be unwise to assume that the required theory, modeling and data analysis program will arise by chance -- generated only by the natural instincts of the community. Rather it must be pro-actively orchestrated. Components must be developed in concert. Observations must feed improvements in the models. Models must be seamlessly linked and new ideas and new concepts injected so that the final product is a working end-to-end model or models accurately depicting the comprehensive knowledge generated by the Living With a Star program.

The SAT believes strongly that a comprehensive theory, modeling and data analysis program needs to be embarked upon immediately. To that end:

1) A Theory, Modeling & Data Analysis Definition Team (TMDADT) needs to be formed, with the same status as Mission Definition Team (MDTs), for the purpose of designing a coordinated and comprehensive theory, modeling and data analysis program. The TMDADT's charge should include:

- a definition of goals and objectives of the programs -- i.e. definitions of the metrics against which a successful LWS theory, modeling and data analysis program will be measured,
- recommendations on the management structure that will be in place throughout the LWS program, and that will ensure coordinated and unified development of theory, modeling and data analysis across the LWS system.
- recommendations on procedures to ensure that the program encourages and promotes new concepts and understanding, and provides for their speedy inclusion in the developing models,
- a preliminary assessment of the data that will be needed for success with the development of theories and models that can provide useful guidance to the MDTs, and

- an assessment of the utility of and necessity of data for theory and model development that can be provided from existing and planned NASA and non-NASA sources.

2) Selected members of the TMDADT should also be appointed to the MDTs to ensure coordination. The converse should also occur: members of the MDTs should have joint appointments with the TMDADT.

3) The TMDADT should disband and be replaced by the permanent management structure that will ensure success of the theory, modeling and data analysis effort.

The LWS program has accepted a daunting challenge -- to deliver comprehensive knowledge and improved predictability of how our changing Sun impacts our society. There are multiple spacecraft, coordinated measurements, and intertwining theories and models. The challenge is one of science and also one of management, and nowhere is the success in meeting the management challenge more crucial for the ultimate success of LWS that it is for theory, modeling and data analysis.

CONCLUDING REMARKS

This report represents SAT activities over an 8 month period during which the team met four times, held a community workshop, and held a great many internal telecons for the various subgroup activities. In the process, members of the SAT have become deeply impressed with the enormous complexity of the LWS program, and excited about the scientific and societal benefits that it offers. The SAT fully recognizes that detailed definition of the program will require a great deal of future effort, and that the view of the program given here is more of a glimpse of the final product than a blueprint. The SAT strongly believes that the processes used by the team can provide an effective means of maintaining a systems approach to LWS, and that only by following such an approach can the programs global goals be attained. Further, the SAT strongly believes that the required coordination within LWS constitute management challenges significantly beyond the previous experience of the community. These challenges are significant for the Mission Definition Teams, but they are much greater for the Data Systems Team and the Theory, Modeling, and Data Analysis Definition Team. We strongly urge the LWS program management to address these issues head-on, and can attest from our own experience that an enthusiastic research community will provide the support required for a successful effort.

Appendices

Appendix 1 - Charter for the Living With a Star (LWS) Science Architecture Team (SAT)

(9/15/00)

The goal of the LWS program is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun–Earth system that directly affect life and society. The SAT will function as a top-level science working group for LWS and report to the Sun Earth Connection (SEC) Science Program Director and the Sun Earth Connection Advisory Subcommittee (SECAS). The main role of the SAT is to examine the LWS program requirements and architecture from an overall systems point of view. The SAT is composed of solar-terrestrial scientists and representatives from the applications community. The members will be selected by the SEC Science Program Director at NASA HQ. It is expected that there will be a periodic rotation in the membership of the SAT as the LWS program evolves.

The SAT team will work closely with HQ and with the Goddard LWS Program Office and produce findings on the following:

- Program level goals and objectives
- System science requirements and priorities
- Top-level requirements for measurements/missions
- Top level system ground segment requirements
- Program success metrics
- Space Environment Testbed system requirements
- Relationships to complementary programs and partnerships

Following the delivery of the findings, the SAT will continue to report to NASA HQ and SECAS and also serve as a top-level science working group for the LWS Program Office and LWS Science Definition Teams.

Appendix 2 - Guidance from Sun-Earth Connections Advisory Subcommittee (SECAS)

March 2000 meeting

The material below from SECAS was supplied to the SAT.

Contributions of SECAS to the definition of the NASA Living With a Star initiative (modified version) Sun-Earth Connection Subcommittee March 2000

LWS Goal

Develop the scientific understanding necessary to enable the US to effectively address those aspects of the Connected Sun-Earth system that directly affect life and society

LWS Objectives

- Identify and understand variable sources of mass and energy coming from our Star 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 of multiple time scales.

- Extend our knowledge and understanding gained in this program to explore extreme solar-terrestrial environments and implications for life and habitability beyond Earth.

Societal Consequences of Solar Variability

Human Radiation Exposure
- Space Station, Space Exploration
- High Altitude Flight
- Space Utilization and colonization

Impacts on Technology
- Space Systems
- Communications, Navigation
- Ground Systems

Global Climate Change
- Near term
- Long term

Science Flowdown: Human Radiation Exposure

- Systems Affected
  - Space Station, Space Exploration
  - High Altitude Flight
  - Space Utilization and Colonization

- Space Weather Hazards:
  - Solar Energetic Particle Events (SPE)
  - Relativistic Electron Events (REE)

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

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

Science Flowdown: Use of Technology in Space

- Systems Affected:
  - Spacecraft (non-Earth orbiting)
  - Satellites (Earth orbiting)
  - Manned Space Flight, Space Station, Shuttle
  - Communications, Navigation, and Radar
  - Ground systems

- Space Weather Hazards:
  - Variable atmospheric drag
  - Enhanced ionospheric ionization
  - Solar X-ray (SX) and Energetic Particle Events (SEP)
  - Relativistic Electron Events (REE)
  - Magnetospheric particles and fields

- Science Questions:

  - What determined the heliospheric, magnetospheric, atmospheric and ionospheric responses to solar variability?

  - What causes onset & development of ionospheric scintillations?

  - What determines when SEPs, REEs, SX and 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?

- Mission Definition Issues:

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

Science Flowdown: Terrestrial Climate

- Impacts on Life and Society:
  - Climate Change (past & future)
  - Ozone depletion and recovery

- Space Weather Sources:
  - Solar Electromagnetic radiation
  - Solar and Galactic Cosmic Rays
  - Upper atmospheric/ionosphere boundary region

- Science Question:
  - What is the role of the Sun and Heliosphere in global climate change on multiple time scales (seasonal, decadal, centennial)?

- MISSION DEFINITION 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 - intermediate regions such as the heliosphere, magnetosphere and the upper atmosphere/ionosphere on climate?

  - How should development of quantitative models proceed?

  - What predictive capabilities will be needed?

Appendix 3 - Priorities

from George Withbroe, SEC Program Director

LIVING WITH A STAR – A PERSPECTIVE ON PRIORITIES 4/4/01

Priority

1. Solar Influences on Global Change.

Why: Global change is the single most important environmental problem facing humanity. This issue involves major national and international policies because of the potential economic impacts of global change and/or mitigation actions.

Key issues for LWS:

- Determine how and why the Sun varies (for assessment of past & future role in global climate change).
- Identify and understand mechanisms by which solar variability affects climate (and possibly weather).

Need: Past, present, future behavior.

2. Space Environmental "climate" data (e.g., specification models)

Need:

- For design of cost-effective systems with minimal or no sensitivity to space weather.
- The goal is to have economical "all weather" systems -- not to be dependent on predictions.

2. Nowcasting Space Environment

Need: For rapid anomaly resolution for space and communication/navigation systems; astronaut safety.

Why:

- If anomaly is known space environmental effect, can "reboot" and get back in operation.
- If unknown cause, may have to do detailed failure analysis requiring system to be down for long time.
- Astronaut can move to shielded area for significant radiation events.

Priority

3. Prediction of:

a) Solar Proton Events (astronaut safety, especially for deep space)

Need:

- Reliable warnings (minimize false alarm rate).
- Forecast of "all clear" periods for EVA's; being away from "radiation storm cellar" in deep space (e.g. when doing surface excursions).

b) Geomagnetic storms for applications where effective mitigation is possible (e.g. electric power grid).

Need:

- Reliable forecasts (storm is coming) and very reliable shorter term (≥ hour) warnings to minimize taking unnecessary mitigation by reducing capacity, etc. which can reduce system efficiency.

c) Space environment for operation and utilization of space systems.

Need:

- To reliably forecast availability / accuracy / sensitivity of communication and navigation systems susceptible to space weather (e.g. ionospheric scintillations).
- To have more operators on call and / or to avoid uploads of software / critical commands during times of extreme space weather (SEU probability, etc.).

Appendix 4 - SAT Meetings & Invited Speakers; SAT Workshop participants

No.	Location / date	Invited Speakers
1	NASA HQ Nov 7-9, 2000	LWS project scientists: A. Poland, L. Zanetti, B. Thompsen, R. Hoffman, A. Szabo, R. Pfaff, M. Hesse, J. Barth
2	Greenbelt, MD Jan 31-Feb 2, 2001	See below for Workshop Report for Workshop participants
3	NASA HQ May 7-9, 2001	ISTP Lessons Learned: Mario Acuña, Art Poland, Jim Slavin
4	NASA HQ July 16-18, 2001	Theory, Modeling, & Data Analysis: Michael Hesse Data System Issues: Joe Bredekamp

Note: This list does not include speakers from the NASA HQ SEC scientists, who participated in all the meetings, or for routine reports from the LWS scientist team at GSFC and JHU/APL.

List of registrants at SAT workshop, January 30, 2001, Greenbelt, MD

Brian	Anderson	JHU / APL
Spiro	Antiochos	NRL
Mark	Baldwin	Northwest Research
Janet	Barth	NASA/ Goddard Space Flight Center
Sanitmay	Basu	AFRL
Sunanda	Basu	AFRL
Bern	Blake	Aerospace
Robert	Cahalan	NASA/ Goddard Space Flight Center
Mike	Calabrese	GSFC
Bob	Clauer	University of Michigan
Gil	Colon	GSFC
Tony	Comberiate	GSFC
Odile	de la Beaujardiere	AFRL
George	Fisher	University of California
Len	Fisk	University of Michigan
John	Foster	MIT
Nicola	Fox	JHU / APL
Tim	Fuller-Rowell	NOAA
Shing	Fung	NASA/ Goddard Space Flight Center
Alan	Gary	NASA/ Marshall Space Flight
Barbara	Giles	GSFC
Peter	Gilman	University of Colorado
Greg	Ginet	AFRL
Charles	Goodrich	UMD
Jack	Gosling	LANL
David	Hathaway	NASA/ Marshall Space Flight
Gary	Heckman	NOAA
Rod	Heelis	University of Texas
Fred	Herrero	GSFC
Michael	Hesse	GSFC
Todd	Hoeksema	NASA HQ
Joanie	Hoffman	NASA/ Goddard Space Flight Center
Robert	Hoffman	GSFC
Mary	Hudson	Dartmouth University
Stuart	Huston	Boeing
Charles	Jackman	NASA/ Goddard Space Flight Center
Mike	Jamilkowski	OSD / C31
Steve	Kahler	AFRL
Steve	Keil	NSO
Paul	Kintner	Cornell University
Lynn	Kistler	University of New
Marsha	Korose	OSD / C31
Terry	Kucera	GSFC

Guan	Le	GSFC
Judith	Lean	NRL
John	Leibacher	National Solar
Xinlin	Li	Colorado University
Dana	Longcope	Montana State
Laura	Madachy	Westover Consultants
Frank	Marcos	AFRL
John	Mariska	NRL
Sara	Martin	Helio Research
Glenn	Mason	UMD
Barry	Mauk	JHU / APL
Dave	McComas	SWRI
Robert	McCoy	ONR
Mary	Mellott	NASA HQ
Dick	Mewaldt	Caltech
Zoran	Mikic	UCSD
Gerald	North	Texas A&M
Arlene	Peterson	GSFC
Rob	Pfaff	GSFC
Michael	Picone	NRL
Vic	Pizzo	NOAA
Art	Poland	NASA/ Goddard Space Flight Center
Kenneth	Potocki	JHU / APL
Shannon	Powell	Westover Consultants, Inc.
Geoff	Reeves	Los Alamos National
David	Rind	GISS
Bob	Robinson	NSF
John	Robinson	GSFC
Dave	Rusch	University of Colorado
David	Rust	JHU / APL
Mike	Schlesinger	University of Illinois
Jesper	Schou	Stanford University
Karel	Schrijver	Lockheed Martin
Neil	Sheeley	NRL
David	Sibeck	JHU / APL
Howard	Singer	NOAA
George	Siscoe	Boston University
Jan	Sojka	Utah State University
Robert	Strangeway	UCLA
Keith	Strong	Lockheed Martin
Ted	Tarbell	Lockheed Martin
Barbara	Thompson	NASA/ Goddard Space Flight Center
Brian	Tinsley	University of Texas
Larry	Townsend	University of Tennesee
Aad	van Ballegouijen	SAO
Guoyong	Wen	UMBC/GSFC

George	Withbroe	NASA
Dick	Wolf	Rice University
Donald	Woods	LASP
John	Wygant	University of Minnesota
Sam	Yee	JHU / APL
Larry	Zanetti	JHU / APL
Ron	Zwickl	NOAA

Appendix 5 - Findings of the SAT May 2001 meeting

Finding of the LWS Science Architecture Team
May 2001 meeting

1) Overall guiding principles

A principal finding of the SAT is that the governing principle under which LWS needs to be developed is that it is an end-to-end system. LWS must be fundamentally concerned with the processes, and in particular the linkages, responsible for the influence of the Sun on Earth.

To that end,

1) There needs to be an interval of time, for a period of years, when all elements of the coupled system are observed concurrently.

2) The management of the program must continuously reinforce the end-to-end nature of LWS through appropriate linkages of the different science disciplines.

3) Emphasis must be placed on quantitative measurements within the Sun-heliosphere-Earth system, to ensure that the inputs from one component of the system to the next are properly measured.

4) The modeling and theoretical efforts need to emphasize the coupled nature of the Sun-heliosphere-Earth system, and serve as a unifying theme for the entire LWS program.

Finding of the LWS Science Architecture Team
May 2001 meeting

2) SDO solar instrument payload

The LWS SAT agrees with the SDO/Science Definition Team that the Helioseismograph/Magnetograph Imager (HMI), Atmospheric Imager Assembly and Spectrometer (AIA and AIS), and EUV Irradiance Spectrometer (EUVIS) instruments together constitute core solar measurements for the LWS program. These instruments are formulated at minimal required capabilities in the May 2001 SDO/SDT draft report.

The SAT finds that vector magnetographic capabilities and coronagraphic observations from Earth perspective are additional critical observations for LWS. These should be available either on SDO, or another identified source including ground-based observatories during much of the LWS program.

Finding of the LWS Science Architecture Team
May 2001 meeting

3) SDO Geospace Instrumentation

The LWS SAT has been briefed on the development of the Solar Dynamics Observatory concept, whose Announcement of Opportunity release is expected in the next few months. As the first spacecraft in the LWS program, the SAT has discussed the possibility of including Geospace Instrumentation on this three-axis stabilized spacecraft, which is in a geosynchronous orbit.

Geospace science measurements that could, in principle, be carried out on SDO can address key LWS issues in both the Radiation Environment and in the Ionosphere/Thermosphere.

Key Radiation Environment measurements are (in order of priority) (1) energetic particles and magnetic field; (2) plasma, and (3) energetic neutral atoms (ENAs).

Key Ionosphere/Thermosphere measurements are ENA and UV imaging for neutral and ionospheric densities and auroral emissions.

The SAT sees obvious value in all these observations for LWS science objectives; however we do not presently have enough information to evaluate the science return against the existing resource constraints or other implementation possibilities. The SAT finds that an investigation of these trade offs be carried out by NASA HQ and the LWS mission scientists would make is possible to determine if including Geospace Instrumentation on SDO would be a desirable use of LWS resources.

Finding of the LWS Science Architecture Team
May 2001 meeting

4) Theory / Modeling and Data Analysis

The LWS SAT holds the Theory/Modeling and Data Analysis (TM&DA) component of the program as a critical end product which uses both physics-based understanding and experimental measurements to test our knowledge of the Sun-heliosphere-Earth system. Our ability to meet LWS goals of environmental specification, research into nowcasting, and forecasting all culminate in the models used to describe the system.

The current program includes focused individual investigations of key science gaps, in the traditional manner of SEC research programs. The LWS finds that an additional component of the TM&DA program is needed: development of end-to-end models for selected Sun-Earth linkages. The efforts envisioned here are well beyond the typical scope of existing grants, and would develop models that emphasize boundaries and linkages among systems and phenomena in order to provide a comprehensive picture. Examples of such end-to-end models are: CME events from eruption in the corona, to interplanetary propagation, to impact on the magnetosphere, to input to the thermosphere/ionosphere; another example is substorms, and their effects on the magnetosphere, thermosphere and ionosphere; a third example is the impact of the solar cycle on active regions in which EUV radiation is enhanced, and the effect of the resultant irradiance modulation on the thermosphere.

The SAT has considered a number of ground-rules for such programs including an open use policy for the full SEC community and periodic review of progress. The SAT anticipates that such programs could require resources of $0.5-1.0M/year, for a initial period of ~3 yrs, with evaluation by NASA to see if the project should be continued. The SAT considers it desirable to have multiple groups working on such projects, providing that sufficiently compelling proposals are identified in the peer review process.

Therefore, the SAT finds that an amendment to the NRA should be released as early as possible that will request:

" end-to-end models that emphasize boundaries and linkages among systems and phenomena in order to provide a comprehensive picture. "

Finding of the LWS Science Architecture Team
May 2001 meeting

5) Instrument Development

The LWS SAT finds that NASA should immediately begin to fund new concepts, prototyping, and development of measurement capabilities in support of LWS objectives. The LWS recognizes that innovative, compact, and cost-effective instrumentation that maximizes access to space is crucial for achieving goals of LWS. Rapid advances in technology beyond that currently available show great promise.

The objectives of LWS require compact instruments, multiple-small spacecraft and/or launches of opportunity focusing on both remove and in situ measurements. Achieving this objective requires smaller, less resource intensive instruments. Some of these instruments may be unique to LWS.

The LWS SAT finds that in the next NASA NRA, it would be highly desirable to include instrument development in support of LWS needs.

Appendix 6 - Findings of the SAT July 2001 meeting

Finding of the LWS Science Architecture Team
July 2001 meeting

1) Geospace Mission Definition Team to include Modelers

The objectives and goals of LWS call for a close and integrated connection between experiments, modeling, and theory leading to breakthroughs in our understanding of the space science that has societal impacts. For this to happen, modeling must play a key component at the initiation of the mission definition process. Experts in geospace modeling should be included on the mission definition team to ensure two outcomes:

(1) to assure that the appropriate measurements are made to advance and validate the models, and

(2) to assure that modelers meet their obligation of making testable predictions for the LWS community.

In addition, a solar/heliospheric expert should be included in the team to ensure overlap and coordination with solar/heliospheric inputs into geospace.

Finding of the LWS Science Architecture Team
July 2001 meeting

2) Theory, Modeling and Data Analysis Program Management

The Living With a Star program will be considered a success if and only if there are substantial improvements in theoretical understanding and modeling of each component of the Sun-heliosphere-geospace system, and in particular of the linkages among these components. Theory and modeling is the embodiment of knowledge acquired by the LWS program. It is a product and an output -- a deliverable that will provide lasting benefits and permit the eventual transition to an operational program. Data analysis will provide one of the key means by which improvements in theory and modeling will occur.

It would be unwise to assume that the required theory, modeling and data analysis program will arise by chance -- generated only by the natural instincts of the community. Rather it must be pro-actively orchestrated. Components must be developed in concert. Observations must feed improvements in the models. Models must be seamlessly linked and new ideas and new concepts injected so that the final product is a working end-to-end model or models accurately depicting the comprehensive knowledge generated by the Living With a Star program.

The SAT believes strongly that a comprehensive theory, modeling and data analysis program needs to be embarked upon immediately. To that end:

1) A Theory, Modeling & Data Analysis Definition Team (TMDADT) needs to be formed, with the same status as Mission Definition Team (MDTs), for the purpose of designing a coordinated and comprehensive theory, modeling and data analysis program. The TMDADT's charge should include:

(a) a definition of goals and objectives of the programs -- i.e. definitions of the metrics against which a successful LWS theory, modeling and data analysis program will be measured,

(b) recommendations on the management structure that will be in place throughout the LWS program, and that will ensure coordinated and unified development of theory, modeling and data analysis across the LWS system.

(c) recommendations on procedures to ensure that the program encourages and promotes new concepts and understanding, and provides for their speedy inclusion in the developing models,

(d) a preliminary assessment of the data that will be needed for success with the development of theories and models that can provide useful guidance to the MDTs, and

(e) an assessment of the utility of and necessity of data for theory and model development that can be provided from existing and planned NASA and non-NASA sources.

2) Selected members of the TMDADT should also be appointed to the MDTs to ensure coordination. The converse should also occur: members of the MDTs should have joint appointments with the TMDADT.

3) The TMDADT should disband and be replaced by the permanent management structure that will ensure success of the theory, modeling and data analysis effort.

The LWS program has accepted a daunting challenge -- to deliver comprehensive knowledge and improved predictability of how our changing Sun impacts our society. There are multiple spacecraft, coordinated measurements, and intertwining theories and models. The challenge is one of science and also one of management, and nowhere is the success in meeting the management challenge more crucial for the ultimate success of LWS that it is for theory, modeling and data analysis.

Finding of the LWS Science Architecture Team
July 2001 meeting

3) Comprehensive Data System Management

The LWS program goal is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. In order to build the required comprehensive observational picture, the LWS program needs to create a data system from which researchers can easily access the multiple observations required to develop, refine, and test theory and modeling of the Sun-Earth system.

The SAT strongly believes that a Data Systems Team should be formed to examine these issues and make specific recommendations to LWS management. Issues to be examined by the DST include

- identification of NASA and non-NASA spacecraft and ground observations that play important, or critical, roles in acquiring the data required to carry out the theory and modeling advances required to achieve the goals of LWS, including mission extension and scientific productivity of existing NASA assets. This assessment might be carried out by the DST in coordination with the TMDADT.
- partnering or other arrangements with non-NASA agencies to help ensure the availability of observations from non-NASA missions that are important or critical to LWS
- creation a system from which individual researchers can easily access the multiple observations required to develop, refine, and test theory and modeling of the Sun-Earth system. This effort could build on existing archives such as those from the ISTP program, or might be a distributed, virtual system.
- Examination of the costs of the data system, and in particular the benefits of adding a particular data set(s) to the system compared with the associated cost.

The SAT points out that in the multi-year period before the first LWS mission is launched, many important LWS problems could be addressed using this system, thus yielding payback from the LWS investments early in the program. Such investigations could include not only topics addressed by current observations, but perhaps more importantly, topics that require investigation of solar-cycle dependences. Improved models of the radiation belts is an obvious example.

It is essential that LWS management and its Data Systems Team initiate this effort in the near future, so that the required system will formed early in the LWS program.

Appendix 7 - Geospace and Heliospheric Mission "1 pager" descriptions, July 2001 SAT meeting

LWS Geospace Missions -- Radiation Belts

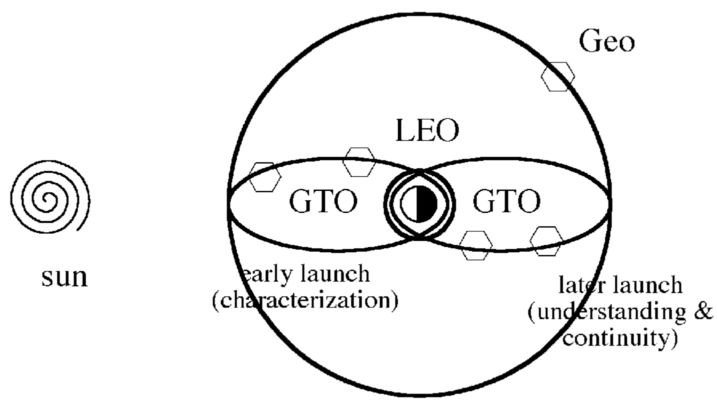
Mission Concept: dedicated S/C & missions of opportunity
GTO-like: 2/3 satellites per launch in two launches phased for solar cycle coverage - core + opportunity; measure B, energetic particles, plasma incl. ion composition on first launch. Second launch spacecraft include above measurements plus waves and E
Geo mission of opportunity: measure B and energetic particles, plasma incl. ion composition, ENA, E
LEO: SEP and SAA measurements for ionospheric, atmospheric, climate, & human radiation exposure similar to SAMPEX or DMSP

Science Questions:

- **What processes control the acceleration, loss, and transport of radiation belt electrons and ions?**
- **What is the geospace response to geomagnetic storms, e.g., development and trapping of ring current, Joule heating of the ionosphere, ground induced currents, and severe S/C charging?**
- **What are the effects of solar energetic particles at low Earth orbit and in the atmosphere/ionosphere?**
- **What is the radial and longitudinal distribution and dynamics of particles in CME and flare-associated solar particle events?**

LWS Target Areas

- **S/C radiation dose and bulk charging**
- **S/C drag**
- **Magnetospheric induced currents**
- **communication, navigation, and radar**
- **upper atmospheric chemistry / ozone**
- **ground induced currents**



Other contributing measurements:
L1: ACE, Wind, Triana
NASA missions: SDO, GEC, ISS, MagCon, MMS, TWINS, Image?, Polar?, Cluster?, SAMPEX? non-NASA missions: GOES, LANL-GEO, GPS, HEO, DMSP, NPOESS, GMS (Japan), ICO, commercial-satellites

LWS Geospace Missions -- Ionosphere/Thermosphere

Mission Concept:

1. LEO Orbits below the exobase; inclination to maximize longitude and latitude coverage within seasonal variations (~70°); *in-situ* measurements of ionosphere and thermosphere dynamics and structure; solar energetic particles/polar cap access and size; SAA

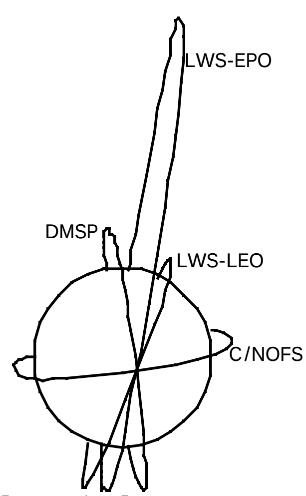
2. Elliptical Polar Orbit (EPO)
Inclination and eccentricity to maximize efficiency of global auroral imaging and O/N2 perturbations and other pertinent parameters; energetic neutral atom imaging for ring current global view

Science Questions:

- **Global Specification and Prediction of Neutral Upper Atmospheric Density and Dynamics; Ionosphere Density, Structure and Irregularities**
- **Dynamics, latitude, longitude, and local time variations in**
  - **Thermospheric winds**
  - **Neutral mass composition and density**
  - **E-field or ExB drift**
  - **Ionospheric mass composition and density**
  - **Scintillation and Density Irregularities**
- **Global Auroral Energy Deposition**
- **Global Neutral Density Perturbations**
- **Ring Current Dynamics**

LWS Target Areas

- **Detection and tracking of space objects**
- **Communication, Navigation and Radar**
- **Geomagnetically Induced Currents**



Other contributing measurements:
C/NOFS: equatorial ionosphere dynamics & structure
DMSP/NPOESS: latitude profiles of neutral density at fixed local times; energetic particle input
Ground Based Observations: Electric Fields, Conductivities, Magnetic Perturbations
L1: ACE, Wind, Triana: specification of IMF and Solar Wind
SDO: EUV spectral irradiance; Geoeffective disturbances

Inner Heliospheric Mappers

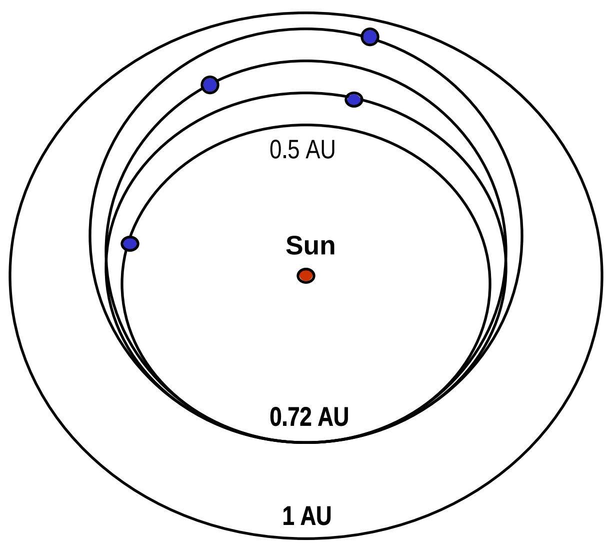
Mission Concept: Four identical spacecraft in elliptical heliocentric orbits (0.5 –0.95 x 0.72 AU)
Objective: Continuous, *in situ*, inner-heliospheric observations to study the structure, dynamics, & radial evolution of CMEs, solar particles, and geo-effective disturbances
Strategy: Multi-point observations distributed in radius & longitude
Instruments: Magnetometer, Solar wind analyzer, Energetic particles, & Radio waves
Launch Vehicle: Single Delta-II launch

Science Questions:

- **What is the ambient structure of the inner heliosphere?**
- **How do large-scale structures evolve during transit to Earth? (CMEs, shocks, fast streams)**
- **What dynamic processes in the corona can be determined from heliospheric observations?**
- **What is the radial and longitudinal distribution and dynamics of particles in CME and flare-associated solar particle events?**

LWS Target Areas

- **Solar impacts on communications, navigation, and radar**
- **Dynamics of the near-Earth radiation environment**
- **Magnetospheric induced currents**
- **Radiation from explosive solar events**



Other contributing measurements:
L1: ACE, Wind, Triana
STEREO: Multi-pt imaging & in situ data on CMEs, SEPs
Inside 1 AU: SOLO?, Messenger?, Beppi-Columbo?
Also upstream: SOHO, IMP, Geostorm?, Magtail Con.
Outside 1 AU: Ulysses, Voyager

Appendix 8 - Abbreviations and Acronyms

ACE	Advanced Composition Explorer
AE	auroral electrojet
Beppi-Colombo	Mission to Inner Solar System (ESA)
Ap	Planetary A index of geomagnetic activity
ARGO S	Advanced Research and Global Observing Satellite
AU	astronomical unit
B	magnetic field
Bz	component of IMF perpendicular to the ecliptic
BATSRUS	Three-dimensional MHD model using adaptive mesh refinement
CCMC	Community Coordinated Modeling Center
CEDAR	Coupling Energetics and Dynamics of Atmospheric Regions
CME	coronal mass ejection
C/NOFS	Command and Navigational Operations Satellite
CTIM	coupled thermospheric-ionospheric model
CTIPE	Coupled Thermosphere Ionosphere Plasmasphere Electrodynamic Model
CY	calendar year
DISS	Digital Ionospheric Sounding System
DMSO	Defense Modeling and Simulation Office
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
Dst	magnetic disturbance storm time index
E-field	electric field
EISCAT	European Incoherent Scatter Radar
ENA	Energetic Neutral Atom
EPO	Elliptical Polar Orbit
ESA	European Space Agency
EUV	extreme ultraviolet
eV	electron-volt
Farside	NASA LWS mission to far side of sun (concept)
FAST	Fast Auroral Snapshot Explorer
foF2	Maximum ordinary mode radio wave frequency capable of reflection from the F2 region of the ionosphere
FY	fiscal year
F10.7	an index of solar radio noise used as a proxy for solar EUV radiation levels
GEC	global electrodynamics connection (NASA mission)
GEM	Geospace Environment Modeling Program
GEO	Geosynchronous orbit

GEOSpace	Workstation software suite of space weather and related applications
Geostorm	mission concept for ~0.95 AU on Sun-Earth line
Geotail	Geotail spacecraft (NASA ISTP mission)
GGS	Global Geospace Science Program
GHz	gigahertz
GIC	geomagnetically induced currents
GLO	Arizona Airglow Experiment
GOES	Geostationary Operational Environmental Satellite
GMS	Japanese meteorological satellite
GPS	Global Positioning System
GPS/MET	Global Positioning System Meteorological Sounding Experiment
GSFC	Goddard Space Flight Center
GSWM	a linear hydrometeorological model for global-scale waves
GTO	Geostationary Transfer Orbit
HEO	highly elliptical Earth orbit
HESSI	High Energy Solar Spectroscopic Imager
HF	high frequency
ICO	Boeing constellation of communication satellites
IFM	Ionospheric Forecast Model
IH-Mappers	Inner Heliospheric Mappers (NASA LWS)
IMAGE	Imager for Magnetopause to Aurora Global Exploration
IMF	interplanetary magnetic field
IMP	Interplanetary Monitoring Platform
IPS	interplanetary scintillation
IR	infrared
IRI	International Reference Ionosphere
ISOON	Improved Solar Observing Optical Network
ISS	International Space Station
ISTP	International Solar-Terrestrial Physics Program
JHU/APL	The Johns Hopkins University/Applied Physics Laboratory
keV	kilo electron-volts
kHz	kilohertz
km	kilometers
Kp	Planetary K index of geomagnetic activity
L1	Lagrangian point, or a mission at L1
LANL	Los Alamos National Laboratory
LANL-GEO	LANL particle instruments on GEO satellites
LEO	low Earth orbit
LORAN	Long-range Radio Navigation

L-shell	Magnetic coordinate appropriate for the Earth's radiation belts, corresponding to 1 Earth radius at the magnetic equator
LT	local time
LWS	Living with a Star Program (NASA)
MagCon	Magnetotail Constellation (Solar Terrestrial Probe multi S/C mission , NASA)
MDT	Mission Definition Team
Messenger	Mission to Mercury (NASA)
MeV	million electron volts
MHD	magnetohydrodynamics
MLTI	mesosphere and lower thermosphere/ionosphere
MMS	Magnetospheric Multiscale Mission (NASA)
MSFM	Magnetospheric Specification and Forecast Model
MSIS	Mass Spectrometer and Incoherent Scatter model
MSM	Magnetospheric Specification Model
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
Neutral ρ	Neutral atmosphere density
NmF2	peak F—region electron density
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSSA	National Security Space Architect
NSSDC	National Space Science Data Center
NSWP	National Space Weather Program
Odstreil-Pizzo	Three-dimensional model for calculating transient disturbances in a structured global solar wind
OES	Office of Earth Science (NASA)
OSS	Office of Space Science (NASA)
PI	power index
POES	Polar Orbiting Environmental Satellite
Polar	Polar Spacecraft (NASA ISTP mission)
PRISM	Parameterized Realtime Ionospheric Specification Model
psd	phase space density
RAO	Relocatable Atmospheric Observatory
R_E	Earth radii
REE	Relativistic Electron Events
RPC	Rapid Prototyping Center
R_S	solar radii

RTSW	Real Time Solar Wind
Salammbo	Radiation belt model for diffusive and convective transport, developed at CERT, France
SAMPEX	Solar Anomalous Magnetospheric Particle Explorer
SAT	Science Architecture Team (NASA LWS program)
S/C	spacecraft
SDO	Solar Dynamics Observatory
SEC	Space Environment Center (NOAA) or NASA's Sun—Earth Connections Program
SECAS	Sun-Earth Connections Advisory Subcommittee (NASA OSS)
SEM	Space Environment Monitor
SEON	Solar Electro—Optical Observing Network
SEP	solar energetic particles
SHINE	Solar Heliospheric and Interplanetary Environment Program
SMEI	Solar Mass Ejection Imager
SMEX	Small Explorer Program
SO	Solar Orbiter Mission (also called SOLO)
SOHO	Solar and Heliospheric Observatory
Solar-B	Solar-B mission (ISAS with US instrument)
SOLO	Solar Orbiter Mission (also called SO)
SONAR	Solar Near-Surface Active Region Rendering (NASA mission concept; renamed SDO)
SPE	Solar Energetic Particle Event
STEREO	Solar Terrestrial Relations Observatory Mission (NASA)
STOA	shock time of arrival
SuperDARN	Super Dual Auroral Radar Network
SW	Solar Wind
SWRN	Space Weather Research Network
SX	Solar X-ray event
SXI	Solar X-ray Imager
TEC	total electron content
TIEGCM	Thermosphere-Ionosphere Electrodynamics General Circulation Model
TIME-GCM	Thermosphere Ionosphere Magnetosphere Energetics -- General Circulation Model (including dynamics and chemistry)
TIMED	Thermosphere-Ionosphere-Magnetosphere Energetics and Dynamics Mission
TIROS	Television and Infrared Observation Satellite
Triana	Triana L1 mission (NASA)

TRACE	Transitions Region and Coronal Explorer
TWINS	Two wide-angle imaging neutral-atom spectrometers (NASA mission)
Tsyganenko field	Semi-empirical best-fit representing for Earth's magnetic field including effects of magnetospheric currents
UARS	Upper Atmosphere Research Satellite
UHF	ultrahigh frequency
Ulysses	Ulysses mission (ESA with US instruments)
URL	World Wide Web Universal Resource Locator
USAF	United States Air Force
UV	ultraviolet
VHF	very high frequency
VLEO	Very Low Earth Orbit
Volland-Stern	Analytical Kp driven magnetospheric electric field model
Voyager	Voyager deep space probe mission (NASA)
Vsw, ρ	solar wind velocity and density
W	watt
Wang-Sheely-Arge	Three-dimensional model for calculating solar wind structures based on a source surface calculated from solar photospheric magnetic field measurements
Wind	Wind spacecraft (NASA ISTP mission)
3D	three-dimensional

Note: many of these abbreviations and acronyms were obtained from the National Space Weather Program Implementation Plan, July 2000

Appendix 9 -- Space Storms Group: Specific Societal Impacts

Solar Impacts on Communications, Navigation and Radar:

- Forecast the effects of variations in the electron density distribution in the ionosphere
- Discover the cause of plasma density irregularities that cause radio scintillation

Tracking and Identification of Objects in Space:

- Understand and predict solar influences on satellite drag

Geomagnetic Induced Currents:

- Develop the capability to forecast induced currents due to ionospheric-geomagnetic current systems

Dynamics of the Near-Earth Radiation Environment:

- Discover the processes that accelerate, transport, and distribute energetic particles during geomagnetic storms
- Understand and predict the intensity of outer-zone electrons due to high-speed solar wind streams

Radiation Associated with Explosive Events on the Sun:

- Develop the capability to forecast solar particles accelerated by flares and CMEs
- Predict the intensity of particles accelerated by traveling interplanetary shocks
- Understand how solar/interplanetary variability governs the entry of energetic particles into the magnetosphere

Solar Impacts on Communications, Navigation and Radar

1) Forecast the effects of variations in the electron density distribution in the ionosphere

Objective: Produce the capability to forecast changes in the large-scale behavior of the ionospheric density from 100 to 1000 km

Societal Impact

- Electron density distribution affects navigation systems, communication signal paths, and radar reflectivity
- Changes in density distributions affect operation of HF communication links.

Primary Current Limitations

- Computational ionospheric models driven by proxies for solar EUV radiation, electromagnetic drivers and solar-wind drivers
- Cause of day-to-day variability in neutral winds and ExB drifts unknown
- Sparse ionospheric data sets
- Limited ability to predict active-region emergence / evolution & solar flare occurrence

5-10 year LWS goal

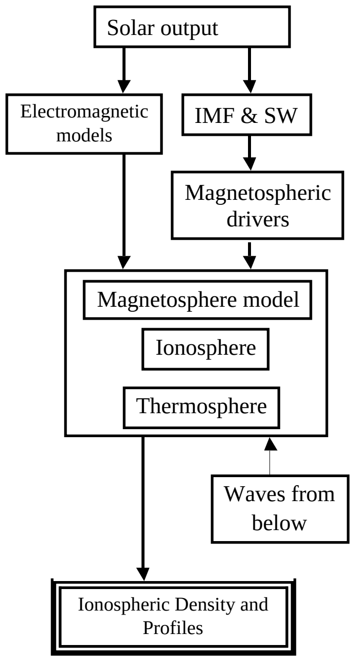
- Validation of physics-based models with variations in input drivers
- Establish data-assimilation processes to accommodate sparse data sets
- Ensure that adequate global ionospheric data sets are available
- Ensure that adequate measurements of EUV and solar-wind drivers exist
- Develop helio-seismic tools for field emergence; magnetographic measures of eruption

>10 year LWS goal

- Validate physics-based data assimilation models for ionosphere
- Refine solar models for improved driver forecasting

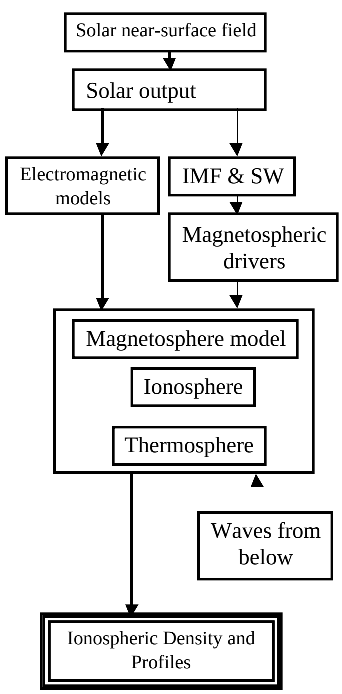
Model and Measurement Development:

Models and Measurements



	Current	**5-10 yr goal**	**> 10 yr goal**
Operational			
	Magnetograms F10.7	Full-disk, high-res $\vert B \vert$	Full-disk, high-res. vector B
	X-rays Protons Ap DISS	EUV spectrum IMF, SW v, ρ GPS, DMSP, COSMIC	NPOESS Auroral Imager Convective Imager Ne LWS-Ionospheric Mapper
	IRI, PRISM	Data Assimilation	
Research			
	IFM, CTIPE, TIEGCM	Coupled Assimilation Models	Mag-Ion-Thermo with Data Assimilation
	TIME-CCM GSWM		Whole Atmosphere Model

Measurement requirements and sources:



Models	**5-10 Yr Goal Measurements**	**Data source**
Flux emergence model	B, images	SOHO & TRACE SDO + Solar B
EUV irradiance Flare x-ray, EUV predict	Multi-wavelength EUV	SDO
CME prediction	CME evolution	SOHO, STEREO
Large-scale heliospheric field	B, Vsw, ρ	L1 (ACE, Wind, Triana) IH-Mappers
IFM, CTIPE, TIEGCM	ground based E E field precipitation	DMSP, NPOESS Super DARN DMSP, NPOESS, + imager (Polar, IMAGE)
Coupled Assimilation Models	Neutral ρ, winds E field	DMSP, NPOESS follow on imager + VLEO middle incl (for neutral ρ, E) 2 s/c
Data Assimilation	Neutral waves	Global remote sensing
		Auroral Imager Ion Convection Imager Ionospheric Mapper

2) Discover the cause of plasma density irregularities that cause radio scintillation

Objective: Produce the capability to forecast changes in the intensity of scintillation activity and in the location of small-scale plasma density irregularities in the 100 to 1000 km altitude region

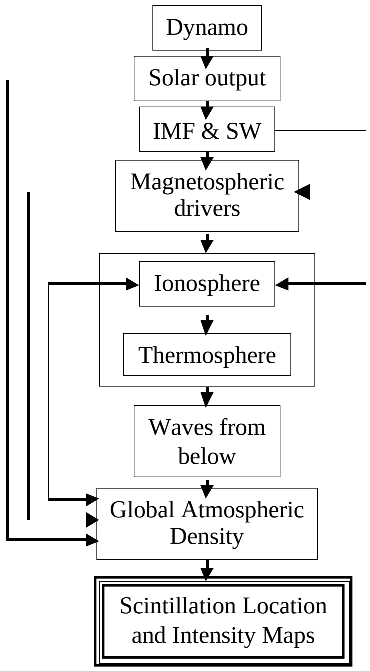
Societal Impact
- Plasma density irregularities compromise performance of navigation, communications, and radar systems

Primary Current Limitations
- Only have climatological model of radio scintillation above some threshold level
- Computational models depend on specification of variable background ionosphere and neutral atmosphere
- Computationally intensive non-linear codes to derive irregularity spectral index

5-10 year LWS goal
- Develop data assimilation models to determine day-to-day variability in background ionosphere and neutral atmosphere.
- Improve 3-D, non-linear, computational plasma density irregularity models
- Develop techniques for forecasting ambient E x B drift velocities

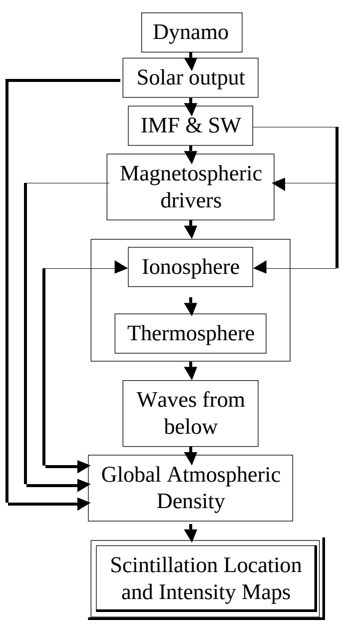
>10 year LWS goal
- Validate physics-based assimilation model
- Validate computation of irregularity spectrum from driver inputs

Model and Measurement Development:



Current	5-10 yr goal	> 10 yr goal
	seismic spec.	→
F10.7	EUV spectrum	→
Ap	IMF, SW v, ρ (near-Earth/inner-heliosph.)	→
Empirical Model Data Assimilation	Coupled Assimilation Models	Global MHD
TIEGCM	Data Assimilation	improve →
GSWM		

Measurement requirements and sources:



model	5-10 yr goal measurements	data source
internal convection	seismic, internal flows	SOHO, SDO
EUV irradiance	EUV, B, images	SDO + Solar B
	B, Vsw, ρ (upstream; inner-helio)	L1 (ACE, Wind, Triana) IH-Mappers
	ground based E E field	DMSP, NPOESS Super DARN
	precipitation	DMSP, NPOESS, + imager (Polar, IMAGE)
	Neutral ρ, winds E field	DMSP, NPOESS follow on imager + VLEO middle incl (for neutral ρ, E) 2 s/c Global remote sensing
		CNOFs, LWS I_Mappers
	Neutral waves	

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
physics-based		validate ---->	assimilation model

Tracking and Identification of Objects in Space:

3) Understand and predict solar influences on satellite drag.

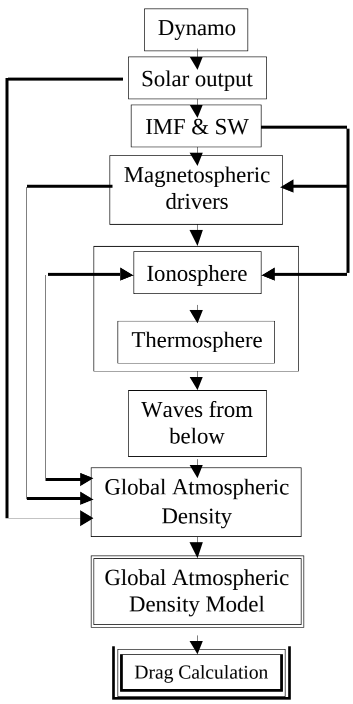
Societal impacts
- Satellite orbits are perturbed by sudden changes in atmospheric drag
- During periods of intense solar activity it is necessary to allow for very large location errors in planning satellite and space operations
- During such periods small orbiting objects can be temporarily “lost”, posing orbital-debris hazards

Primary Current Limitations
- Empirical models have very large uncertainty (>30 percent)
- Poor altitude specification below 350 km.
- Computational models driven by proxies for solar EUV and electromagnetic drivers.
- Sensitive to poorly specified small-scale motions at lower boundary.
- Cause of day-to-day variability in neutral winds is unknown
- Sparse neutral atmosphere data sets
- Insufficient knowledge of atmospheric-ionospheric-magnetospheric coupling process

5-10 yr LWS goal:
- Refine empirical model of winds and density with new data & inputs.
- Validate physics-based models with variations in measured input drivers.
- Establish data-assimilation processes to accommodate sparse data sets
- Ensure that adequate neutral atmosphere global data sets are available

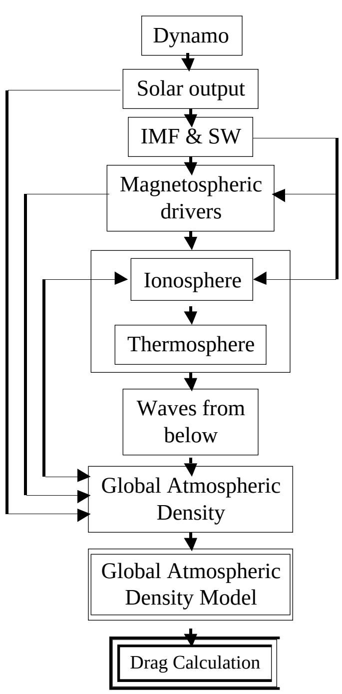
> 10 yr LWS goal:
- Validated physics-based data assimilation and forecast model

Model and Measurement Development:



Current	5-10 yr goal	> 10 yr goal
	seismic spec.	→
F10.7	EUV spectrum	→
Ap	IMF, SW v, ρ	→
Empirical Model Data Assimilation	**Coupled Assimilation Models**	**Global MHD**
TIEGCM	Data Assimilation	improve →
GSWM		
MSIS empirical model	Refine MSIS w new data; validate physics based models	validated physics based assimilation models
~20% error	~10% error	~5% error

Measurement requirements and sources:



Model	5-10 yr goal Measurements	Data source
internal convection	seismic, internal flows	SOHO, SDO
EUV irradiance	EUV, B, images	SDO + Solar B
	B, Vsw, ρ	L1 (ACE, Wind, Triana)
	ground based E	DMSP, NPOESS
	E field	Super DARN
	precipitation	DMSP, NPOESS, + imager (Polar, IMAGE)
	Neutral ρ, winds E field	DMSP, NPOESS follow on imager + VLEO middle incl (for neutral ρ, E) 2 s/c Global remote sensing
	Neutral waves	

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
MSIS	refine w new data----------->		
physics-based		validate ---->	assimilation model
ITM		develop model --->	improve

Geomagnetic Induced Currents

4) Develop the capability to forecast induced currents due to ionospheric-geomagnetic current systems

Societal impact
- Ionospheric current systems induce extraneous currents in electrical power grids and other long-distance systems causing outages and degradation of system operations

Primary Current Limitations
- Poor ability to predict geo-effective solar wind characteristics
- Poor ability to predict magnetospheric electric and magnetic field
- Poor ability to predict ionospheric conductivity

5-10 yr LWS goal
- Develop improved capability to forecast current systems from solar wind (L1) data
- Develop magnetospheric and ionospheric models to forecast and specify the electrojet location and intensity
- Develop ability to forecast upstream solar wind conditions upstream up to several hours in advance for large geo-effective structures
- Develop improved capability to extrapolate solar field to heliosphere and predict the Z-component of the magnetic field, CMEs, and fast/slow solar wind streams

>10 yr LWS goal
- Improve models that forecast and specify the electrojet strength and location
- Improve models that predict solar wind conditions upstream of the magnetosphere up to a week in advance

Model and Measurement Development

Model	Current	5-10 yr goal	> 10 yr goal
Photosphere-Chromosphere Models Coronal Fields Model	Can forecast CME with high error rate (e.g. sigmoid structure)	Forecast CME and its primary characteristics before it erupts Forecast large-scale heliosph. field structure	Forecast direction, extent and structure of CME before it erupts
Erupting Flux Model Lower Corona CME	Can identify major CME but not direction, internal structure, or arrival time ± 1 day	Specify directions, extent and structure of CME from remote observations	
Global Heliospheric Model		Use remote data for initial models of CME propagation	Use remote observations to accurately model CME propagation from Sun to Earth
CME and Shock Propagation Model	Forecast of major field variations 1 hour in advance	Develop ability to forecast SW conditions upstream from magnetosphere up to several hours in advance.	
Magnetospheric coupling models	Solar-wind data from L1 drive Kp, DST algorithms		
Magnetosphere models Ionospheric conductivity model	Can specify approximate location and intensity of currents from solar wind input	Forecast current location and intensity 6 hours in advance including major variations in time and space	Accurately forecast currents 2-3 days in advance including major variations in time and space

Measurement requirements and sources:

Model	5-10 yr Measurements	Data source
Photosphere-Chromosphere Models	Full-disk magnetic field	SOHO, SDO, Ground-based, Solar B
Coronal Fields Model (steady state)	Multi-soectral, high spatial and temporal resolution EUV Multi-height vector magnetic fields in the low atmosphere	SOHO/TRACE SDO Solar B
Erupting Flux Model	Sub-photospheric velocity measurements--helioseismology	SDO, Farside
Global Heliospheric Model	4 Pi photospheric vector magnetic field In situ solar wind and magnetic fields at various radial distances and longitudes simultaneously to calibrate models	SDO, Farside L1, STEREO, IH-Mappers SOLO
CME and Shock Propagation Model	Stereoscopic remote observations In situ solar wind and field observations at various radial distances and longitudes Remote observations via heliospheric imager Remote radio observations from multiple points Composition of SW to identify structural components of CMEs on the Sun and in situ	STEREO, SDO L1, near-Earth, STEREO, IH-Mappers STEREO WIND, Ulysses STEREO ACE, Ulysses
Magnetospheric coupling models	N,T,v,B upstream from Earth	L1
Magnetosphere models	Ground Magnetic Field Magnetosphere ExB Ionospheric images	Magnetospheric mapper DMSP, NPOESS Super DARN DMSP, NPOESS, + imager (Polar? IMAGE?) Ground magnetometers Ground-based radars
Ionospheric conductivity models	Ground Magnetic Field Ionospheric images	Auroral Imager Ion Convection Imager Ionospheric Mapper IMAGE Ground magnetometers

The Dynamic Near-Earth Radiation Environment

5) Discover the processes that accelerate, transport, and distribute energetic particles during geomagnetic storms

Societal impact

- Energetic particles cause destruction and mutation of human tissue
- Dielectric charging, electrical upsets surface charging cause malfunction and failure of spacecraft sub-systems

Primary Current Limitations

- Inadequate monitoring of the radiation belts and ring current, including ion composition
- Poor understanding of the acceleration / transport of relativistic electrons in the radiation belts
- Poor understanding of the coupling of interplanetary variations with impacts in the magnetosphere and effects on the radiation belts and ring current

5-10 yr LWS goal

- Sufficient measurements to determine relative importance of physical processes
- Sufficient measurement to specify source populations for physics-based models
- Construct models describing the local and regional acceleration processes
- Establish data assimilation processes to accommodate distributed observations

>10 yr LWS goal

- Validated Physics-based assimilation model

Model and Measurement Development:

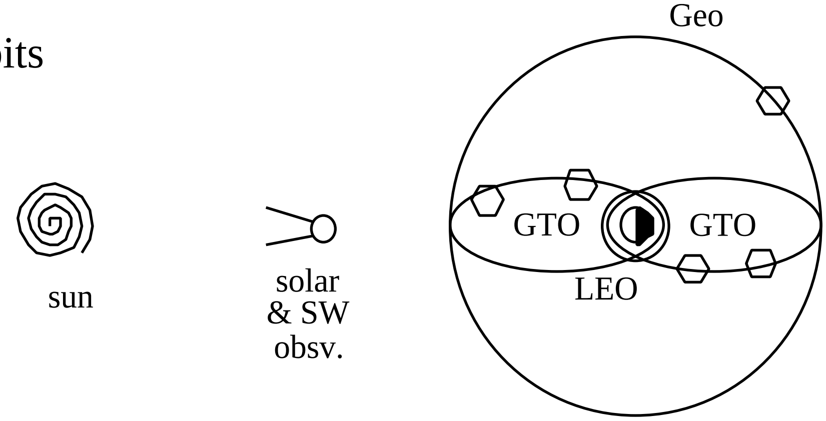
	Current	5-10 yr goal	> 10 yr goal
Energetic Particle (Radiation) Environment Radiation Belt SEP, S/C charg	Monitoring radiation from geosynchronous and polar orbits and from GPS	3-D particle model with physical source and loss processes and accurate outer magnetosphere fluxes	Data assimilative 3-D particle transport model with physical source and loss processes
Particle specification (flux, phase space density, spatial distribution, spectrum, etc.)		Nowcasts of radiation-belt fluxes, based on data from elliptic-orbit, near eq. s/c	Validated physical model for relativistic outer-belt electrons
B-field specification model			
E-field Specification model			
Waves, fluctuations, diffusion			
Particle boundary conditions			
SW/IMF input			
CME			
High-Speed streams			
Coronal Holes	(Same as that for Environment Group)		

Measurement requirements and sources:

	Model	5-10 yr goal Measurements	Data source
Energetic Particle (Radiation) Environment Radiation Belt SEP, S/C charg			
Particle specification (flux, phase space density, spatial distribution, spectrum, etc.)	MSM - convection/drift AE/AP-8 AF-Geospace Salammbo	Fluxes measured at L=2 to 8 near equatorial plane for full range of equatorial pitch angles	Spacecraft in elliptic, near-equatorial orbit, along with geosynchronous and polar-orbit
B-field specification model	MHD Ring Current event models Tsyganenko Type		
E-field Specification model	Volland Stern Mapped Ionosphere MSM	Same as above, but also measurements of E, B, waves	Spacecraft in elliptic, near-equatorial orbit, along with geosynchronous and polar-orbits
Waves, fluctuations, diffusion	Statistical Studies Theories		
Particle boundary conditions	MHD or observations		
SW/IMF input	S&S Petrinec		
CME	?		
High-Speed streams	?		
Coronal Holes	?	(Same as that for Environment Group)	

Measurement Goals:
To make a sufficient set of measurements to determine which physical processes are most important, at which locations, and under which conditions

Orbits



GTO
1) B & Energetic Particles together
2) Plasma and ion composition
3) Waves and E

Geo
1) B & Energetic Particles together
2) Plasma and ion composition
3) ENA
4) E

LEO
SEP and SAA measurements
similar to Sampex, DMSP, etc

S/W
IMF
density
velocity
psd < 200 keV
etc.

Solar
similar to SOHO, Yohkoh, etc.

(from Group 2)

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
Statistical models Research models based on empirical diffusion coefficients Research models based on global MHD and test particles Analytic theory	Inner-magnetosphre analysis model that provides snapshots of radiation belts, tested on historical data	Inner-magnetosphere analysis model providing nowcasts of radiation belts, using flux and B-field data provided by elliptic-orbit, near-equatorial spacecraft Validated first-principles model of transport/ acceleration of relativistic electrons in inner magnetosphere First-principles model of outer-magnetosphere source population	Validated, first-principles radiation-belt model based on global MHD, with assimilation of radiation-belt fluxes and magnetic fields.

(From the Environment Group)

6) Understand and predict the intensity of outer-zone electrons due to high-speed solar wind streams.

Societal impact

- Dielectric charging causes malfunction and failure of spacecraft sub-systems
- Energetic particles cause destruction and mutation of human tissue
- Dielectric charging, electrical upsets surface charging cause malfunction and failure of spacecraft sub-systems

Primary Current Limitations

- Inadequate monitoring of the radiation belts
- Limited understanding of the acceleration / transport of relativistic electrons in the radiation belts
- Understanding of the coupling of interplanetary solar-wind variations with effects on the radiation belts
- Solar wind currently monitored only at L1

5-10 yr LWS Goal

- Use STEREO data to forecast solar wind environment at Earth several days in advance
- Improved physics-based acceleration / transport model driven by interplanetary data

>10 yr LWS goal

- **Validated physics-based assimilation model**

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
Outer- magnetospheric model based on empirical diffusion coefficients predicts fluxes at L=6.6 Empirical combination of solar wind parameters provides magnetospheric driver	Extension of model to lower L-shells	Augmentation of model to predict relativistic electrons at L = 2 - 8 near the equatorial plane for the full range of equatorial pitch angles	Validated, first-principles radiation-belt model.

Radiation Associated with Explosive Events on the Sun:

7) Develop the capability to forecast solar particles accelerated by flares and CMEs.

Societal Impact
- Solar particle radiation dose to astronauts in high-inclination orbits or on missions beyond Earth's magnetosphere
- Sudden radiation damage to on-orbit space systems
- Radiation exposure of crew and passengers in high-altitude aircraft

Status and Current Limitations
- Very rapid rise in particle fluxes may occur following flares and CME emission
- Forecasts of these events currently based on statistical association with other solar activity such as x-ray flares
- Current forecasts have high false-alarm rate; forecast intensities uncertain by factors of 10

5-10 year LWS Goal
- 1-hr to 1-day forecast with improved accuracy
- Refine empirical models with new in-situ and remote-sensing data; improve empirical relations
- Establish data-assimilation process to incorporate interplanetary and remote-sensing data
- Develop physics-based acceleration/transport and data-assimilation model to predict intensities and spectra based on upstream in-situ observations and remote-sensing data

>10-year LWS Goal
- Precise 20-minute prediction, improved 1-hr to 1-day predictions; 2-week "all-clear"
- **Validate physics-based assimilation model that relates particle intensity to solar events and interplanetary observations**

Model and Measurement Development

	Current	5-10 yr goal	> 10 yr goal
Photosphere-Chromosphere Models	Observation-based flux injection and flow shear	Understanding of helicity injection & evolution	MHD model of coronal field evolution with surface drivers
Active Region Field Model			
Coronal Fields Model (steady State)	Potential, or linear force-free model	General force-free to compare to observed corona	General force-free based on vector magnetic field
Flare/CME Energy Release Model with particle acceleration	Empirical models	Coupled empirical models with physical models in some segments	Field-evolution model with particle acceleration
Global Heliospheric Model	Source-surface extrapolation model	Data assimilation of multi-pt interplanetary measurements	Coupled physical models with data assimilation
Particle Acceleration/Transport Models	Shock acceleration & wave-particle interaction models	Acceleration & transport model: predict intensity & time-profile	Global acceleration & transport model
Solar Energetic Particle Flux at One AU	Statistical Models	1 hr to 1 day yes/no forecast with improved (90%) accuracy	1-hr to 1-week yes/no forecast with 90% accuracy; ability to forecast large event (>10^7) or small with improved (90%) accuracy & 4 hour lead time; 2-week "all-clear" forecast

Measurement requirements and sources:

Model	5-10 yr Goal Measurements	Data Source
Photosphere-Chromosphere Models	2 pi magnetic field	SDO, Ground
Active Region Field Model	Multi-soectral, high spatial and temporal resolution EUV Multi-height vector magnetic fields in the corona	SDO, Ground, Solar-B Solar-B
Coronal Fields Model (steady State)	Sub-photospheric velocity measurements--helioseismology	SDO, Farside
Flare/CME Energy Release Model with particle acceleration at the Sun	X/γ-ray spectra CME evolution B-field-configuration.	< HESSI, GOES STEREO, SDO, IH-Mappers, L1 SOLAR-B
Global Heliospheric Model	4-pi photospheric vector magnetic field In situ solar wind and magnetic fields at various radial distances and longitudes simultaneously to calibrate models	L1, STEREO, IH-Mappers, SOHO Solar Prob, Mercury missions?
Interplanetary Acceleration & Transport Models	SEP observations at various radial distances and longitudes; interplanetary conditions	L1, STEREO, IH-Mappers, Solar Probe, SO, (Mercury missions?)
Solar Energetic Particle Flux at One AU		

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
Empirical flare/CME trigger		Approximate flare trigger scenario	Understanding of instability criteria
Empirical flare brightness		Approximate flare spectrum	Understanding of flare brightness evolution
Source-surface heliospheric field model	MHD heliospheric field model	Dynamic heliospheric field on large scale	Dynamical heliospheric field model with statistical knowledge of perturbations
Backside imaging for Long-term forecasts	Improved back-side imaging techniques	Flux-emergence helioseismic imaging techniques for ±12 hr warning of major events	
Particle intensity scaled from x-ray intensity and location	Also include CME-speed and location	Incorporate STEREO in-situ & remote-sensing data	Physics-based assimilation model
Particle transport based on connection longitude only	Investigate dependence on interplanetary conditions	Develop assimilation model using multi-pt in-situ data	Global acceleration/transport model
Technique Development			
Photospheric vector field measurement technique	Chromospheric vector field measurement technique in active regions		Chromospheric vector field on full disk

8) Predict the intensity of particles accelerated by traveling interplanetary shocks.

Societal Impact:
- Solar-particle radiation dose to spacecraft and astronauts in high-inclination orbits unexpectedly increases when traveling shock reaches Earth
- Radiation exposure of crew and passengers in high-altitude aircraft

Status and Current Limitations
- During large SEP events (e.g., 10/89) the highest intensities sometimes occur 1-2 days after event onset when a traveling interplanetary shock reaches Earth
- Data from L1 can provide warning of the approaching shock-accelerated particles many hours in advance, but predicted particle intensities are highly uncertain
- Shock development and interaction with heliospheric field cannot be accurately modeled

5-10 yr LWS goal
- Refine heliospheric field and shock propagation models
- Refine empirical models with new inner-heliospheric *in situ* and remote-sensing data; improve empirical relations; investigate cosmic-ray precursor signal
- Establish data assimilation process to incorporate L1-interplanetary and remote-sensing data
- Develop physics-based acceleration/transport and data assimilation model to predict shock-associated intensities & spectra from upstream *in situ* observations and remote-sensing data

>10 yr LWS goal
- Validate physics-based assimilation model that relates shock-accelerated particle intensity to interplanetary and remote sensing observations

Model and Measurement Development:

Model	Current	5-10 yr goal	>10 yr
Lower Corona CME	No quantitative model	CME initial evolution model	
Global Heliospheric Model	Wang-Sheeley-Arge	Dynamic model with Data assimilation	Physics/empirical model with data assimilation
CME and Shock Propagation Model	Odstreil-Pizzo BATSRUS	Include particle acceleration	Include global, dynamic, heliospheric background
Particle Acceleration Model	Empirical algorithm based on down-stream particles	Physics/empirical accel./transport model with data assimilation	Refine and validate Physics/empirical model including data assimilation
Particle Transport Model	Empirical model for forecasting Physics models exist	Physics/empirical Accel/transport model with data assimilation	Refine and validate Physics/empirical model including data assimilation
Geomagnetic Cutoff Model	Particle tracing model In static field or Empirical cutoff model L1-driven cutoff var.	Comprehensive cutoff model driven by L1/Magnetosph. data	Dynamic cutoff Model with real-Time calculations

Measurement requirements and sources:

Model	5-10 Yr Goal Measurement	Data source
Lower Corona CME	CME precursor formation, initial CME evolution	SOHO/TRACE STEREO, SDO
Global Heliospheric Model	Multi-point SW & CME data, especially closer to Sun	STEREO, L1, IH-Mappers, SOLO, Solar Probe
CME and Shock Propagation Model	Stereo tracking of CME speed & characteristics; in situ and radio data	SOHO, STEREO, SDO, L1, IH-Mappers, Wind, Ulysses,SMEI ground-based
Particle Acceleration Model	Spectra of particles escaping downstream, shock characteristics closer to Sun	STEREO, L1, IH-Mappers, SOLO
Particle Transport Model	Multi-point particle data; Interplanetary conditions	STEREO, L1, IH-Mappers, Ulysses, SOLO
Geomagnetic Cutoff Model	B-field and solar wind at L1 or further upstream; State of magnetosphere; Cutoff data from SEPs	L1, IH-Mappers SAMPEX/Polar MMS, LEO/GTO

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
MHD CME/shock transport without acceleration (BATSRUS)	Add acceleration and refine	Comprehensive CME/shock/accel/transport model with data assimilation fed by new multi-point measurements	Validate and refine Model
MHD ideal shock transport with acceleration (Zank)	More realistic SW, shock parameters		
Analytic accel./transport model with assumed conditions (Lee)	Compare with data and refine	Combined accel./transport model with data assimilation, and new multi-point data	Validate and refine model
Numerical wave-particle Transport model w/o acceleration (Ng)	Extend to higher energy, refine, add in acceleration (?)		

9) Understand how solar/interplanetary variability governs the entry of energetic particles into the magnetosphere

Societal Impact:

- Solar-Particle radiation dose to spacecraft and astronauts in high-inclination orbits increases during geomagnetic storms
- Energy-deposition of solar particles into upper atmosphere also suddenly increases
- Radiation exposure of crew and passengers in high-altitude aircraft

Status and Current Limitations

- Geomagnetic cutoffs evaluated in Tsyganenko field using particle tracing techniques, but only at grid of points and Kp values at ISS altitude
- Geomagnetic cutoff variations during geomagnetic storms correlate with geomagnetic indices, but sometimes lead rather than lag these indices
- Current physics-based models are driven only by Kp, and are relatively untested
- Predictions of Bz based on interplanetary propagation from the Sun are not as yet developed

5-10 yr LWS goal

- Refine empirical models with new data and improved empirical relations
- Extend particle tracing calculations to additional altitudes and local times
- Establish data assimilation process to incorporate L1-interplanetary input, additional geomagnetic indices, and cutoff measurements
- Develop comprehensive, physics-based, assimilation model to predict geomagnetic cutoff variations

>10 yr LWS goal

- Validate physics-based assimilation model that relates geomagnetic access to interplanetary / magnetospheric environment

Model and Measurement development:

Model	Current	5-10 yr goal	>10 yr
Lower Corona CME	No quantitative model	CME initial evolution model	
Global Heliospheric Model	Wang-Sheely-Arge	Dynamic model with Data assimilation	Physics/empirical model with data assimilation
CME and Shock Propagation Model	Odstreil-Pizzo BATSRUS	Include particle acceleration	Include global, dynamic, heliospheric background
Particle Acceleration Model	Empirical algorithm based on down-stream particles	Physics/empirical accel./transport model with data assimilation	Refine and validate Physics/empirical model including data assimilation
Particle Transport Model	Empirical model for forecasting Physics models exist	Physics/empirical accel/transport model with data assimilation	Refine and validate Physics/empirical model including data assimilation
Geomagnetic Cutoff Model	Particle-tracing model in static field or empirical cutoff model	Comprehensive cutoff loookup model driven by L1 & magnetosph. data	Dynamic cutoff model with real-time calculations

Measurement requirements and sources

Model	5-10 Yr Goal Measurement	Data source
Lower Corona CME	CME precursor formation; Initial evolution of CME	SOHO/TRACE STEREO/SDO
Global Heliospheric Model	In situ SW data closer to Sun; Multi-point SW & CME data	IH-Mappers, Solar Probe, SOLO, STEREO, L1
CME and Shock Propagation Model	Stereo in-situ/remote sensing data on CME speed, structure,& characteristics; radio observations	SOHO, STEREO, SDO, L1, ground-based
Particle Acceleration Model	Multi-point particle spectra, composition; interplanetary conditions	STEREO, L1 IH-Mappers, SOLO
Particle Transport Model	Multi-point particle data; Interplanetary conditions	STEREO, L1 IH-Mappers, SOLO
Geomagnetic Cutoff Model	B-field and solar wind at L1 or further upstream; State of magnetosphere; Cutoff data from SEPs	L1, IH-Mappers, SAMPEX/Polar MMS, LEO/GTO

Model development --

Current	LWS: 0-5 yr	5-10 yr	> 10 yr
Particle-tracing in static Tsyganenko field param'tized by Kp; world grid at ISS altitude only (Smart et al.)	Refined model adjusted to agree with measured cutoffs; Use L1 data to predict Kp.	Comprehensive cutoff model with table lookup driven by L1 and magnetospheric data. Adjusted to agree with empirical relations	Validate model and refine
	Start development of dynamic cutoff Model ??	Test/Refine Dynamic cutoff model	Validate dynamic cutoff model with real-time calculations
Empirical quiet-time cutoff model fit to data (SAMPEX)	Refined relation using additional data	Real-time cutoff measurements using polar-orbiting spacecraft	Operational real-time cutoff measurements during SEP events
Empirical cutoff vs Kp and DST relations (SAMPEX, TIROS)	Refined empirical data Using additional events		
MHD CME transport in a homogeneous solar wind	MHD transport in Inhomogeneous wind	MHD transport and internal CME dynamics	Predict CME structure near Earth using data assimilation.

Appendix 10 -- Space Environment Group: LWS Geospace Goals

Atmosphere-Ionosphere-Magnetosphere Research:

- Determine the effects of long and short term variability of the Sun on the global-scale behavior of the ionospheric density from 100 to 1000 km.
- Discover the influence of solar variability and the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.
- Determine the effects of long and short term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe them with accuracy better than 5%.

Radiation Environment:

- Understand the processes responsible for the acceleration, loss, and transport of radiation belt electrons and ions responsible for radiation dose and bulk charging effects
- Understand the geospace response to geomagnetic storms such as the development and trapping of the ring current, Joule heating of the ionosphere, ground induced currents, severe spacecraft surface charging environments, etc.
- Reveal and characterize the effects of solar energetic particles at low Earth orbit and in the atmosphere/ionosphere

Climate:

- Identify and quantify the Earth's near-surface temperature changes attributable to solar variability (from both direct and indirect solar energy forcings).
- Identify and quantify the changes in ozone distribution attributable to solar variability (in the form of electromagnetic radiation and energetic particles).

Heliospheric

- Develop the capability to specify and predict solar activity (on time scales of active regions to the solar cycle) and heliospheric modulation of energy inflow from the Sun and the galaxies to the Earth’s space environment.

Atmosphere-Ionosphere-Magnetosphere Research

1) Determine the effects of long and short term variability of the Sun on the global-scale behavior of the ionospheric density from 100 to 1000 km.

Produce the capability to specify and predict the large-scale behavior of the ionospheric density from 100 to 1000 km.

- **Societal impact:**
  - **Ion density distribution affects navigation and communication signal paths.**
  - **Changes in density distribution affect operation of hf communication links.**
- **Primary Current Limitations:**
  - **Poor altitude specification below 350 km and above 600 km**
  - **Computational models driven by proxies for solar EUV radiation and electromagnetic drivers.**
  - **Sensitivity to inadequate knowledge of neutral winds and ExB drifts.**
- **5-10 yr LWS goal:**
  - **Refine empirical models with new data & inputs.**
  - **Validation of physics-based models with variations in input drivers.**
  - **Establish data assimilation processes to accommodate sparse data sets.**
- **> 10 yr LWS goal:**

Validated physics-based global-scale assimilation model.

2) Discover the influence of solar variability and the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.

Produce the capability to specify and forecast the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region

- **Societal impact:**
  Irregularities compromise performance of GPS navigation.
  Radar and communications systems can be inoperable in regions of irregularities.
- **Current limitations:**
  Only probability of radio scintillation above some threshold level
  Computational models dependent on poorly understood relationships between variable background and seed distribution.
  Computationally intensive non-linear codes to derive irregularity spectral index are not validated.
- **5-10 yr LWS goal:**
  Create empirical model of irregularity spectrum as a function of background characteristics.
  Discover the variations in seed perturbations that provide the seat for irregularities.
  Improve computational models in 3-D and create capability for data assimilation.
- **>10 year LWS goal:**

Validated physics-based assimilation model
Validate computation of irregularity spectrum from driver inputs.

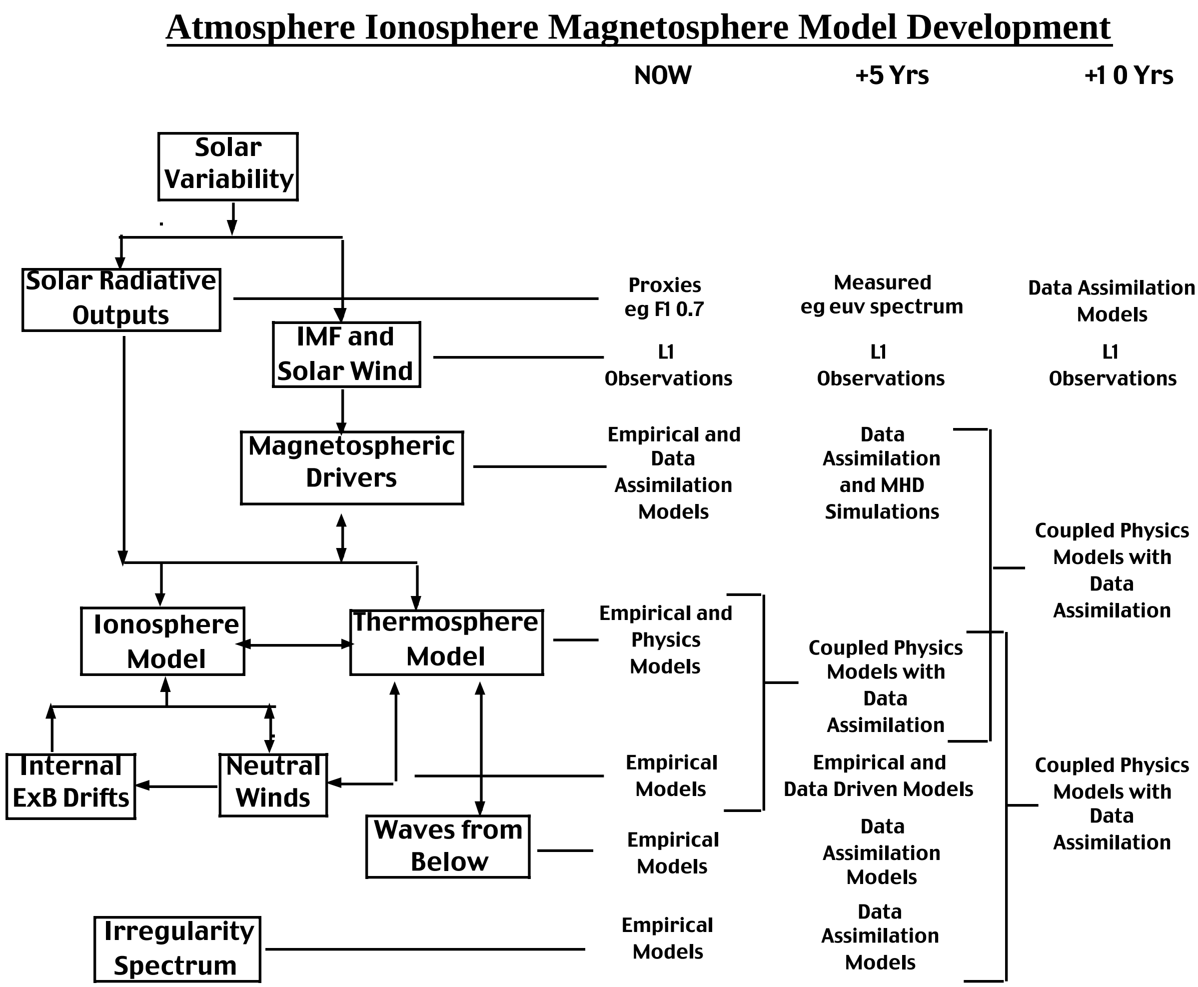
3) Determine the effects of long and short term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe them with accuracy better than 5%.

Produce the capability to specify and predict the mass density of the atmosphere between 120 and 600 km altitude with accuracy better than 5%.

- **Societal impact:**
  Satellite orbits are perturbed by atmospheric drag.
  Atmospheric conductivity is critical parameter for determination of induced ground-currents, and ionospheric radio scintillation.
- **Primary Current Limitations:**
  Empirical models with large uncertainties are inconsistent with model outputs
  Poor knowledge of global distribution of state variables in the region above 200 km.
  Computational models driven by proxies for solar EUV radiation and electromagnetic drivers.
  Sensitive to poorly understood small scale motions at lower boundary.
- **5-10 yr LWS goal:**
  Refine empirical model of winds and density with new data & inputs.
  Validation of physics-based models with variations in measured input drivers.
  Establish data assimilation processes to accommodate sparse data sets
- **> 10 yr LWS goal:**

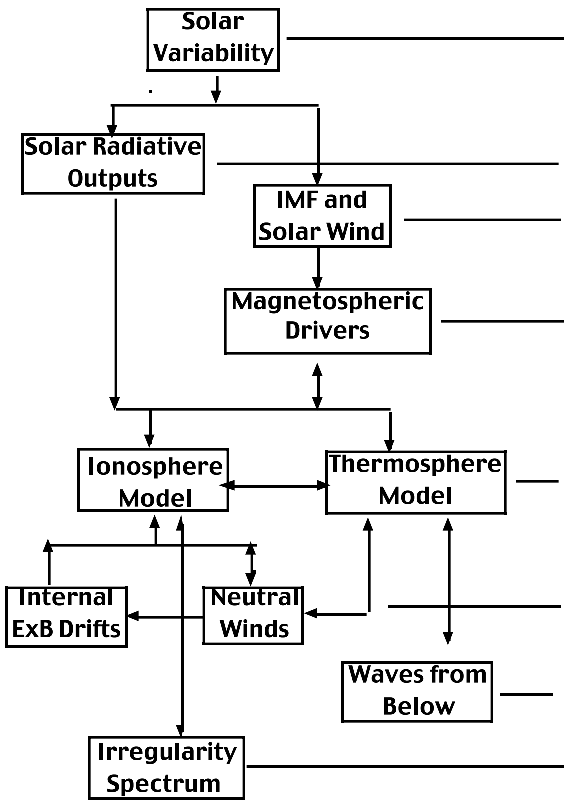
Validated physics-based assimilation model.

Model and Measurement development:



Measurement requirements and sources

Atmosphere Ionosphere Magnetosphere Data Sources



NOW	+5 Yrs	+1 0 Yrs
Yohkoh TRACE	TRACE Solar B	
Ground-Based Fl 0.7	SDO	SO
IMP, ACE WIND	L1 STEREO	L1 SENTINELS
Radars Magnetometers DMSP	Radars Magnetometers DMSP MMS	Radars Magnetometers NPOESS MagCon
Ground and Sat GPS Ionosondes DMSP	DMSP COSMIC Low and Mid Inc Satellites	NPOESS GEC Low and Mid Inc Satellites
Ground Radar Ionosondes FPI	Low and Mid Inc Satellites. TIMED	Low and Mid Inc Satellites
Ground All-Sky	SMEX	SMEX
Ground Scintillation Rcvrs DMSP	Ground Scintillation Rcvrs DMSP C/NOFS	Ground Scintillation Rcvrs NPOESS Low and Mid Inc Satellites

Radiation Environment:

4) Understand the processes responsible for the acceleration, loss, and transport of radiation belt electrons and ions responsible for radiation dose and bulk charging effects

Produce the capability to specify and predict the acceleration, loss, and transport of radiation belt electrons and ions responsible for radiation dose and bulk charging effects

- **Societal impact:**
  Energetic particles cause destruction and mutation of human tissue.
  Total dose is a primary limitation on the operational lifetime of spacecraft
  Dielectric charging causes sensor performance degradation and malfunction or failure of spacecraft sub-systems.
  Relativistic electrons may influence atmospheric electricity or chemistry and thereby climate
- **Primary Current Limitations:**
  Only specification of integrated dose.
  Current models do not include time dependence
  Poor specification of radial and azimuthal dependencies.
  Insufficient information to determine physics of acceleration and transport properties.
- **5-10 yr LWS goal:**
  Sufficient measurements to determine relative importance of physical processes
  Sufficient measurements to specify source populations for physics-based models
  Construct models describing the local and regional acceleration processes.
  Establish data assimilation processes to accommodate distributed observations.
- **> 10 yr LWS goal:**

Validated physics-based assimilation model.

5) Understand the geospace response to geomagnetic storms such as the development and trapping of the ring current, Joule heating of the ionosphere, ground induced currents, severe spacecraft surface charging environments, etc.

Produce the capability to specify and predict the geospace response to geomagnetic storms such as the development and trapping of the ring current, Joule heating of the ionosphere, ground induced currents, severe spacecraft surface charging environments, etc.

- **Societal impact:**
  - **Geomagnetic storms are the geospace response to high solar/solar wind energy input.**
  - **Geomagnetic storms create large-scale and large-amplitude changes from the normal or average conditions in the magnetosphere and ionosphere**
  - **Most space weather effects, such as Joule heating, ionospheric scintillation, ground induced currents, relativistic electron enhancements, etc., occur during geomagnetic storms**
- **Primary Current Limitations:**
  - **Insufficient characterization of the global electric fields, magnetic field, and field-aligned currents during storm conditions**
  - **No measurements of plasma sheet/geosynchronous plasma ion composition for ring current models**
- **5-10 yr LWS goal:**
  - **Measurement of temperatures, densities, and composition of ring current source population**
  - **Sufficient measurements to characterization of the global electric fields, magnetic field, and field-aligned currents during storm conditions**
  - **Construct and validate physics-based data assimilation models**
- **> 10 yr LWS goal:**

Construct and validate coupled solar-magnetospheric-ionospheric models of storm responses

6) Reveal and characterize the effects of solar energetic particles at low Earth orbit and in the atmosphere/ionosphere

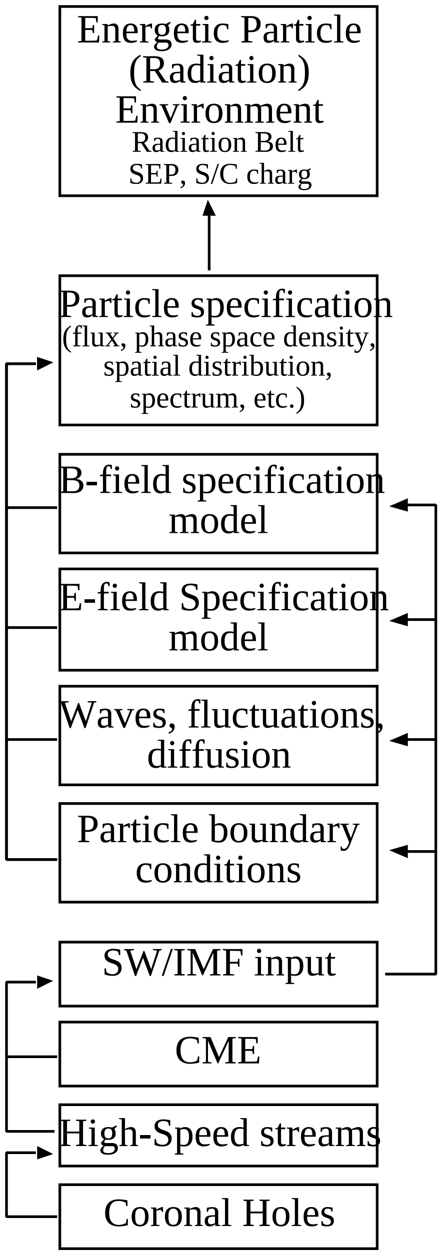
Produce the capability to specify and characterize the effects of solar energetic particles at low Earth orbit and in the atmosphere/ionosphere

- **Societal impact:**
  - **Solar energetic particles (SEPs) cause destruction and mutation of human tissue.**
  - **SEPs are the primary cause of single event upsets and latchups**
- **Primary Current Limitations:**
  - **No capability to predict event amplitude, fluence, spectrum, or composition**
  - **Geomagnetic cut-off calculations require storm-time magnetic field models**
- **5-10 yr LWS goal:**
  - **Measurement and characterization of amplitude, fluence, spectrum, and composition of SEPs**
  - **Development of physics-based SEP models based on solar and heliospheric observations**
  - **Construction and validation of SEP magnetospheric transport models for storm-time conditions**
- **> 10 yr LWS goal:**

Validated physics-based solar-heliospheric-magnetospheric acceleration and transport models

Model and Measurement development:

Radiation Environment Flow Chart



Models

MSM - convection/drift
AE/AP-8
AF-Geospace
Salammbo

MHD
Ring Current event models
Tsyganenko Type

Voland Stern
Mapped Ionosphere
MSM

Statistical Studies
Theories

MHD or observations

S&S
Petrinec

?

?

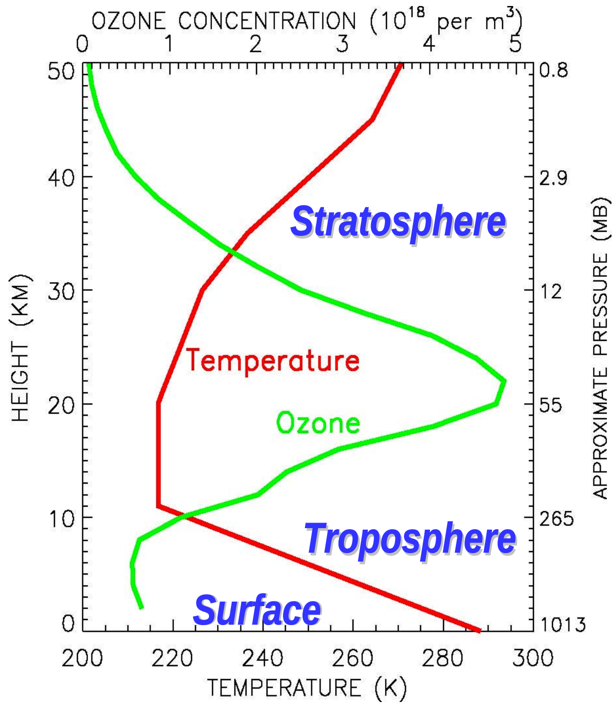
?

Climate:

7) Identify and quantify the Earth's near-surface temperature changes attributable to solar variability (from both direct and indirect solar energy forcings).

- **Societal impact:**
  Climate response to solar variability may obscure detection of climate change from greenhouse gases and aerosols - ***economy, habitat***
- **Primary Current Limitations:**
  Knowledge of long-term solar irradiance variability is poor - based on evidence from proxies - ***cosmogenic isotopes and Sun-like stars***
  Climate models may lack relevant physical processes - ***coupling of solar effects on ozone, excitation of natural climate modes***
- **5-10 yr LWS goal:**
  Improved historical irradiance from physical connections to proxies .
  Identify spatial patterns of climate response to solar forcing - ***GCMs*** **.**
  Investigation of climate mode excitation and vertical couplings .
  Examine current and paleo data for solar-induced variations .
- **> 10 yr LWS goal:**
  Plausible long-term solar variability, including from dynamo scenarios
  Improved GCM simulations of climate response to solar variability - ***past and future***

Changes in Ozone and the Stratosphere Can Influence Climate



Stratosphere

CO_2 increase → *cooling*

Volcanoes → *warming*

Solar increase → *warming*

Surface

CO_2 increase → *warming*

Volcanoes → *cooling*

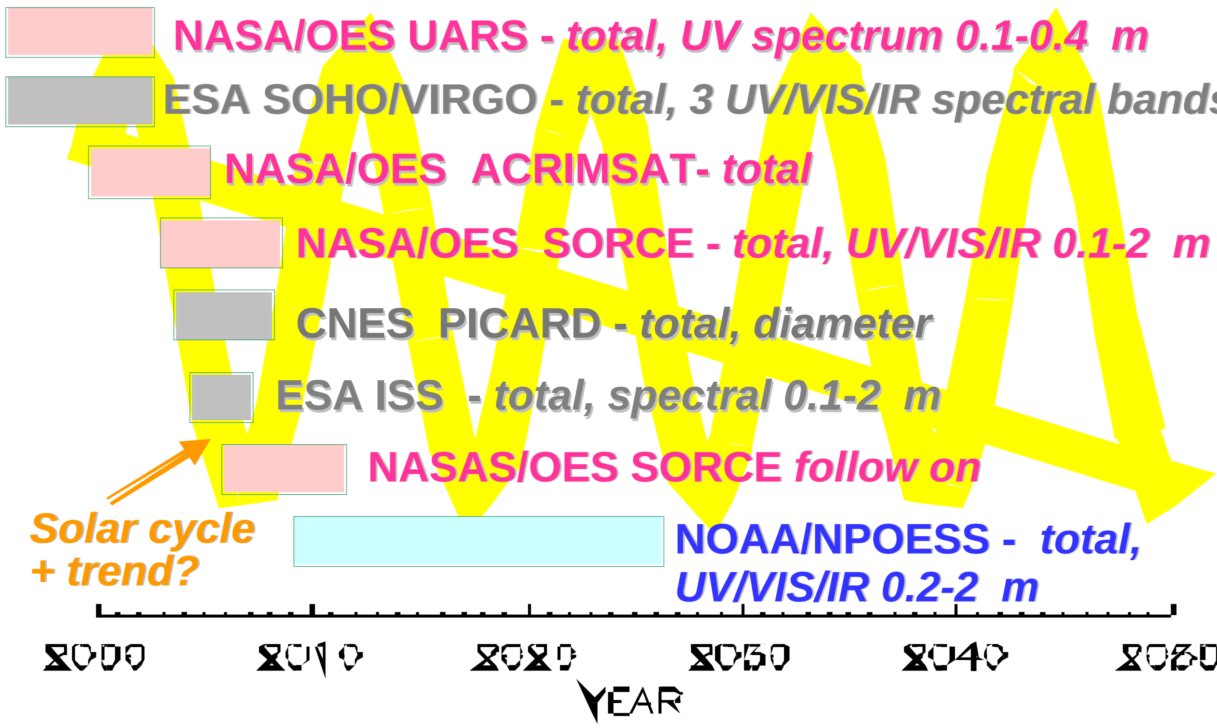
Solar increase → *warming*

8) Identify and quantify the changes in ozone distribution attributable to solar variability (in the form of electromagnetic radiation and energetic particles).

- **Societal Impact:**
  Solar variations can mask CFC ozone depletion and inhibit verification of Montreal Protocol - ***climate change, biological UV effects***
- **Primary Current Limitations:**
  Knowledge of long-term solar irradiance and ozone variability is poor.
  No middle atmosphere GCMs with couplings from below and above .
- **5-10 yr LWS Goal:**
  Reconstructions of solar UV (& X-ray) spectrum and particles.
  Validate models of ozone distributions with specified solar inputs.
  Improved specification of NOx and HOx role in solar response.
- **>10 yr LWS Goal:**
  Ozone (and climate) simulations with coupled middle atmosphere GCMs over multiple time scales, compared with observations.

Predictions of solar-induced ozone variations in upcoming decades.

Future Solar Irradiance Observations



Heliospheric

9) Develop the capability to specify and predict solar activity (on time scales of active regions to the solar cycle) and heliospheric modulation of energy inflow from the Sun and the galaxies to the Earth's space environment.

- **Societal Impact**
  - Duration of manned interplanetary missions is presently limited by cosmic-ray radiation dose
  - Cosmic rays an important component of near-Earth radiation environment affecting space hardware

- **Status and Current Limitations**
  - Cosmic-ray intensity at 1-AU is modulated by solar-wind in the outer heliosphere (including both steady flows and transients)
  - Several variables (and/or proxies) identified that correlate with cosmic-ray intensity variations (current-sheet tilt, solar-wind speed, magnetic field variations, formation of merged interaction regions)
  - Current empirical models driven by proxies have limited accuracy; physics-based models presently lack predictive capability

- **5-10 yr LWS goal**
  - Refine empirical models with new data and improved empirical relations
  - Establish data assimilation process to incorporate solar/heliospheric data
  - Develop physics-based assimilation model

- **>10 yr LWS goal**
  - Validate physics-based assimilation model

Model development:

Model	Current	5-10 yr goal	> 10 yr goal
Empirical spectra, composition, with solar cycle variations	CRÈME (NRL)	Refined fit to data; 22-year solar cycle	
Empirical, driven by sun-spot number	Nymmik		
Empirical, driven by neutron monitor data	JSC/LRC Models		
Physics-based, driven by S/C and neutron monitor data	ACE (Davis)	Global (0.5-80 AU) 2-D model for nowcasting And forecasting; tied to 22-year solar cycle, S/C & neutron monitor data	Validated global assimilation model
Physics-based Transport models	Arizona, Potchefstroom	3-D model with diffusion, convection, energy-loss, drift effects	

Measurement requirements and sources:

Model	5-10 yr goal Measurements	Data Source
Empirical spectra, composition, with sine-wave solar cycle		
	Spectra and composition of Z = 1 to 28 over the solar cycle.	ACE, Ulysses,, Voyager, IMP, Balloons, AMS
Empirical, driven by sun-spot number		
Empirical, driven by neutron Monitor	Continuing neutron monitor and in situ S/C comparison.	ACE, Ulysses,, Voyager, IMP, Balloons, AMS & neutron monitor
Physics-based driven by S/C and neutron monitor data	Cosmic ray spectra & composition over solar cycle; neutron monitor data	ACE, Voyager, Ulysses, IMP, AMS, Balloon-instruments, ground-based
Physics-based Transport models	Radial and latitudinal. Cosmic-ray gradients. Global solar wind & magnetic field data	Voyager, Ulysses, L1, STEREO, IH-Mappers, Solar Probe

Appendix 11 -- Space Environment Group Narrative Report

Long-Term Variations of the Space Environment

An important legacy of the LWS initiative will be an improved ability to specify and predict the behavior of the near-space environment and its variations produced by solar influences on time scales of months to decades. A framework for design and operational space environment specification will exist when empirical and physics-based models that specify key parameters in terms of external drivers, are available. An initial challenge to the LWS initiative will be to ensure that models are developed that will provide the required accuracy to be useful for design and operational purposes. Conceptually a long-term product of LWS will be to define a minimum set of parameters which, if provided indefinitely in the future would, in conjunctions with the models, provide the necessary specification of the space environment for design and operations. Our overarching goal therefore is ***specification of the Sun-Earth connections that change the space environment in ways that affect life and society on time scales of months to centuries.***

Our understanding of the important Sun-Earth connections will be embodied in detailed models of regions of the space environment that account for the couplings of neighboring regions, responses to external drivers. In addition these models will provide a means to represent variations in the regions state that are sufficient for accurate large-scale Sun-Earth coupled models to be developed. In some cases the physical underpinnings of these models – such as those that are statistically based -- will need to be established. In other cases existing physics-based models will require rigorous validation with the generation or improvement of empirical models. Thus the important components of the LWS program will be

- Observe the space environment system on time scales from months to cycles with high reliability, emphasizing those parameters needed to understand societal impacts.
- Analyze and characterize the system responses to variable forcings (sun, magnetosphere, lower atmosphere, internal).
- Construct faithful statistical descriptions of the space environment system and its variability – semi-empirical / statistical models – with robust relations to the forcing functions.
- Construct reliable theoretical descriptions of the space environment system and its variability – physics-based models – which describe the system responses to forcing functions.
- Improve the model capabilities by assimilating observations.

- Test the improved/assimilative model capabilities by predicting future observations.
- Develop transitional pathways to enable efficient use of assimilative model products for operational efforts.

Here we consider 5 components of the space environment that will require understanding and specification for design and operational purposes.

1) Ionospheric Densities and Dynamics

Knowledge of the global distribution of electrons in the ionosphere is needed operationally for communication and navigation. The location of the bottomside ionospheric density gradient determines the propagation paths for ground-to ground hf communications. The total electron content is an important parameter that must be accounted for when using single frequency GPS signals for navigation. Irregularities in the ionospheric number density produce radio scintillation and signal fading due to scattering. The ionospheric number density influences magnetospheric effects on the neutral atmosphere by modulating the ion drag. Finally the distribution of the ionospheric density determines the ionospheric conductivity which influences the intensity of currents that can flow within it and its coupling to the magnetosphere above it. Ionospheric currents can induce currents on the ground with deleterious effects on communication and power lines.

2) Neutral Densities and Dynamics

The upper atmosphere neutral density directly impacts the drag on large and small orbiting vehicles, ranging from the space station to space debris. Accurate specification of the neutral density is required for adequate planning of maneuvers, re-entry, and tracking of space vehicles, and the debris fields that surround them. Variations in the density can be significant with short-term variations produced by magnetic storms and solar EUV radiation in flares, and long-term variations produced by solar rotation and cycle variations in the EUV radiation. The ionospheric density is influenced by the neutral atmosphere through changes in the neutral composition. Neutral winds, resulting from pressure gradients drive currents and create electric fields, which affect the ionospheric density distribution.

3) Energetic Particle Environment

Energetic particles pervade the entire geospace environment, come from a diverse set of sources, and have a range of effects on natural and man-made systems. The Earth's radiation belts are a population of geomagnetically trapped electrons and ions with energies greater than a few MeV. The radiation belt populations contribute to total radiation dose, single event effects (transient and destructive), internal spacecraft charging, and ionization/heating of the high latitude ionosphere and thermosphere. Solar energetic particles, produced in the solar wind, have energies greater than several tens of MeV and therefore can penetrate both the geomagnetic field and spacecraft shielding producing risks of short-term radiation exposure and single event effects. Injections of electrons with energies of several to hundreds of keV from the plasma sheet to the inner magnetosphere produce spacecraft surface charging events which commonly affect spacecraft design and operations and other populations of energetic particles such as the ring current have important effects on the dynamics and electromagnetic structure of geospace.

4) Climate and Global Change

Climate exhibits pronounced fluctuations as a result of internal motions – for example, oscillatory couplings of the atmosphere and ocean such as ENSO and the NAO. However, there is also extensive empirical evidence that some long-term (decadal to millennial) changes in the climate, the lower atmosphere and the stratosphere are directly related to changes in the Sun, either its radiative output or solar induced changes in the energetic particle populations (including cosmic rays). Successful mitigation and adaptation strategies applied to climate change and ozone depletion make it essential to isolate solar induced variations.

5) Solar and Heliospheric Long Term Behavior

The Sun and the Heliosphere are primary drivers of the space weather effects that occur in the ionosphere, upper atmosphere and radiation belts. Models describing the properties of the space-environment and climate system must account for systematic responses to variations in these forcing functions which propagate to the Earth in different ways. Solar electromagnetic radiation travels to the top of the Earth's atmosphere unimpeded by the heliosphere, whereas energetic particles and plasma wind propagation experience considerable heliospheric and magnetospheric interactions. Both the direct impacts and those that precipitate through couplings among neighboring space environment regions must be properly understood and specified.

The most crucial solar and heliospheric components for LWS are direct measurements of their forcing functions that alter the energy inputs and boundary conditions of the various geospace regions. These include electromagnetic and particle radiation fields, solar wind parameters, and interplanetary conditions. Lacking such physical inputs, space weather models presently adopt simple proxies – typically F10.7 and Kp – to represent these energy drivers. Ultimately our ability to predict the long-term behavior of the space environment will reply on understanding the temporal responses of the coupling functions and the direct inputs. This requires an understanding of the solar sources of the various forcing functions.

Within each of the categories above we have identified some target milestones in order to expose our present capabilities and to discover the data acquisition, model development and data analysis that would be required to move forward.

Ionospheric Densities and Dynamics

Tasks:

1. Produce the capability to specify and predict the large-scale behavior of the ionospheric density from 100 to 1000 km
2. Produce the capability to specify and forecast the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.

Existing and Planned Capability:

Many measurements of TEC and electron densities are being made presently, or are planned in the near future, including by DoD, COSMIC, and IGS.
Global ionospheric models exist. Physics-based models and statistical models (IRI) have been evolving together and new efforts are underway to assimilate observations into the models (e.g, MURIs). The physics-based models and, of course, the empirical models are highly dependent on the dynamics of the neutral atmosphere and the ionosphere and inadequate specification of these states impacts the capabilities of the physics-based models and the validity of the empirical models. Specification of the longitude, season, and solar activity variations in the low and middle latitude electric fields is presently inadequate. At high latitudes the magnetospheric electric field is derived from empirical models driven by specified conditions in the solar wind or by assimilation of in-situ and ground-based data. Under many conditions the distribution and quality of measurements is insufficient to determine the large-scale convective flows with a high degree of confidence. This is especially true for cases when the IMF has a northward component and/or in the winter hemisphere. In these cases insufficient information is available concerning the coherence lengths and time scales of convection cells.

At high latitudes magnetospheric particle precipitation may dominate the ionization rates. Empirical models presently specify the large-scale distribution of particle precipitation. However, changes in precipitation boundary locations have dramatic effects on the computed ion density distributions, and these changes are specified by a rather limited set of in-situ measurements. The relationships between precipitation and convection regions also needs to be placed on a firm footing for both northward and southward IMF conditions.

Empirical models of ionospheric structure presently provide a measure of the intensity of ionospheric irregularities at tropical and high latitudes and an estimate of the associated radio scintillation using a simple phase-screen model. These models are impacted by the rather poor distribution of data covering different longitudes and solar activity levels. Physics-based models of ionospheric structure will utilize global models of ionospheric density coupled with a specification of the ion and neutral dynamics. Thus the deficiencies in the global models are also reflected in irregularity specification and forecast models.

Measurement of neutral and ion motions are of fundamental importance to the future development of space environment models. While specific observational investigations focus on gathering simultaneous measurements of density and drift there are presently no global or regional data sets that allow specification of the neutral and ion motions over significant regions of latitude, longitude, altitude and solar activity.

Model Inputs:
Present ionospheric models, both theoretical and empirical, use proxies to account for variable solar-helisospheric inputs. The 10.7 cm radio flux is used to scale the EUV radiation and the Kp index is used to represent geomagnetic activity. In the next generation of models envisioned for development under LWS actual physical inputs should replace these simple proxies. The required physical inputs include:

Solar EUV radiation inputs are presently poorly specified in terms of the 10.7 cm radio flux. Empirical EUV irradiance variability models are unreliable because of the very poor observational database. Improved specification of the EUV spectrum in the wavelength range 1 to 120 nm by direct measurements is crucial for LWS. Physics-based models that account for the irradiance variations in terms of solar magnetic sources will improve the capability of upper atmosphere density and ionosphere models to account for solar electromagentic radiative forcing, and provide the basis for a predictive capability.
Neutral Winds are important drivers that affect the distribution of ionization along the magnetic field and which generate dynamo currents resulting in internally generated electric fields. Winds are presently poorly specified since no good empirical model exists, direct measurements are very sparse, and inputs from neutral atmosphere models are not validated.
Electric Fields are important drivers that if not self-consistently generated, must be obtained from a sparse measurement set. Uncertainties in the specification of the electric field at high and low latitudes introduce significant uncertainty into the specification and forecasting process.
Neutral composition, density, and temperature affect the chemistry in the ionosphere and thus the large-scale distribution of ion density. These inputs are obtained from an empirical model or from a general circulation model. Uncertainties in the model-input variables and in the adequacy of the empirical model are discussed in the next section.
Magnetospheric particle inputs may dominate the ionization rates at high latitudes. Inadequate specification of the large-scale extent of the precipitation

zones and the structure within them is reflected in uncertainties in ionization regions and spatial gradients in density at high latitudes.

Expected Assets and LWS Measurements:
Because of the initiatives and measurement infra structure already in place, a program for direct measurement of electron densities is probably not the highest priority for LWS. Measurements that can better specify the dynamical motions of the charged and neutral particles are a higher priority for a LWS mission. Coverage at high latitudes will be available from at 4 local times from 2 sun-synchronous DMSP satellites. For specification of the electric field, these measurements may be combined with ground-based radar and magnetometer networks in assimilative models. Valuable contributions to this procedure could be made from an additional high latitude orbit observing at local times different from those populated by the DMSP and future NPOESS satellites. The future GEC spacecraft could play this role with attention to appropriate phasing of the LWS initiatives.

The high-latitude precipitation pattern is a key input to both ionospheric and neutral models. It is important to obtain the best self-consistencies between the derived convection and precipitation patterns and presently the configuration of these patterns is most reliably obtained from assimilation of measurements. Latitude profiles of the energy flux and average energy from in-situ measurements should be combined with global auroral imagery to provide the precipitation pattern. This pattern will be used as a model input in addition to continuous validation of global MHD magnetosphere models. Auroral imagery is presently available from POLAR and IMAGE. However, it is important to retain this capability into the period when new LWS initiatives in this area are undertaken.

At low and middle latitudes improved knowledge of the local time and longitude gradients in neutral winds and electric fields is required. These measurements should be coordinated with those made from high-latitude orbits so that the variations in latitude, modulated by magnetic activity, are combined with local time and longitude variations associated with internal dynamo fields modulated by changes in the neutral winds. The future C/NOFS opportunity provides a pathway to establishing data assimilation procedures, but future middle and low latitude in-situ measurements should be optimized for the broader-based inputs required to fulfill the LWS objectives. A higher inclination orbit with lower perigee altitude providing access to latitudes where semi-diurnal tides are important and to altitudes where the neutral dynamo is active would more optimally fulfill the purpose.

The model drivers are all sensitive function of the solar EUV output and conditions in the interplanetary medium. Thus, the development of adequate empirical models for validation and sensible initial conditions will require that these external drivers be adequately specified at all times. Electric field and ion composition measurements, which describe the longitude variations associated with the magnetic field are required for validation of improved ionospheric models.

Data Mining:
Implement/coordinate electron density data assimilation into global ionospheric models – Need a new LWS effort and/or augment the existing MURIs?

Neutral Densities and Dynamics

Tasks:
1. Produce the capability to specify and predict the mass density of the atmosphere between 300 and 600 km altitude with accuracy better than 5%.

Existing and Planned Capability:
Neutral densities, composition, temperature and winds are not presently measured. As a result the global and regional scale variations of the upper atmosphere are poorly known, at best. Since the last space-based measurements by AE-E, over 20 years ago, technology and instrumentation has been developed to enable a new capability (e.g., UV remote sensing) and some composition measurements from LEO DOD spacecraft can be expected in the future. Such measurements will be a useful tool to validate physics-based models, but are inadequate to provide the global data sets needed to improve empirical specification of the atmosphere and its long-term variability for advanced planning of LEO missions, or to validate existing thermosphere-ionosphere general circulation models. Measurements of the neutral atmosphere motions are even less abundant leading to uncertainties in the specification and propagation properties of atmospheric waves above 120 km altitude and to the associated dynamo generated electric fields in the ionosphere.

Model Inputs:
As for the ionospheric models, neutral density models, both TIGCM and MSIS, use proxies to account for variable solar-helisospheric inputs. The required physical inputs for the next generation LWS models include:

<u>Solar EUV radiation</u> inputs are presently poorly specified in terms of the 10.7 cm radio flux. See above.
<u>Neutral Winds</u> specifying the wave amplitudes and phases at the lower boundary of a model region are important drivers that affect the density and winds in the regions above. Winds are presently poorly specified since no good empirical model exists, and direct measurements are very sparse.

<u>Electric Fields</u> are important drivers that if not self-consistently generated, must be obtained from a sparse measurement set. Uncertainties in the specification of the electric field at high latitudes introduce significant uncertainty into the Joule heating rates and any resulting forecast.
<u>Ion composition, density, and temperature</u> principally affect the ion drag by which momentum is transferred .to and from the charged and neutral species. Uncertainties in the model-input variables and in the adequacy of the empirical model are discussed in the previous section.
<u>Magnetospheric particle inputs</u> may dominate the ionization rates at high latitudes and significantly affect the neutral heating and subsequent circulation. Inadequate specification of the large-scale extent of the precipitation zones and the structure within them is reflected in uncertainties in the neutral composition and velocity.

Expected Assets and LWS Measurements:

These satellites are not configured to make neutral wind measurements that are of importance to specification and forecast models of the neutral atmosphere. The high-latitude Global measurements of neutral composition and velocity are badly needed inputs to validate physics-based models, to upgrade and extend the present empirical model and to advance our understanding of the coupling between the lower and upper atmosphere. Measurements of neutral composition showing the global changes in neutral composition produced by external drivers are important validation tools that can be obtained from GEO. Altitude profiles of neutral density and measurements of the neutral wind will require more detailed observations from LEO. Gravity wave forcing from below (amplitude and phase velocity of wave fields) also need to be determined.

Data Mining:
Information about total densities can be derived from spacecraft drag. DOD spacecraft tracking can provide these data, if they are saved (now they are not). How much of these type of data might be available, and would they benefit LWS?

Upgrade and extend MSIS models – new observations and understanding of both the upper atmosphere and the solar EUV radiation have been achieved since the original formulation of MSIS. The present MSIS is not adequate for LWS needs, but significant improvements are now possible and should be implemented.

Improving the interaction/complementarity of MSIS-type (composition and winds) and GCM models (as per global ionospheric models and IRI) will enhance overall capability be developing internal self consistency. LWS should motivate such an effort.

Energetic Particle Environment

Tasks:

1. Produce the capability to specify and predict the acceleration, transport, and distribution of energetic particles affecting humans in space, spacecraft systems, and properties of the ionosphere and thermosphere

Existing and Planned Capability:

The discovery of the Earth's radiation belts was one of the first discoveries of the space age. Since that time many measurements of the radiation belts have been made and, as recently as ten years ago, the radiation belts and the processes affecting them were considered to be relatively well-understood. At that time the empirical AE-8 (for electrons) and AP-8 (for protons) radiation belt models (each in solar maximum and solar minimum versions) were produced and became the standard for spacecraft design and anomaly assessment.

A dramatic change in that perception can be traced to the March 1991 CRRES satellite observation that an entirely new belt of >25 MeV electrons was produced in the magnetosphere in a matter of minutes. Observations by geosynchronous satellites, by CRRES, SAMPEX, and POLAR (among others) have now shown that the radiation belts are highly structured and highly dynamic exhibiting variability on time scales of minutes, days, season, and solar cycle.

New observations of the radiation belts have also led to a greater appreciation of the forces and processes that affect the radiation belt populations. Among the most important is an increased understanding that the three-dimensional structure and dynamics of the geomagnetic field has a profound effect on the radiation belt environment. The geomagnetic field defines the coordinate system for gradient-curvature drift as well as radial and pitch angle diffusion. Dramatic changes in the intensity and distribution of radiation belt particles typically occur during geomagnetic storms when the magnetic field is highly distorted, asymmetric, and dynamic, making specification of the global magnetic field a major challenge to developing models and extrapolating point measurements to other locations.

The radiation belts are maintained through the competing processes of acceleration from a lower-energy source population and loss through precipitation into the atmosphere or loss to the magnetopause. Thus, developing the capability to specify and predict the radiation belt populations requires measurement and understanding of the plasma sheet source population, how those particles are transported from magnetically untrapped to trapped orbits, and the extent to which other (as yet unspecified) acceleration processes affect the energy and spatial distribution of the radiation belts. Similarly the effects of magnetopause compression, adiabatic transport due to changes in the ring current (the “Dst effect”), and precipitation (or acceleration) due to a variety of wave-particle interactions are poorly measured or understood.

The number of questions raised by these new observations is reflected in the number of competing theories for radiation belt acceleration, transport, and loss. They include: betatron acceleration through resonant interaction with shocks propagating through the magnetosphere, large-scale recirculation through radial and pitch angle diffusion, localized recirculation in the vicinity of the plasma pause, classical diffusion from a variable plasma sheet source, enhanced radial diffusion through substorm inductive electric fields, ULF waves, VLF waves, or other processes, acceleration and diffusion of particles from the cusp, and direct resonant heating through ULF or VLF waves. *A primary goal of the Living With A Star program should be to make the observations which can clearly distinguish which of these processes is dominant and under what circumstances.*

Solar energetic particles are an entirely different class of energetic particles which affect humans and systems in space. The source of those particles is in the solar wind and their high energies imply that they are relatively unaffected by processes within the magnetosphere. Solar energetic particles have direct access to the polar caps along open magnetic field lines but the energy-dependent latitudes of the geomagnetic cutoffs can vary strongly during geomagnetic storms. For the purposes of understanding and modeling long-term variations in the space environment, though, the primary need is for measurement and understanding of the production of solar energetic particles in the solar wind and of the statistical distribution of the frequency, spectrum, and intensity of solar energetic particles.

Models and Inputs
A central challenge to the geospace component of Living With A Star and the development of radiation belt models is to understand which processes are the dominant contributors to the acceleration, transport, and distribution of radiation belt particles.

<u>Radiation Belt Particles</u>: The primary need is to measure the phase space density of radiation belt electrons and ions as a function of time, energy, and magnetic coordinates. Multi-point measurements are required to advance the state of knowledge. In practice this requires measurement of the differential flux with good energy resolution for energies greater than several hundred keV, good pitch angle resolution, and magnetic field measurements. *Simultaneous measurements at different radial distances are the single most important requirement for modeling acceleration and transport.* Good energy, pitch angle, radial and local time coverage are needed for development of empirical and data assimilation models and for developing and validating physics-based models. The bulk of the radiation belt population is best

measured near the geomagnetic equator where all equatorial pitch angles can be observed. However, the precipitating population is best observed from low altitude where the loss cone is broad.

Large-Scale Magnetic Field: The large-scale magnetic field defines the "coordinate system" in which radiation belt particles move. Energetic particles respond strongly to these large-scale fields because their drifts orbit the earth in a very short interval of time. Global magnetic field models (including MHD, statistical/empirical, and "magneto-friction" models) require upstream solar wind specification, new event-specific ring current models, and multi-point magnetic field measurements within the magnetosphere.

Lower-Energy Source Populations: The source for radiation belt particles is the lower energy population which is both accelerated to higher energies and transported from larger radii into the inner magnetosphere. In effect, the bulk distribution of plasma are needed to provide the boundary conditions (in energy and spatially) for any successful models of the radiation belts. Energetic particles in the 1-100 keV range are considered to be the "seed population" which is subsequently accelerated to MeV energies and can also have important and frequent deleterious effects in their own right through spacecraft charging.

Waves and Field Fluctuations: Waves and field fluctuations (such as shocks and substorm inductive fields) also have strong effects on the radiation belt particles. Wave-particle interactions are the primary mechanism for pitch angle scattering which precipitates particles from the trapped population into the ionosphere and atmosphere. Waves and field fluctuations are the primary cause of radial diffusion and transport and waves and transient fields of various types have been proposed as possible mechanisms for direct energetic particle acceleration.

LWS Measurements and Candidate Orbits

The parameters that need to be measured by the LWS geospace missions in order to understand and model the magnetospheric energetic particle populations are (1) ions and electrons over a broad range of energies, (2) magnetic fields, (3) electric fields, and (4) ULF-VLF waves. These measurements need to be made in a variety of regions of geospace. Three sets of candidate orbits should be considered for a minimum configuration.

1) The most important is a set of near-equatorial elliptical orbits. Geosynchronous transfer orbits (GTO) are a likely candidate but there are compelling reasons to measure the source population outside geosynchronous orbit. Multiple, simultaneous measurements at different radii are the most important requirement but there is an obvious trade-off

among radial coverage, spacecraft orbital period, local time coverage, number of spacecraft, and mission cost.

2) A geosynchronous orbit component to LWS has many important advantages. The geosynchronous environment is the most heavily populated orbit for military and commercial satellites. Geosynchronous satellites also provide continuous, high-resolution monitoring of the radiation belts at fixed radial distance which can be used as a reference point for multi-point measurements without the spatial/temporal aliasing inherent in elliptical orbits. The Solar Dynamics Observatory should be considered an excellent candidate platform.
3) A low earth orbiting (LEO) component for LWS can directly measure the precipitating radiation belt particles in situ and for input to ionospheric and atmospheric models. It can also directly measure the geomagnetic cutoffs and inputs of solar energetic particles. The International Space Station should be considered as one potential platform for LWS instruments.

Data Mining:

Data mining is not just desirable but is essential to achieving the LWS objectives with regard to magnetospheric energetic particles. Large, relevant data sets have been acquired in the past and space assets currently exist and/or are expected to exist during the LWS program. These assets are needed because, with anticipated funding, the primary LWS program will require spatial extrapolation and data assimilation in order to develop global specification of the geospace environment.

Several issues are important in planning the LWS geospace missions. Most of the instruments and platforms are not designed or operated to achieve high scientific understanding and are typically limited in one or more aspects. For example, few if any, non-NASA missions include magnetic field measurements along with good energy-resolved particle measurements. Typically the agencies which own those missions fly space environment monitors for very specific and very limited purposes and are reluctant or unwilling to provide funding for, processing, dissemination, or scientific exploitation of those data sets.

Never-the-less, while the quality of the measurements and available mission resources from non-NASA missions vary greatly, they can greatly extend the value and utility of the LWS measurements and will likely form the foundation for future NOAA or Air Force operational models.

An incomplete but representative list of possible adjuncts to the LWS program follows.
<u>GEO Assets</u> include NOAA's GOES satellites and the 'LANL geosynchronous' series. Multi-satellite data are continuous since 1979 and are anticipated into the future

GTO Assets include the CRRES satellite which operated in 1990-1991. Few other GTO platforms have been available and none are anticipated
LEO Assets include NASA's SAMPEX mission which has taken continuous measurements since 1983 as well as NOAA's DMSP and the follow-on NOAA/DOD NPOESS systems.
MEO Assets include the GPS constellation which hosts dosimeters on 1 of 6 of the current satellites and will be flown on every GPS Block IIF system.
Other Assets include the "HEO" dosimeters on US government satellites in highly elliptical orbits, NASA's POLAR satellite which has made high quality scientific measurements since 1995 and which can continue as long as funding is available. Non-US satellites also make measurements which could be valuable to the LWS objectives.

Climate and Global Change

Tasks:
1. Identify and quantify the Earth's near-surface temperature changes attributable to solar variability (from both direct and indirect solar energy forcings).
2. Identify and quantify the changes in ozone distribution attributable to solar variability (in the form of electromagnetic radiation and energetic particles).

Existing and Planned Capability:
Most of the measurements and models needed for the effort exist or are planned by NASA OES. The primary missing components, needed especially for understanding ozone variability and its climatic effects, are odd nitrogen and odd hydrogen in the middle atmosphere, and the general state of the mesosphere and lower thermosphere, which is the upper boundary of the middle atmosphere.

Climate and Ozone Model Inputs:
Solar electromagnetic radiation inputs to climate and ozone models will be measured by OES and transitioned to NPOESS, including solar spectral irradiance longward of 120 nm.

LWS Measurements:
NOx and HOx in middle atmosphere.
Composition (including ozone), temperature, winds, waves in mesosphere and lower thermosphere.

Data Mining:
Extensive climate and ozone databases exist, together with observations of chemical species, dynamics and radiation. Understanding climate change and ozone depletion are key foci of the OES and the primary measurements

needed are part of the "24 measurements" that OES considers core to its program. Included are the total solar irradiance and the solar spectrum longward of 120 nm. LWS must facilitate the use of these datasets and models in studies that specifically address solar influences on global change. Without LWS support, it is unlikely that such interdisciplinary studies will be undertaken. A challenge for LWS is to develop a viable critical mass community working in this area, instead of isolated, uncoordinated efforts undertaken at present.

A crucial data mining effort is developing more credible estimates of long term solar irradiance variations and understanding climate responses. Much data exist that could contribute to this problem if LWS provided resources. Needed for better specifying long term solar forcing is a self consistent understanding of how the Sun generates long term changes in magnetic fields that cause observed variations in the geomagnetic and cosmogenic proxies (with subsequent heliospheric modulation), versus the electromagnetic radiation.

Solar and Heliospheric Long Term Behavior

The key solar and heliospheric parameters needed for LWS are those energy variations that impact space weather –namely solar EUV radiation, energetic particles, the solar wind and shocks, and the interplanetary environment. Direct measurements of these various quantities will facilitate improved models and analysis of the space environment in the near term and recent past. But they will not enable reliable predictions, either of the future or historically. This capability requires understanding the origins of the solar cycle and solar activity, the generation and transport of magnetic field within the solar convection zone, and of magnetic field impacts on the solar atmosphere and heliosphere.

Tasks:

1. Produce the capability to specify how solar variability and the heliosphere modulates the energy inflow from the Sun and the galaxies to the Earth's space environment.
2. Produce the capability to specify and forecast solar activity (on time scales of active regions to the solar cycle) and its effect on energy inputs to the Earth's space environment.

Existing and Planned Capability:

The primary solar observations currently undertaken to understand the interior and atmosphere of the Sun and the heliosphere are those from SOHO, TRACE, Yohkoh, Wind, ACE etc. IN general, these missions are not expected to continue into the LWS time frame. Relevant planned capabilities include solar observations by Stereo and Solar B, and heliospheric observations by ??

Model Inputs:
Magnetic fields are the primary cause of solar energy output variations. The magnetic fields are generated near the base of the Sun’s convection zone, erupt into the overlying atmosphere, and extend into the heliosphere. The alteration and restructuring of the solar atmosphere by magnetic fields is a primary cause of energy output fluctuations, For example, models of solar irradiance variability use as inputs either directly observed magnetic fields or their tracers, such as sunspots and plages. Other models attempt to explain coronal mass ejections and energy release in flares by reconnecting coronal magnetic fields. As well, there are models that transport magnetic fields over the solar surface, to account for the evolution of magnetic structures, and the partitioning of open and closed fields that affect solar wind generation.

LWS Measurements:
The Solar Dynamics Observatory will make the primary solar measurements needed for LWS. For this purpose, the SDO Science Definition Team has identified three crucial instruments (Doppler Magnetogram, Atmospheric Imaging Assembly and EUV Irradiance Spectrometer) and four key instruments (Atmospheric Imaging Spectrometer, Coronagraph, Thermal Brightness Mapper and Vector Magnetograph).

NOWCAST

		ENVIRONMENT			
		Neutral Atmos	Ionosphere	Radiation	Global Change
MEASUREMENT REGION	PARAMETER				
	Neutral Density	X	X		
THERMOSPHERE	Mass Composition	X	X		
	Neutral Winds		X		
	Waves	X			
	Electron Density	X	X		
	Density Structure		X		
IONOSPHERE	Scintillation		X		
	Precipitating Pcls.	X			
	Electric Field	X	X		
	Field-Aligned Cur.				
	Waves			X	
MAGNETOSPHERE	Energetic Particles			X	X
	Magnetic Field			X	
	Electric Field				
	Plasma Density		X	X	
HELIOSPHERE	Wind Speed		X	X	
	Magnetic Field		X	X	
	Cosmic Rays				
	EUV flux	X	X		
SUN	Magnetic Field				
	Irradiance				X
	Mass Ejections				

FORECAST

		ENVIRONMENT			
		Neutral Atmos	Ionosphere	Radiation	Global Change
MEASUREMENT REGION	PARAMETER				
	Neutral Density	X	X	X	
THERMOSPHERE	Mass Composition	X	X		
	Neutral Winds	X	X		
	Waves	X			
	Electron Density	X	X	X	
	Density Structure		X		
IONOSPHERE	Scintillation		X		
	Precipitating Pcls.	X			
	Electric Field	X	X		
	Field-Aligned Cur.			X	
	Waves			X	
MAGNETOSPHERE	Energetic Particles	X	X	X	X
	Magnetic Field			X	
	Electric Field			X	
	Plasma Density	X	X	X	
HELIOSPHERE	Wind Speed	X	X	X	
	Magnetic Field	X	X	X	X
	Cosmic Rays				X
	EUV flux	X	X		
SUN	Magnetic Field			X	X
	Irradiance				X
	Mass Ejections			X	

Parameter	Range	Spatial Location	Data Source Ground Space	Data Coverage Ground Space
Ni Profiles	50 - 5 x10^6 cm^{-3}	Global 100 - 600 km	GPS recvrs, ISR, Ionosonds Occultations C/NOFS COSMIC	Spot ± 40 all lat and lt ± 90 all lat and lt
Ion Comp.	1 - 64 amu	Global 100 - 600 km	None None	
Nn Profiles		Global 100 - 500 km	None DMSP	 lat and long
Neut. Comp.	1-64 amu	Global 100 - 500 km	None DMSP	 lat and long
Neut. Wind	0 - 1 km/s	Global 150 - 500 km	FPI sites None	Spot
Ionospheric E or ExB drift	0 - 5 km/s	Global > 200 km	Superdarn, ISR DMSP	High lat lat and long
Irreg Spect ΔN/N(k)	> 1% >10m	Global 150 - 500 km	Scint Rcvr C/NOFS DMSP	Spot long and lt lat and long
Mag Pert. ΔB		Global > 150 km	Mag. Chains None	Lat
Energetic Particles		Global ~300 km >800 km	None None, DMSP	 lat and long