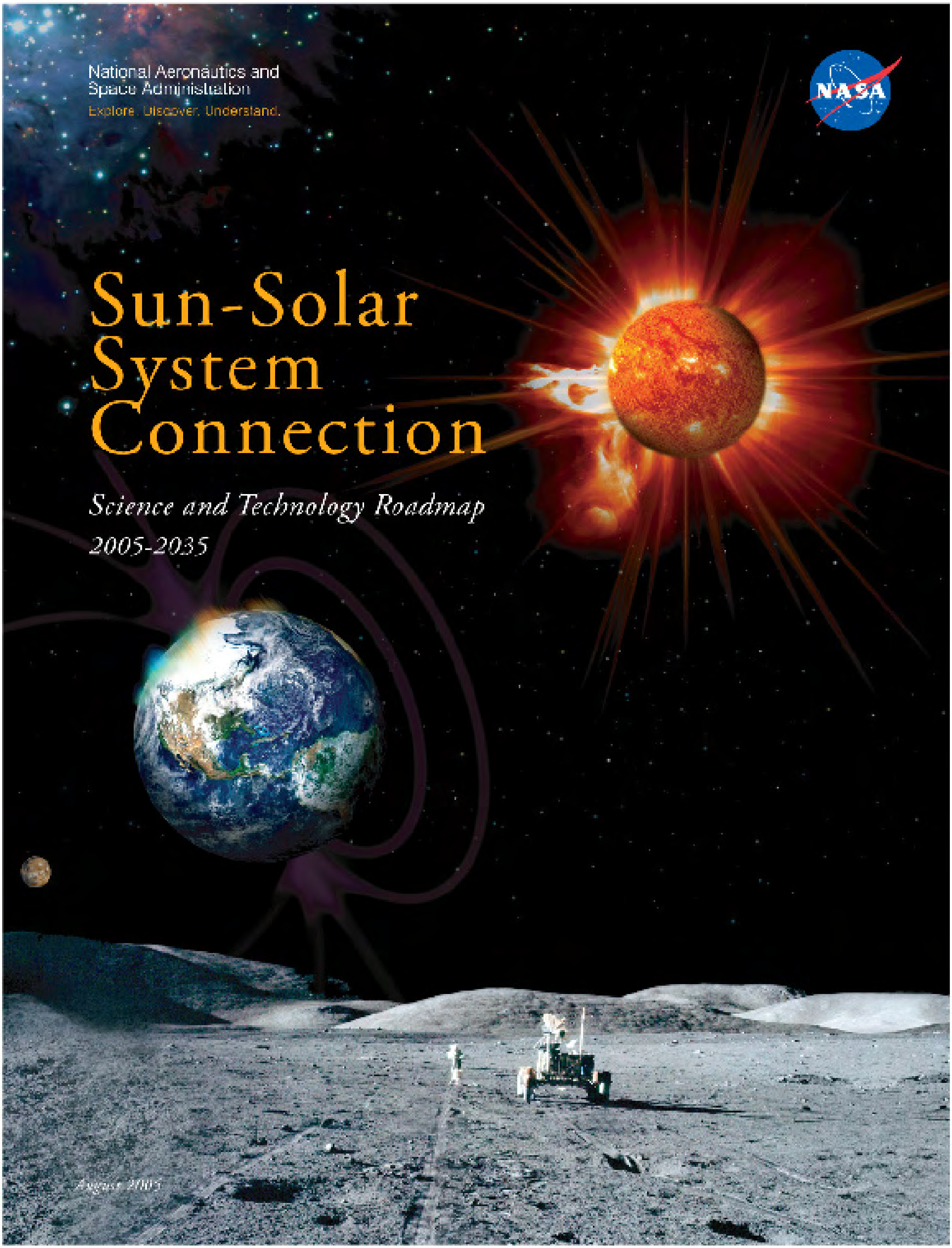
National Aeronautics and
Space Administration
Explore. Discover. Understand.

Sun-Solar System Connection

Science and Technology Roadmap

2005-2035



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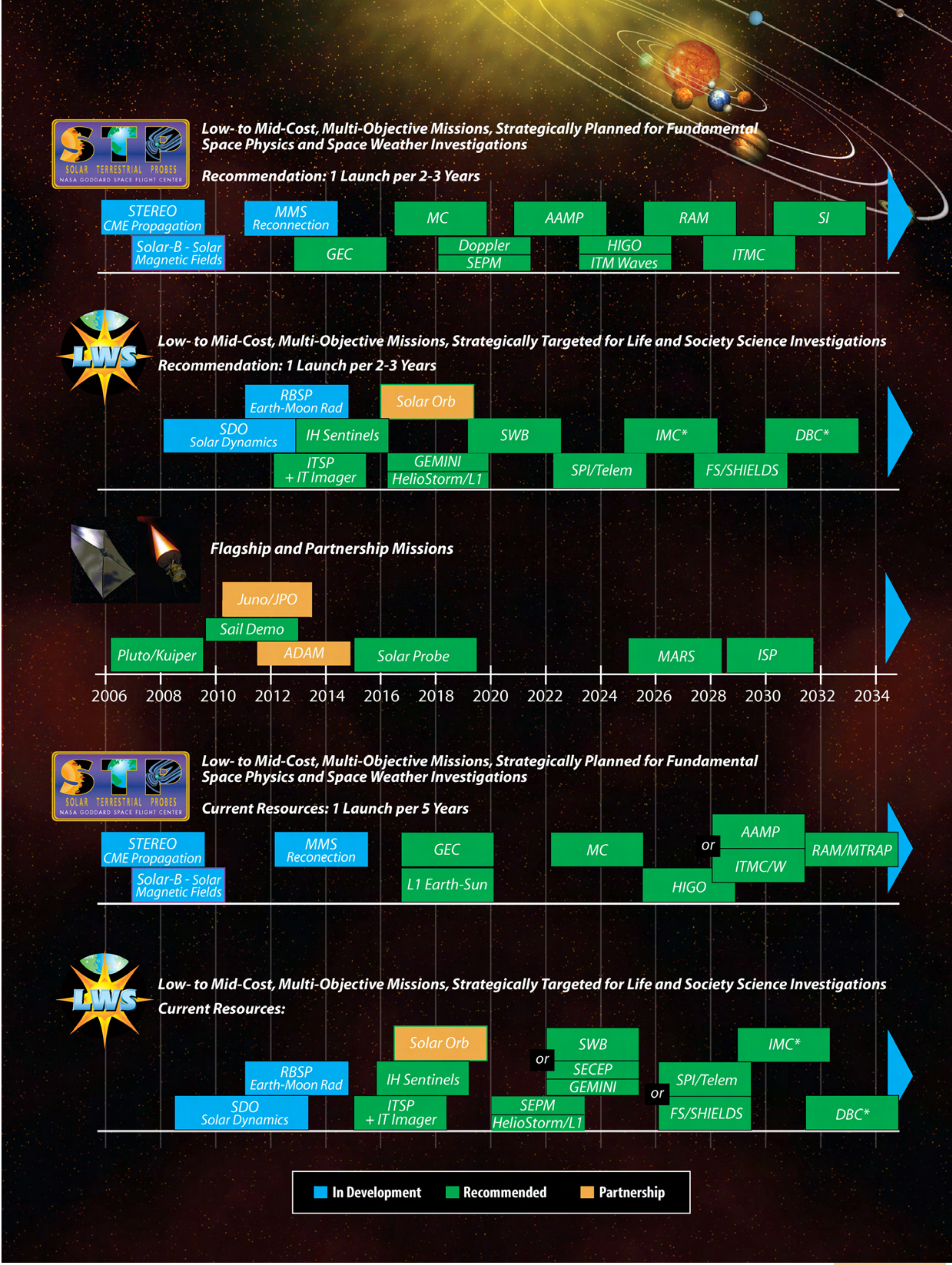

SOLAR TERRESTRIAL PROBES
NASA GODDARD SPACE FLIGHT CENTER
Low- to Mid-Cost, Multi-Objective Missions, Strategically Planned for Fundamental Space Physics and Space Weather Investigations
Recommendation: 1 Launch per 2-3 Years
STEREO CME Propagation
Solar-B - Solar Magnetic Fields
MMS Reconnection
GEC
MC
Doppler
SEPM
AAMP
HIGO
ITM Waves
RAM
ITMC
SI
LWS
Low- to Mid-Cost, Multi-Objective Missions, Strategically Targeted for Life and Society Science Investigations
Recommendation: 1 Launch per 2-3 Years
RBSP Earth-Moon Rad
Solar Orb
SDO Solar Dynamics
IH Sentinels
SWB
IMC*
DBC*
ITSP + IT Imager
GEMINI
HelioStorm/L1
SPI/Telem
FS/SHIELDS
Flagship and Partnership Missions
Juno/JPO
Sail Demo
Pluto/Kuiper
ADAM
Solar Probe
MARS
ISP
2006
2008
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SOLAR TERRESTRIAL PROBES
NASA GODDARD SPACE FLIGHT CENTER
Low- to Mid-Cost, Multi-Objective Missions, Strategically Planned for Fundamental Space Physics and Space Weather Investigations
Current Resources: 1 Launch per 5 Years
STEREO CME Propagation
Solar-B - Solar Magnetic Fields
MMS Reconection
GEC
L1 Earth-Sun
MC
HIGO
AAMP
or
ITMC/W
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LWS
Low- to Mid-Cost, Multi-Objective Missions, Strategically Targeted for Life and Society Science Investigations
Current Resources:
Solar Orb
RBSP Earth-Moon Rad
IH Sentinels
SDO Solar Dynamics
ITSP + IT Imager
SEPM
HelioStorm/L1
SWB
or
SECEP
GEMINI
or
SPI/Telem
FS/SHIELDS
IMC*
DBC*
In Development
Recommended
Partnership

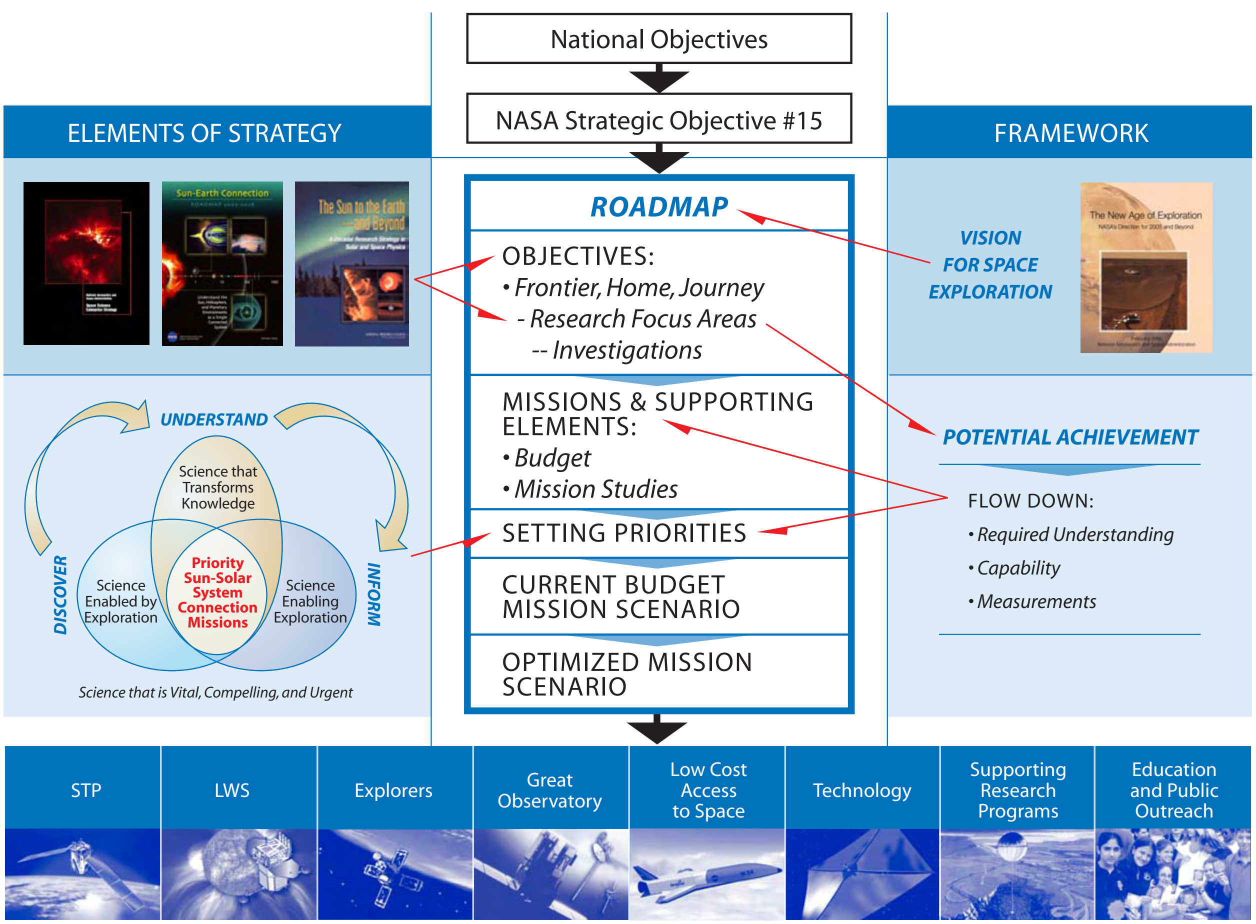
Chapter 2

Sun-Solar System Connection: The Program

The NASA strategic objective addressed with this roadmap is intrinsically one of connections, of influences that extend over vast distances and that produce dramatic effects throughout the solar system. Because these connections are generally mediated extremely locally by largely invisible agents – plasmas and magnetic fields – investigation of the unknown processes at work across this system requires three approaches: a) detailed observations of the key unknowns within the system and b) simultaneous observations of the important source and interaction regions across the Solar System, and c) modeling and theory on all scales.

Careful management of the resources available to address these problems points to a two-prong implementation strategy. First, science focused missions must be deployed to solve the fundamental physical problems identified as key impediments in understanding how magnetic and gravitational physical pro-

Sun-Solar System Connection Roadmap Development



cesses operate. Second, these targeted science missions should be strategically ordered to ensure that complementary measurements are taken at a sufficient number of locations. Data from multiple sources must be synthesized through analysis, modeling, and theory to develop scientific understanding and practical knowledge of the system-wide behavior as solar storm erupt. In this way, the science of Sun-Solar System Connections can be most efficiently addressed with platforms deliberately and strategically distributed throughout the important interaction regions.

In recent years the power of simultaneous observations at multiple vantage points has been clearly demonstrated by what we now call the Sun-Solar System Connection "Great Observatory." The current SSSC Great Observatory is a fleet of widely deployed solar, heliospheric, geospace, and planetary spacecraft that are working together to help understand solar activity and its interaction with geospace and other planetary systems throughout the solar system. Like NOAA's system for observing and predicting terrestrial weather, this observatory utilizes all assets available – remote sensing, in situ measurements, theory, data analysis, and models – to provide physical understanding and predictive capability for space weather research. The diverse measurements across distributed spatial scales are linked by a variety of improving models that serve to fill in the gaps in the observations and provide the knowledge that will lead to predictions of tomorrow's space weather. The opportunity exists now to deliberately evolve this distributed observatory to meet the needs of the Vision for Space Exploration. This is the SSSC community's highest priority.

The following program is constructed to address the most important fundamental Sun-solar system science problems and to prioritize those investigations to have the greatest impact on providing understanding of the entire system from the solar sources to the planetary impacts.

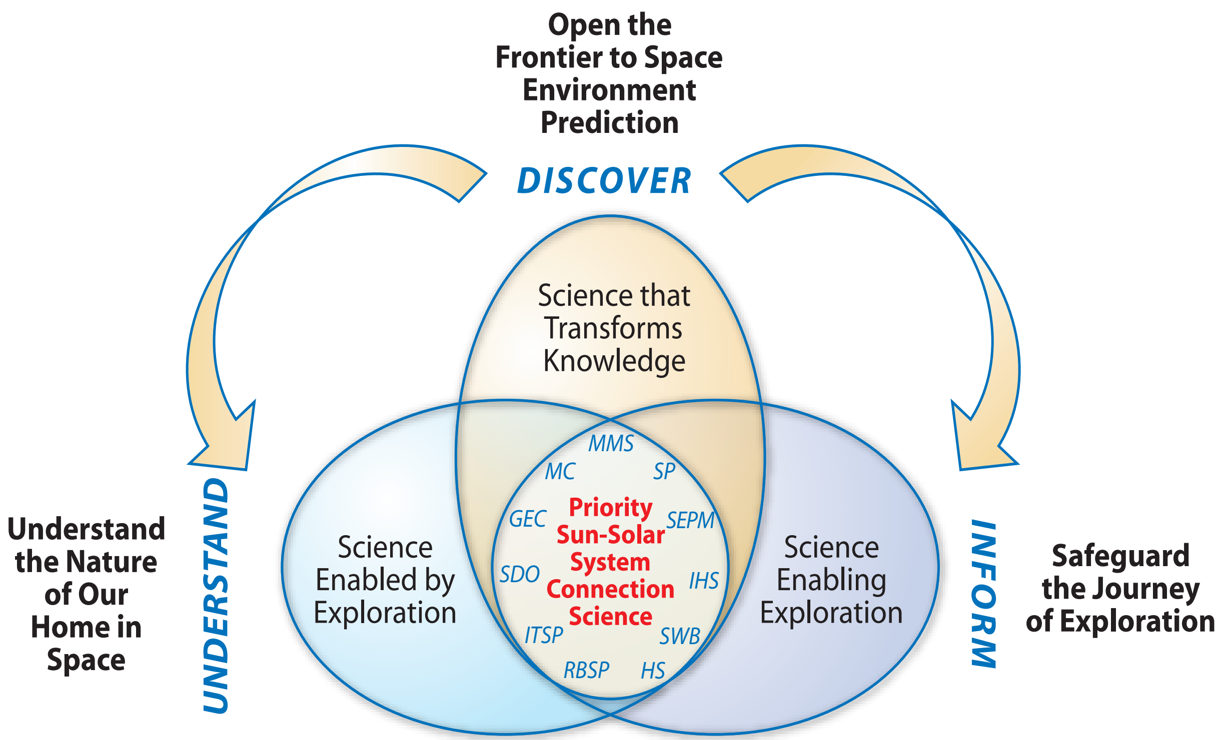
The strategy presented in this document has been derived from the NASA Objective for SSSC that addresses the vital, urgent, and compelling space weather needs of our nation. The community-based SSSC Roadmap committees solicited input from the many stakeholders of the program, both internal and external, in formulating the plan. The proposed SSSC Program implements the best science and exploration effort that can be accomplished within the budget constraints of the program. The recommended program has two options, one that fits within the expected resource cap with some specifically identified augmentations, and another that is optimized to address the science goals in a more reasonable time frame with increased mission synergy. The program is highly responsive to the requirements for the Vision for Space Exploration and consistent with the recommendations of the relevant decadal surveys of the National Academies and previous Roadmaps (See Appendix C).

Implementation Strategy

The science and exploration program described in the previous chapter constitutes a valuable sector of the NASA Science Mission Directorate. SSSC research will develop knowledge that transforms our physical understanding of the universe and our place in it. SSSC investigations provide practical understanding and measurements of areas that affect our technological society and enable safe and productive exploration of the Moon, Mars, and beyond. The missions and technology developed to explore the solar system ultimately contribute to the science aspirations of the entire directorate.

The interplay of exploration, discovery, and understanding provide guidance for prioritizing the program elements. Exploration of Mars and other destinations in the solar system provides the opportunity to measure conditions in different environments that help us understand our own world. New physical understanding of the Sun and its interactions with planetary magnetospheres provide information about the habitability of worlds near other stars. Understanding our space environment to the point of prediction contributes to developing future operational systems that support the needs of our increasingly technological society and informing of our future exploration endeavors.

The objectives, research focus areas, and investigations defined in the previous chapter describe realms of scientific inquiry that will take decades to complete. The road to progress has been charted by identifying a series of targeted outcomes necessary to accomplish the desired objectives. The targeted outcomes in the accompanying achievements table have been established after careful consideration of the research focus areas, consolidation of investigation requirements, anticipation of the capabilities likely to be available and required at different times, and estimation of available resources. The outcomes have been ordered in phases to develop the scientific understanding necessary to support the needs of society and the exploration program.



The intersecting ovals illustrate the intersection of three categories of science: scientific understandi that is enabled by exploration, science that transforms our knowledge, and science that informs to enable exploration. At the intersection is the 'sweet spot' where the highest priority SSSC missions lie.

Strategic Considerations

The SSSC objectives identify robust goals that are vital, urgent and compelling. Obviously no unique strategy exists now that addresses the scientific and programmatic needs, fits within the anticipated budget profile, and anticipates all developments over the next 30 years. The developing requirements of the Vision for Space Exploration, the increasing need for understanding external influences on our home planet, and the transformational science required to develop predictive capabilities for the space environment require a broad approach to address interlocking needs and demand considerable flexibility in the implementation.

The program relies on several elements: strategically planned missions in the Solar Terrestrial Probes (STP) and Living With a Star (LWS) lines to address widely recognized critical problems; competitively selected Explorers to optimize responsiveness to strategic needs; continued operation of existing space assets as part of the SSSC Great Observatory; support for the low cost access to space program for unique science, community health, and instrument development needs; technology de-

Anticipated SSSC Science and Exploration Achievements

	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025-Beyond
Open the Frontier to Space Environment Prediction	Measure magnetic reconnection at the Sun and Earth	Model the magnetic processes that drive space weather	Predict solar magnetic activity and energy release
	Determine the dominant processes and sites of particle acceleration	Quantify particle acceleration for the key regions of exploration	Predict high energy particle flux throughout the solar system Predict the transfer of mass and energy through planetary systems
	Identify key processes that couple solar and planetary atmospheres to the heliosphere and beyond	Understand non-linear processes and couplings to predict atmospheric and space environments	Understand the interactions of disparate astrophysical systems
Understand the Nature of Our Home in Space	Understand how solar disturbances propagate to Earth	Identify precursors of important solar disturbances	Enable continuous scientific forecasting of conditions throughout the solar system
	Identify how space weather effects are produced in Geospace	Quantify mechanisms and processes required for Geospace forecasting	Determine how stellar variability governs the formation and evolution of habitable planets
	Discover how space plasmas and planetary atmospheres interact	Determine how magnetic fields, solar wind and irradiance affect habitability of solar system bodies	Analyze the first direct samples of the interstellar medium
	Identify impacts of solar variability on Earth's atmosphere	Integrate solar variability effects into Earth climate models	Forecast atmospheric and climate change (joint with Earth Science)
Safeguard Our Outward Journey	Determine extremes of the variable radiation and space environments at Earth, Moon, & Mars	Integrate solar variability effects into Earth climate models	
	Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Reliably forecast space weather for the Earth-Moon system and begin nowcasts at Mars Determine Mars atmospheric variability relevant to Exploration activities	Provide situational awareness of the space environment throughout the inner Solar System Reliably predict atmospheric and radiation environment at Mars to ensure safe surface operations

***Develop Technologies, Observations, and Knowledge Systems that Support Operational Systems**

Each anticipated achievement in the table has been developed from teh SSSC research focus areas. Each targeted outcome requires advances in understanding of physical processes. Measurement capabilities must be available to develop that knowledge. Deployment of missions, development of theoretical understanding, and availability of infrastructure systems are required to provide that measurement capability. For each outcome in the table the necessary understanding, capabilities, and implementation have been traced. The scientific flow-down charts are available at the SSSC 2005 Roadmap web site (sun.stanford.edu/roadmap) and an example chart will be found in an Appendix. The requirements in the flow-down charts often overlap; so the results have been consolidated. Finally a balanced set of missions was chosen to address the most critical science and exploration topics in each phase. The missions have been assigned to program elements and resources identified to implement them. Information gained in earlier missions must be used to decide the selection and ordering of later flight opportunities.

velopment; supportive, targeted research and analysis programs; and a strong effort in education and public outreach. Partnerships with other areas of NASA and other agencies, both U.S. and international, are essential. Each of these program elements is described in more detail below.

Flagships missions address very difficult problems in scientific areas that present major roadblocks to future progress. Flagship missions have great promise for scientific advance, but may cost four or more times as much as an Explorer mission. Missions of this scope cannot be accomplished within the current resource limits without fatally compromising the rest of the program. Flagship missions are identified separately as top priorities for supplemental funding.

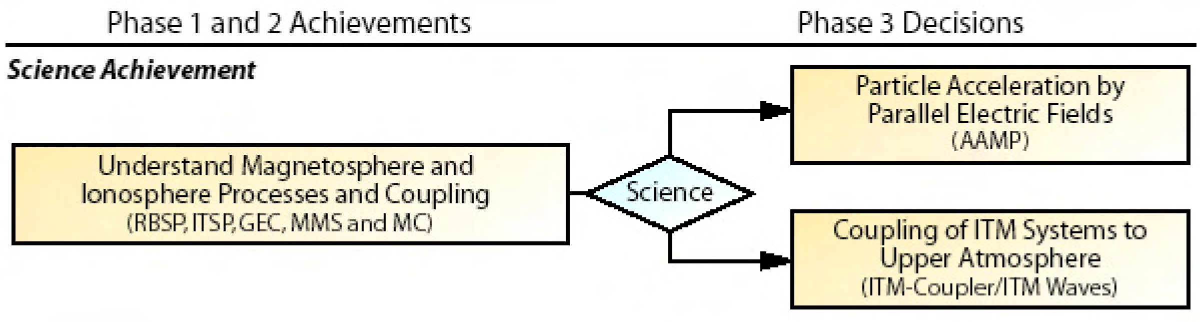


Table 2.1. Schematic illustrating a decision point for selecting a future mission.

Science by Phase

The Roadmap committees considered three decade-long phases in formulating a plan. The achievements of each phase inform decisions made about implementation in subsequent phases. The phases roughly correspond to development cycles in the Exploration Initiative. Phase 1 ends in 2015 and includes missions launched by that date; Phase 2 ends in 2025 and Phase 3 in 2035. The potential achievements identified in Table 2.1 correspond fairly well to these phases.

Our Phase 1 program presumes the continued operation of the current missions in the SSSC Great Observatory. Because of resource constraints, the baseline Phase 1 program necessarily includes only those missions that are already in development or whose announcement is expected in the very near future. These are STEREO, Solar-B, and MMS in the STP program; SDO and RBSP in the LWS program; and the selected Explorers: AIM, THEMIS, and IBEX. The selection of future Explorers will close gaps in the program. A solar sail demonstration mission and the ADAM Mars Scout mission also occur in Phase 1. Solar Probe should be launched in this phase, though data from this flagship mission's first plunge through the solar corona will not be available until Phase 2. This set of investigations provides a very powerful tool for accomplishing the achievements listed in Table 2.1.

An optimized program would accelerate these missions in time and some of the missions identified for early in Phase 2. The multiple synergies and comprehensive views afforded by the SSSC Great Observatory as it evolves and develops during this interval are a testimonial to the investments and achievements of the past decade in Sun Earth Connection science at NASA. The first crucial set of questions required to open the frontier to space weather predictions, understand the nature of our home planet, and safeguard our outward journey have been largely anticipated in the existing program plan. SSSC is clearly poised to make significant progress in the next 10 years on these important objectives.

Phase 2 includes missions scheduled for launch between 2015 and 2025. GEC and MagCon address the next set of fundamental problems in the STP program. They too depend on continued context observations from the evolving SSSC Great Observatory. The LWS Program plans to launch two missions relatively early - ITSP and the Inner Heliosphere Sentinels. These rely on continuous measurements from SDO and RBSP to realize their full potential. Later two smaller missions, SEPM and Heliostorm/L1 will address questions about hazardous space weather directed toward the Earth-Moon system in support of the human flight initiative. Toward the end of Phase 2 a choice between terrestrial and heliospheric mission priority will need to be made (as described in the previous section). The pace of launches is somewhat slower and the comprehensive coverage of the connected system available early in phase 2 will likely diminish toward the end of the decade if missions do not continue to function past their expected life times.

Missions beyond 2025 in Phase 3 have been identified in the previous chapter because we already know many of the scientific questions that will probably remain unanswered. The priorities will be adjusted depending on what is learned and on progress in the Exploration

Initiative, but it is clear that constellations of spacecraft will be required in new regions to resolve spatial and temporal changes in the magnetosphere and in interplanetary space where remote global sensing is not possible. Technological development and selection of Explorers may allow some objectives to be achieved earlier.

Several missions of great interest cannot be implemented even during this time period. A few are limited by technology, but more are limited by resources, particularly those having to do with comparative magnetospheres and planetology.

The SSSC Roadmap promises significant accomplishment. Most of the science requirements derived from the national objectives for NASA can be accomplished with the resources available. With additional resources an optimized plan has been crafted that will be significantly more productive. The near term course is clear and decision points for the future have been identified. The overall program is shown in Figure XX on page XX.

Program Elements

The implementation of the SSSC program is currently funded though several sources. Missions come from the Solar-Terrestrial Probe Program, the Living With a Star Program, and the Explorer Program. The fleet of existing missions makes up a Great Observatory that evolves as new missions are launched and new combinations of observations are made. Larger flagship missions are not part of the baseline funded program and require additional resources. Rockets and balloons provide low-cost rapid access to space. Focused research and analysis programs lead to new understanding and contribute to new investigation requirements. The support of data, computing, and community infrastructure ensures that progress will continue to be made. Each of these program elements is described below. We first describe briefly the mission strategy for each line. We then discuss each phase of the program and how the proposed mission set meets the requirements in the tables described above.

The figure shows the STP missions identified for flight through 2035 in our current budget projection. Boxes represent anticipated SSSC resources, in units of medium sized missions. Mission names in blue boxes indicate that resources are committed and development is underway. Green boxes represent new missions assigned here to anticipate resources. When two green boxes appear above a blue box resource, a decision is to be made, based on information to become available in the future.

Solar Terrestrial Probes

The Solar Terrestrial Probe investigations focus on specific scientific areas required to advance our fundamental understanding of the Sun – Solar System Connection. Successive missions target the 'weakest links' in the chain of understanding. STP missions are strategically defined and investigations are competitively selected.

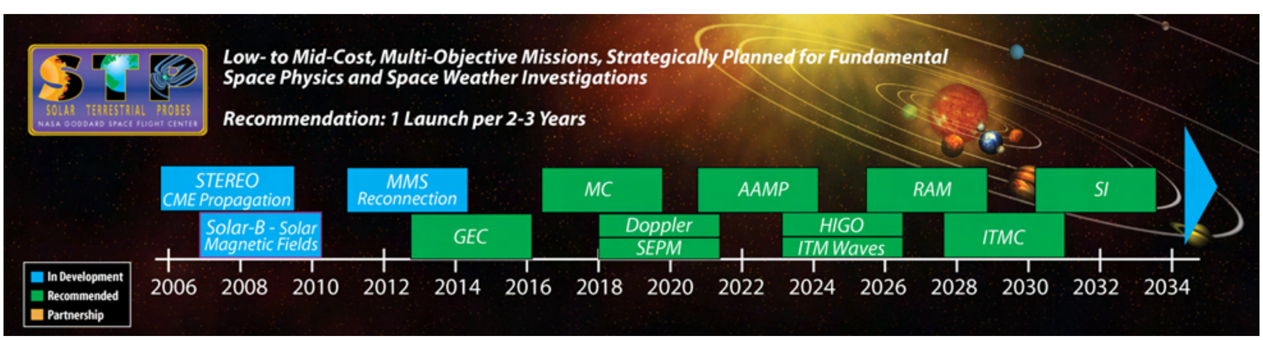
STP is one of two funded strategic lines for the Sun-Solar System Connection. Strategic mission lines afford the space physics community the opportunity to plan specific missions to address one or more of the research focus areas and thus make significant progress in elucidating the fundamental processes of the coupled Sun-Earth system. In addition, such capable spacecraft missions often result in unexpected new discoveries.

The future and existing mission priority has been re-evaluated in light of the new priorities at NASA that are reflected in the objectives derived in this Roadmap and in the reduced funding available for this line. STP missions currently in development are STEREO, Solar-B, and MMS. The first STP mission, TIMED, was launched in 2001 to study the influences of the Sun and humans on the mesosphere and lower thermosphere/ionosphere. These missions strongly support the current objectives explained in this Roadmap and musts be completed as scheduled. Solar-B is a joint mission with the Japanese space agency, JAXA, and it will provide the high-resolution solar observations needed to understand magnetic energy storage and release in the solar atmosphere. STEREO will observe coronal mass ejections and other structures moving in the interplanetary medium from two spacecraft in solar orbit to understand how CME's reach Earth. The set of four MMS spacecraft will probe the most critical regions of geospace to measure magnetic reconnection.

In order to support the fundamental science necessary to open the frontier for prediction of space weather effects, this Roadmap identifies GEC and MagCon as the next two STP missions. GEC will measure the vitally important yet poorly observed region just below stable satellite orbits to resolve issues of ion-neutral coupling and the processes linking the ionosphere and magnetosphere. MagCon, now slated for launch in 2022, provides comprehensive measurements of processes in the magnetosphere with a fleet of spacecraft. These and the other missions we identify are described in more detail in the next chapter.

Coupled with the rest of the program, these missions promise the best assault on the important problems facing SSSC. The slowed five-year spacing between launches in the current budget is not ideal, not only because progress is slow, but because synergy between missions is curtailed. We have identified participation in the L1 Earth-Sun mission that is being proposed in the Earth Science roadmap as one exciting candidate for augmentation of the STP line. Measurements of the external radiation and particle inputs to the Earth environment are essential for understanding the radiation budget. The scope of the SSSC portion of this mission will depend on the timing and capabilities of the Earth science mission.

If additional funds can be made available to restore the planned 2.5 year cadence of STP missions the MMS, GEC, and MagCon missions should be flown more quickly. They should be followed by Doppler & SEPM, two smaller missions candidates that could be combined to obtain measurements for understanding the initiation (DOPPLER) and the coronal evolution (SEPM) of flares, current sheets, and CME shocks that produce solar energetic particles. These two missions particularly benefit from overlap with the inner heliospheric and solar missions planned in the LWS line. Next, AAMP focuses on particle acceleration too, but in the auroral region around Earth. Two more small missions, HIGO and ITM Waves, complete phase 2 of our plan in this optimized scenario. A revamped HIGO complements the IBEX Explorer recently selected to explore the outer boundary of the heliosphere; HIGO will measure the components of the interstellar medium that survive into the sub-Jovian solar system. ITM Waves concentrates on the



The figure shows the mission identified for flight through 2035 in our optimized scenario. The improved synergy of missions is apparent.

wave processes fundamental to the coupling between distinct altitude regions and on the overall dynamics of the Earth's atmosphere.

Phase 3 STP missions will measure reconnection near the Sun and observe lower latitude disturbances in the ionosphere-thermosphere-mesosphere; a stellar imager (likely a flagship mission) will resolve activity on other stars to enable us to complete our objectives. Even later, more ambitious missions to explore the interactions of external drivers with other worlds in the solar system, specifically Titan, Venus, and Io, could be accomplished in partnership with others to address questions of habitability and atmospheric evolution. Larger telescopes to remotely probe the solar transition region would complete our understanding of how energy propagates from the Sun outward and remote sensing of other planetary environments would close the path at the receiving end.

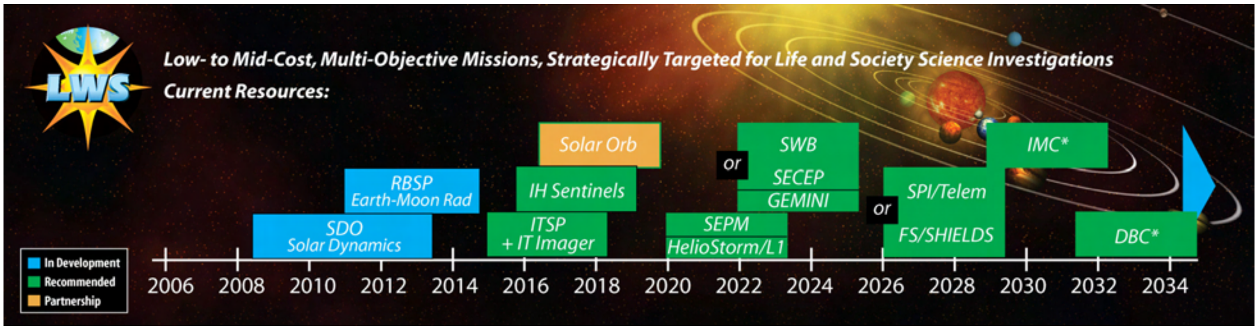
Living with a Star

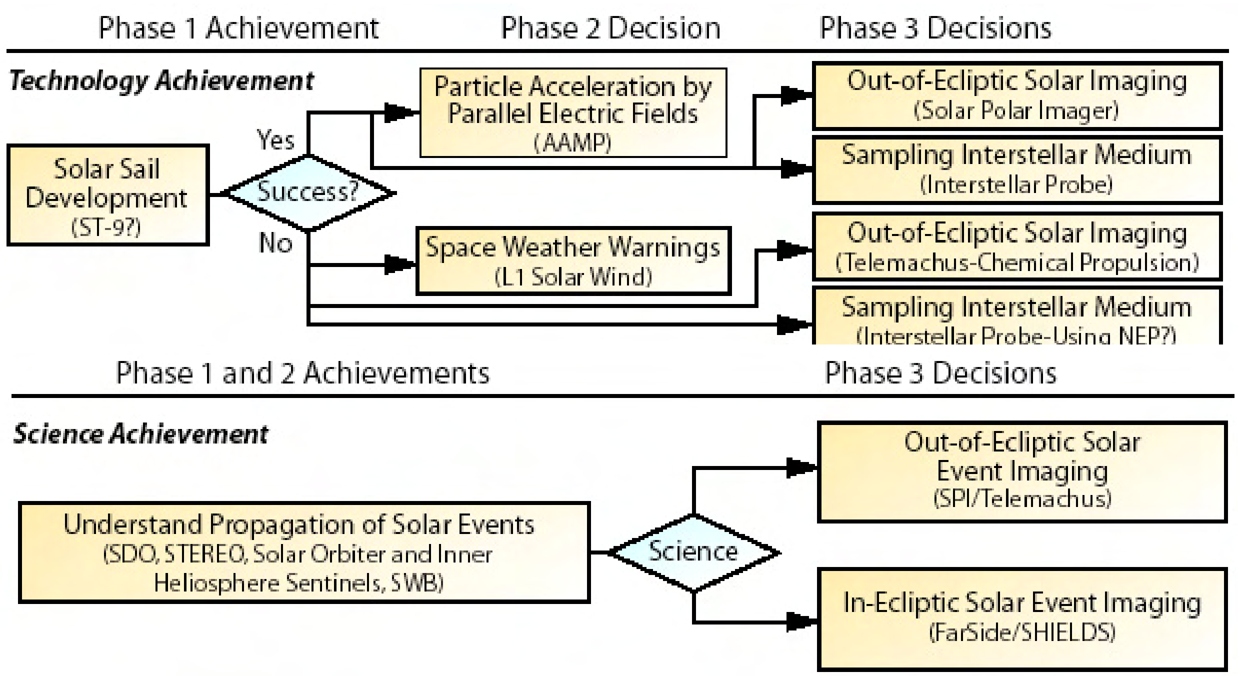
The Living With a Star program emphasizes the science necessary to understand those aspects of the space environment that affect life and society. The ultimate goal is to provide a predictive capability for the space weather that has important consequences. LWS missions have been formulated to answer specific science questions needed to understand the linkages among the interconnected systems that impact us. LWS investigations build on the fundamental knowledge gained by the STP missions and very directly address the needs of the Vision for Space Exploration and Objectives H and J of this Roadmap. Significant planning has already informed the crafting of a coordinated LWS program that includes strategic missions, targeted research and technology development, a series of space environment test bed flight opportunities, and partnerships with other agencies. Partnerships are crucial to LWS because the vast number of complex physical connections between and within the Sun-Earth system cannot be addressed by a few missions.

Two LWS missions are currently in development: the Solar Dynamics Observatory (SDO) and the Radiation Belt Storm Probes (RBSP). The first LWS mission, SDO, is expected to launch in 2008 to understand the mechanisms of solar variability by measuring the solar interior, atmosphere, and EUV spectral irradiance for at least five years. Two geospace storm probe missions complement SDO to measure the terrestrial environment; all three should fly simultaneously. The first, RBSP, is planned for a 2011 launch; it will quantify the source, loss, and transport processes that generate Earth's radiation belts and cause them to decay.

Our Roadmap concurs with earlier recommendations that the next two LWS missions should complete the geospace storm probes by investigating ionospheric disturbances with the Ionosphere-Thermosphere Storm Probes (ITSP) and exploring radial evolution of solar wind structures with the Inner Heliosphere Sentinels mission. The priority of the ITSP mission is driven by the very practical need to aid communications and navigation; by revealing the complex interplay of plasma - neutral processes that frequently produce unexpectedly large electron density plumes and the subsequent formation of small-scale ionospheric irregularities. ITSP includes a separate imaging instrument. The Exploration Initiative raises the priority of the IH Sentinels mission because hazardous space weather near Earth cannot be understood without it. In our "current resources" scenario for LWS these two missions are launched within a year of each other in 2015 and 2016. Our optimized scenario moves these missions ahead three years to provide the synergy with RBSP and SDO and to provide earlier information for the design of systems for the return to the Moon later in the decade. We also identify an important partnership opportunity with ESA's Solar Orbiter mission that complements the IH Sentinels in situ measurements and will provide solar observations from a different vantage point.

Subsequent LWS missions in Phase 2 address understanding energetic particle production near the Sun with the Solar Energetic Particle Mission (SEPM) and crucial measurements of the solar wind and energetic particle inputs to geospace with Heliostorm or an L1 Heliostorm Mission. These mission candidates can be smaller in cost than typical strategic missions. The choice between Heliostorm and





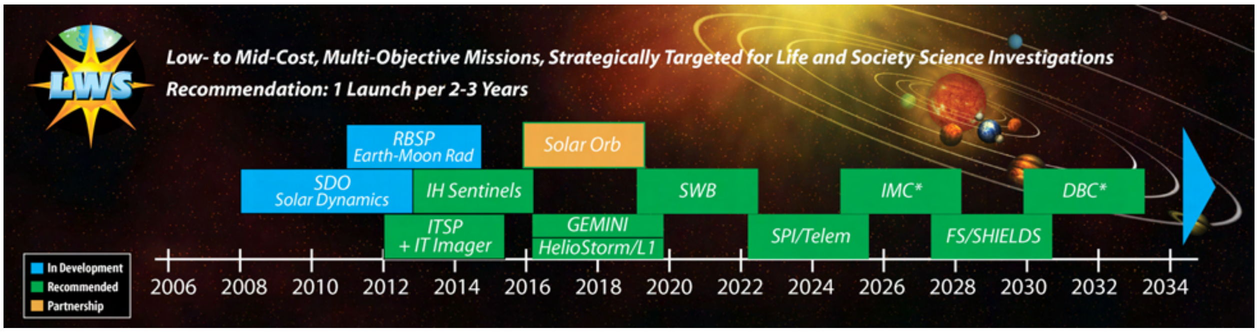
The diagrams suggest decision points for future missions based on technology or science criteria.

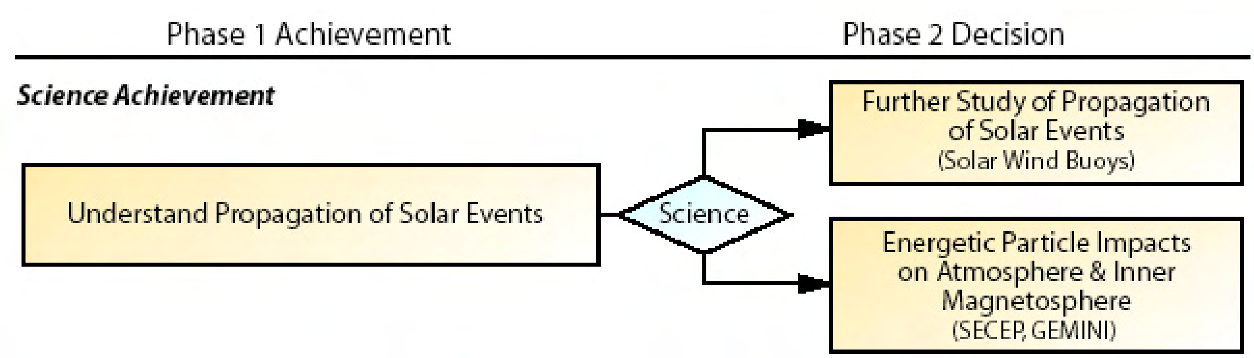
an L1 mission is complex (see box on page 69). Heliostorm would use solar sails to hover twice as far upstream of the L1 point in the solar wind for advanced warning of geospace disturbances. The mission will measure the same solar wind parameters as L1-Heliostorm. This is the preferred option. Measurement of incoming solar wind parameters is crucial to many other investigations, so depending on Heliostorm, the status of the Earth Science L1-Earth-Sun mission, the lifetime of existing assets, and partnerships with other agencies, we have reserved some small amount of resources for L1 observations.

Subsequent Phase 2 mission selection in the LWS program depends on future developments in the program. Priorities will shift based on progress of the Exploration Initiative and what we learn from spacecraft launched in the next ten years. Our baseline program shows a choice preceding the 2022 launch of either Solar Weather Buoys (SWB) or a pair of smaller missions, SECEP and GEMINI. The SWB mission provides for about a dozen in situ observing platforms circling the Sun near 1 AU to fully understand how the solar wind and hazardous disturbances propagate outward from the Sun. SWB could become part of the early warning system needed to support safe and productive journeys to Mars and beyond. SECEP (Sun Earth Coupling by Energetic Particles) will explore the destruction of ozone by solar energetic particles; SECEP will measure the precipitating energetic particle influx as well as the descending odd nitrogen and odd hydrogen compounds and ozone densities. The Geospace Magnetosphere-Ionosphere Neutral Imagers (GEMINI) will provide the first 3-D observations of the global geospace dynamics in response to external solar drivers and internal coupling. The decision will be based on what is learned from STEREO, SDO, and the IH Sentinels missions on the one hand and MMS, RBSP, ITSP, and GEC on the other.

Later Phase 3 choices in the LWS program would select among high-latitude solar observations necessary to understand the solar cycle and interior, two or three solar imagers stationed far from Earth to provide global coverage, a constellation of spacecraft to understand the inner magnetosphere, and exploration of the day-side boundary layer where energy from the solar wind crosses the magnetopause. The prioritization of these missions depends on results from earlier investigations.

In our optimized scenario the ordering changes slightly as shown in the accompanying chart. The SEPM mission has moved to the STP timeline to improve its overlap with the IH Sentinels and Solar Orbiter.





The Explorer Program

The Explorer program is an indispensable element of the strategic Roadmap plan. Explorer missions fill important gaps in the prescribed program. These investigations target very focused science topics that augment, replace, or change strategic line missions. Highly competitive selection assures that the best strategic science of the day will be accomplished.

Missions currently in development, AIM, THEMIS, and IBEX, address important targeted outcomes. AIM (Aeronomy of Ice in the Mesosphere) will explain polar mesospheric clouds formation and variability as well their relationship to global change in the upper atmosphere and the response of the mesosphere to solar energy deposition. THEMIS (Time History of Events and Macroscale Interactions during Substorms) addresses the spatial and temporal development of magnetospheric substorms – one of the fundamental modes of the magnetosphere. IBEX, the Interstellar Boundary Explorer, will image the entire 3D configuration of the boundary region of our heliosphere, the vast (~100AU thick) region where the solar wind decelerates because of the pressure of the local interstellar plasma.

Because future selections are determined competitively in response to evolving strategic conditions, identification of specific future accomplishments at this time is impossible; however, numerous candidate missions have been identified (see the Quad charts in Appendix D and the SSSC Roadmap web site for examples). The Explorer program has long been critical to maintaining the strength of the Sun-Earth Connection (now Sun-Solar System Connection) science program. It affords a regularly recurring opportunity to fly exciting new missions, selected by peer-review for the best science with a relatively short response time, utilizing state-of-the-art instrument development. In addition, the program provides the opportunity for instrument teams to participate in missions-of-opportunity provided by other agencies (DoD, etc.) or international programs. These missions-of-opportunity allow the space physics community to obtain the data necessary for specific strategic goals at a fraction of the cost of a dedicated mission. SEC Explorers have been responsible for major scientific achievements that have profoundly transformed our understanding of the Sun-Earth system. Some highlights include: visualization of the global dynamics of the geospace system by IMAGE, the first solar gamma ray imaging by RHESSI, discovery of coronal magnetic complexity by TRACE, discovery of trapped anomalous cosmic rays in Earth's magnetosphere by SAMPEX, and discovery of small-scale size parallel electric fields in the auroral acceleration region by FAST.

Explorers demonstrate the ability of the science community to respond rapidly to decision points, an important element in the strategy put forth in the Vision for Space Exploration initiative. Decision points can allow us to take advantage of a new scientific discovery that suggests the need for a new mission, new instrumentation development that provides the opportunity to address questions previously not accessible, or new technologies or analysis techniques that enable a less costly mission. Enabling rapid response of the SSSC community to such promising scientific opportunities ensures that science goals are met in the most cost- and time-effective manner. Results from such missions in turn may lead to development of new strategic missions or modifications of existing ones.

The Explorer program also plays a key role in developing and maintaining the scientific and engineering community needed to meet the objectives of the Roadmap, NASA, and the nation. Explorers provide hands-on training of instrumentalists, both scientists and engineers, thus enabling SSSC strategic missions, and directly contributing to the NASA Mission element "to inspire the next generation of explorers". Managing cost-constrained missions such as Explorers requires specialized expertise.

Flagship and Partnership Missions.

Urgent need for progress across a range of topic areas means that all of the SSSC resources cannot be applied to a single problem for an extended interval. Yet some major roadblocks to progress simply cannot be overcome with missions supportable in the strategic lines available to SSSC. Solar Probe in the immediate term, and Interstellar Probe and Stellar Imager in the more distant future are flagship missions that address such problems (see inside back cover).

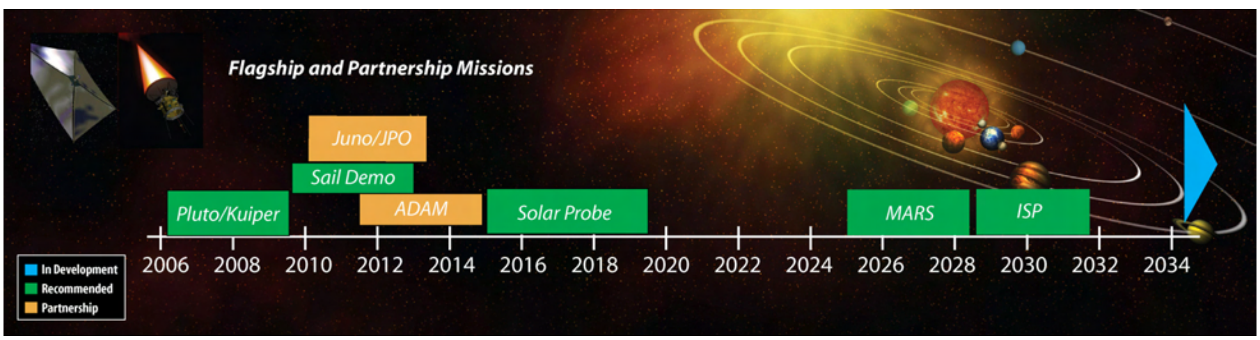
Solar Probe will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity. Solar Probe is the first flight into the Sun's corona, only 3 solar radii above the solar surface. Accurate predictions of events that disturb both Earth's human systems and affect deep space explorers require this understanding. Solar Probe can only be achieved with specific budget augmentation owing to the cost of ensuring its survival in an extreme environment. That said, the science and technology definition team currently investigating Solar Probe concludes that the mission is ready for a new start now. The decadal surveys and this roadmap identify Solar Probe as the highest priority flagship mission requiring an augmentation in funding.

Interstellar Probe will be the first mission to leave our heliosphere and directly sample and analyze the interstellar medium. It requires an advanced in-space propulsion system, such as a solar sail or nuclear electric propulsion, to reach the upstream interstellar medium at a distance of 200 AU within 15-20 years. The mission will be the first specifically designed to directly measure the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields. On its way, it will provide only the second opportunity after Voyager to directly observe the region of interaction between the solar wind and the interstellar medium, from the termination shock to the heliopause and beyond.

Stellar Imager (SI) is a challenging mission that will obtain the first direct resolved (1000 pixel) images of surface magnetic structures in stars like the Sun. The SI will develop and test a predictive dynamo model for the Sun and Sun-like stars using asteroseismology and by observing the patterns in surface magnetic fields throughout activity cycles on a large sample of Sun-like stars.

Partnerships provide another method to increase scientific return. Several missions have been identified in our plan that rely on partnerships with other parts of NASA, as well as other U.S. government and international agencies. Within NASA the solar sails demonstration project will lay the ground work for Heliostorm, Solar Polar Imager, and Insterstellar Probe. The Jupiter Polar Orbiter (JUNO) planned by the solar system exploration division has direct relevance to understanding planetary magnetospheres. Pluto-Kuiper will provide another opportunity to explore the outer heliosphere. Multiple opportunities for partnership have been identified as part of the International Living With a Star (ILWS) program. Partnership with ESA on Solar Orbiter should be explored in the very near term as a way to optimize and enhance the IH Sentinels, SEPM, and SHIELDS investigations.

Enabling information about the aeronomy and dynamics of the Mars atmosphere is required for aerocapture, entry, descent, and landing. The Mars Scout program provides an opportunity for a collaborative mission such as ADAM. Future missions to refine our knowledge of the interaction of the Martian environment with the Sun will also be collaborative. The SECEP mission, designed to understand ozone production, is a prime candidate for collaboration with our Earth Science colleagues. The L1-Earth-Sun mission to understand the Earth's radiation budget is another potential partnership with Earth Science.



Measurements of the Solar Wind Up-stream from Earth

Partnerships and Decision Points for SSSC Near L1:

In principle the operational solar wind monitoring function should be the responsibility of other U.S. government agencies. However, the L1 vantage point remains critical to SSSC science because in situ solar wind conditions about an hour upstream from the Earth can be continuously determined by a single spacecraft. Without knowledge of the external drivers, understanding space weather effects in geospace is problematic. Reliable prediction of geospace conditions requires accurate measurements of the incoming solar wind parameters. Short-term forecasts based solely on solar observations will never be detailed enough for terrestrial space weather needs. This Roadmap identifies three possible L1 partnering options for long-term replacement of the continuous solar wind monitoring currently provided by the ACE and WIND spacecraft. Only one mission needs to be implemented by SSSC.

Heliostorm uses solar sails to hover twice as far upstream as an L1 mission. The mission will measure the same solar wind parameters as L1-Heliostorm. This is the preferred option.

L1-Heliostorm provides basic measurements of the solar wind plasmas, fields, and energetic particles from the L1 position using conventional technology.

L1 Earth-Sun is a joint Earth-Sun Science mission that includes an in situ solar wind package. The mission simultaneously conducts spectral imaging from XUV to IR of both the Earth and the Sun.

Decision Points and Partnerships:

If the Solar Sail Demonstration is successful, then Heliostorm would use a solar sail to provide double the time interval for forecasting and data assimilation into nowcasting models. The SSSC mission cost would be similar to an Explorer if NOAA and DoD partner with NASA.

If the Solar Sail Demonstration does not fly or is not successful, then L1-Heliostorm will use conventional technology at L1 to provide operational solar wind data. The mission cost is small and should be very small to SSSC when shared with DoD and NOAA partners.

If L1 Earth-Sun goes forward as a science mission in partnership with Earth Science, then the total SSSC component should be of moderate cost; the SSSC cost for the solar wind component should be small. L1-Heliostorm would not be necessary in this case.

The Sun-Solar System Connection Great Observatory – Evolving to Meet the Needs of the Vision for Exploration

The very large "Halloween Solar Superstorms" described on page 4 demonstrate the unique and powerful capability of the SSSC Great Observatory to view this system of systems. The effects of the solar storms were observed simultaneously from the Sun, to the Earth, to Mars, and beyond to the edge of the solar system. It would not have been possible to link the consequences of these superstorms at Earth and Mars to the solar drivers that produced them without this collection of satellites and the human and computational resources to interpret the observations. The power of the Great Observatory comes from the combination of multiple operational assets, timely and convenient data access, large-scale models, and associated data analysis. Many of the spacecraft are SSSC missions, but additional "observation posts" are provided by spacecraft supported by other programs such as Mars Global Surveyor (MGS), Cassini and the Hubble Space Telescope. For example, from MGS, we learned that the fluxes of solar energetic particle radiation caused by the superstorms were quite different at Mars and Earth. Our Great Observatory will need to evolve and expand to fully understand why space weather effects vary so much at different locations in our solar system.

The Great Observatory is vital to our quest to understand the fundamental physical processes at work throughout the complex, coupled system that is the Sun-Solar System Connection. For example, magnetic reconnection between the interplanetary and terrestrial magnetic fields is the critical physical process determining the size of a geomagnetic storm. Our strategic mission Magnetosphere Multiscale (MMS), currently in development, is being deployed to observe the physics at work within the small-scale diffusion region that ultimately regulates the effectiveness of solar effects on the Earth system. This single mission will transform our understanding of this universal plasma process. However, by utilizing existing missions in flight at the time of MMS, we have the opportunity to greatly increase our understanding of the impacts of this process by connecting the in situ MMS data near the small dayside reconnection site to upstream solar wind measurements and to satellite-based images of corresponding ionospheric airglow emissions. The resultant increase in knowledge improves our capability to predict the space environment that human and robotic explorers will experience and provides the foundation for future operational systems.

The Great Observatory will continue to evolve as new spacecraft join and older ones retire or change their operating modes. Missions both in their prime phase and in extended phases (supported by the SSSC MO&DA program) provide the variety of observation posts needed to study the Sun-Solar System Connections, as demonstrated by the 2003 Halloween Storms. A great strength of the Great Observatory fleet is that it is regularly evaluated and reviewed to maximize the return on the agency investments. This Senior Review process determines which spacecraft are most necessary to meet the needs of the Sun-Solar System Connection program as defined by the community-developed Roadmap document. The criteria for continuation include relevance to the goals of the SSSC; impact of scientific results as evidenced by citations, press releases, etc.; spacecraft and instrument health; productivity and vitality of the science team (e.g., publishable research, training of younger scientists, education and public outreach); promise of future impact and productivity (due to uniqueness of orbit and location, solar cycle phase, etc.); and broad accessibility and usability of the data. The SSSC **Guest Investigator (GI)** program is a critical component of the SSSC Great Observatory. The GI program enables the broadest community of SSSC researchers in universities and institutions across the country to use Great Observatory data in innovative scientific investigations pursuing the goals of this roadmap. The focus of competitively selected research funded by the program continuously evolves to ensure that the most important current questions are addressed.

New missions will be selected for inclusion in the Great Observatory on the basis of their demonstrated ability to satisfy the same criteria discussed above for successful operating missions. The most important of these, from the perspective of strategic planning, is relevance to NASA scientific goals. To meet the needs of the Vision for Space Exploration as articulated in this roadmap, will necessarily require new missions in order to characterize, understand and predict the dynamic environmental conditions in space. At the same time, some existing missions are demonstrably vital and irreplaceable and will need to be maintained in order to meet the agency objectives.

Low Cost Access to Space

The Low Cost Access to Space (LCAS) program, whose key elements are the sounding rocket and balloon (suborbital) programs, is an essential component of NASA's space physics research program. LCAS provides cutting-edge new science discoveries utilizing state-of-the art instruments developed in a rapid turn-around responsive environment. The capabilities of the LCAS program need to evolve and improve to stay at the cutting edge of research. These investigations, selected for the best science, serve two additional important purposes that can not be adequately addressed in other flight programs - training of experimental space physicists and engineers and the development of new instruments and instrumental approaches that are verified by actual spaceflight.

A recent example of this three-pronged role is the new understanding of auroral physics obtained in a series of rocket flights that developed both the state-of-the-art instrumentation and the pathfinding science discoveries that led to one of the first NASA small explorers, FAST. Figure 1 [to be provided in the final roadmap] shows how new, higher altitude rockets demonstrated the importance of microphysics and the need to make extremely high time resolution measurements to elucidate the acceleration processes. The 'top hat' plasma detectors, developed by for these rockets, are now common on space plasma missions, providing 3D, high time resolution electron and ion measurements. The rocket program provided the investigator (who became the FAST PI after a long association with the sounding rocket program) with the opportunity to develop project management skills and also provided the hand-on training of graduate students who became the instrument leads on the FAST satellite.

The other key component of LCAS are solar physics balloon missions, which have an outstanding record of scientific discoveries. For example, the LASCO coronagraph on board the SOHO spacecraft enabled systematic studies and arrival time predictions of coronal mass ejections aimed at Earth. The solar telescopes on the RHESSI Explorer mission used hard X-ray imaging spectroscopy, high-resolution nuclear gamma-ray line spectroscopy, and gamma-ray line flare imaging to observe the surprising energy release process in solar flares in greater detail than ever before. These achievements trace their heritage to balloon-borne instruments flown in the continental U.S. and in Antarctica.

An essential ingredient of the Vision for Exploration is a source of well-trained engineers and scientists who understand the demands of building and delivering spaceflight systems and hardware. The LCAS program provides an important, hands-on training ground for these human resources. Graduate students participate in the entire life cycle of a scientific space mission, from design and construction to flight, and data analysis. No other flight programs have time scales that fit that of a Ph.D. thesis. The rocket program alone has resulted in more than 350 Ph.D.s. In addition, a rocket or balloon project offers the chance for younger scientists to gain the project management skills necessary for larger projects such as Explorers or larger missions.

The combination of science, advanced instrument development, and training makes LCAS a critical path item for achieving NASA's national space science goals.

Scientific Research and Analysis

Achieving NASA's objectives requires a strong scientific and technical community to envision, develop, and deploy space missions, and to apply results from these missions for the benefit of society. Such a community currently exists within the United States. It is a world leader in space physics research and exhibits a diverse spectrum of sizes and specialties, based at universities, government facilities, and industrial labs.

The continued health of our research community, and thereby the ability to achieve NASA objectives, is dependent on many factors. These factors include a robust infrastructure of funding opportunities and resources to enable and maintain research initiatives; low-cost access to space for science, prototype development, and training; and a strong education and public outreach program to inspire and recruit new scientists and engineers.

The term infrastructure often refers to tangible assets, such as launch facilities, design and test facilities, or communications enabled by the Deep Space Network (DSN). These assets are a critical element of mission conception and execution. For example, long before major strategic missions are selected an extensive development program begins with first generation ‘brass board’ instrument concepts; this is followed by near-Earth testing exploiting Low Cost Access to Space (LCAS) opportunities. More mature concepts can be tested in Explorer-class missions. The IMAGE and STEREO mission concepts provide two excellent, current examples of this process.

However, in addition to investing in hard assets and flight missions, NASA must invest heavily in intellectual infrastructures through its programs of research grants: SSSC Supporting Research and Technology (SR&T), LWS Targeted Research and Technology (TR&T), SSSC Theory Program, Applied Information Systems Research (AISR), Guest Investigator (GI), Virtual Observatories (VXO), etc.

NASA must also invest in analysis infrastructures that support computing and data analysis efforts. This is a critical element in the symbiotic advance of scientific understanding through mission design: scientists use data from existing missions to improve theories and models, which then suggest measurements for the next mission. Large-scale numerical calculations, such as the temporal evolution of fundamental equations in three dimensions, require massive supercomputers. Without a cutting edge computing infrastructure such computations are not possible. A strong computing structure is also needed to support data analysis and data assimilation, especially for increasingly large and complex data and modeling structures.

Fortunately, much of this supporting infrastructure is in place, as evidenced by examples ranging from computing architectures such as the Columbia supercomputing project, the Community Coordinated Modeling Center (CCMC), the Virtual Observatory efforts, and NASA’s Applied Information Systems Research Program, to strong EPO efforts and innovative programs such as NASA’s Summer Faculty Fellowship program.

Nonetheless, our research community faces significant challenges in the immediate future, challenges that directly affect our ability to meet NASA’s goals and support national objectives. The most significant challenges are those of training new researchers while maintaining the corporate memory of an experienced work force. NASA and its supporting contractors will soon have large portions of their work force eligible for retirement. By some estimates the services of as much as two-thirds of the most experienced scientists, technicians, and managers could be lost in the near future.

Support for a competitive number of research teams and investigators is of paramount importance to a healthy and robust scientific community. There is a real danger that the loss of ‘critical mass’ of research teams has already begun to impinge on NASA’s science and exploration goals. This is especially important for hardware development teams that have a high startup investment and have difficulty retaining technical expertise in uncertain funding cycles. NASA support for low-level hardware development is generally deemed insufficient to support truly innovative instrument development. Only the largest teams are perceived as capable of competition for hardware development. Paradoxically, the opposite can be said about modeling support, in that large-scale modeling efforts are not sufficiently funded for the tasks they face. In all cases, there must be a balance between large and small research efforts, as well as between pure and applied science.

Training opportunities at the graduate and undergraduate levels provide an introduction to all aspects of space missions, including instrument development, mission operations, data analysis, and theory and modeling. These often provide the first opportunities for students to experience the excitement of working in space physics and provide the primary means of recruiting these students into the space physics community. NASA programs that provide low-cost access to space such as rocket, balloon, and airplane missions, are especially useful for training in that students can contribute to mission design and operations while obtaining data in a timely fashion for analysis. This is particularly important in light of the long development times for complex missions that can exceed the normal tenure of graduate education.

Universities have traditionally provided the bulk of the training function, though innovative co-operative programs provide additional training opportunities in non-University settings. The needs for a robust training program are necessarily tightly linked to the health and number of graduate education programs and to the education and public outreach goals that attract students.

The challenges discussed above are not new. The community has previously considered these problems and voiced concerns and suggested mitigation efforts through community efforts such as the recent NRC Decadal Survey, which offered specific recommendations for education and public outreach efforts as well as strengthening the solar and space physics enterprise. These recommendations remain relevant and are endorsed by this Roadmap.

NASA's SR&T, TR&T, and GI programs are the traditional underpinning of most research teams and individual investigators and have been repeatedly recognized as such in community strategy documents. These content of these competitively selected programs continuously evolves to address new questions with innovative new methods. They have provided a significant contribution to the vast body of knowledge needed for direction and implementation of NASA's initiatives. It is worse than foolish to collect expensive data and not provide adequate resources to exploit it. Unfortunately, recent budget pressures have forced delays in some of these programs and the potential impact of these delays must be acknowledged.

NASA SSSC also benefits from the research and analysis programs funded by other agencies, such as NSF's CEDAR, GEM, and SHINE research programs and the Center for Integrated Space-Weather Modeling (CISM), an NSF Science and Technology Center. In light of the importance of non-NASA research to NASA's research infrastructure, inter-agency cooperative programs must continue to be nurtured and supported.

In summary, this Roadmap recommends that NASA pursue programs across a broad spectrum of size and duration and that a portion of the budget be reserved for smaller strategic projects that might otherwise be overlooked. NASA should also seek to expand current partnerships with industry, universities, and other agencies.

Evolving SSSC Great Observatory

Chapter 3

Sun-Solar System Connection: The Missions

Previous sections of the Roadmap have described the science and exploration objectives of the SSSC division, identified targeted outcomes for the next 30 years, listed investigations and mission candidates that can provide the necessary data, and recommended two alternative program implementation strategies based on an optimized and the current budget expectations. This chapter gives a little more information about the specific missions and how they fit into the program.

Numerous mission options were considered by the committee based on prior knowledge, community input, and 12 new mission studies commissioned by the Roadmap team. The missions described below are those specifically recommended in the two alternative program strategies. Not included are many exciting Explorer candidates and missions that cannot be accomplished in the time period we considered, even with the optimistic resource scenario. In the past Explorers have replaced some strategic missions. However, the number of missions may still seem large because of the unique challenges presented by SSSC system science; the evolving SSSC Great Observatory requires distributed multi-point measurements. Other factors are the 30-year time span, the relatively modest cost of many missions, particularly partnerships, and the number of mission alternatives suggested in the SSSC strategy.

The following brief descriptions answer three key questions:

- What is the main purpose of the mission?
- Why does the SSSC strategy require the mission?
- When should the mission be implemented?

Further details about these and other SSSC mission candidates can be found in the Quad Charts in an Appendix to this report.

Candidate Mission Reference List

The first seven missions are currently under development, including four Explorers.

The next seven near-term missions (those with launch planned by 2015) include one partnership and a flagship mission. All have all been the subject of thorough science and technology definition team (STDT) studies.

The 13 intermediate-term mission candidates for the following decade include two partnerships and several alternative choices. The intermediate-term missions have either been considered by an STDT or have undergone an intensive, objective conceptual evaluation and costing by the GSFC or JPL mission study teams.

The nine future missions (those expected to launch after 2025) have been studied to varying degrees.

The seven missions described in the Partnership section are the primary responsibility of other divisions at NASA.

SSSC utilizes several mission resources. Strategic fundamental science missions are executed as Solar-Terrestrial Probes (STP). The Living With A Star (LWS) mission line is also strategic, dedicated to research on understanding and mitigating effects of space weather. Flagship Missions (FLG) are grand challenge missions that require separate new starts outside of the STP or LWS programs. Explorer (EXP) missions are smaller than the others and present opportunities for open competition to address strategic scientific questions that are relevant and timely. MOO's, missions of opportunity, are inexpensive components flown as part of another mission. Some missions receive external (EXT) funding, either from other parts of NASA, other U.S. agencies, or other national entities. Below, we list and define acronyms for SSSC mission candidates, and categorize them, to the degree possible at this time, according to these mission lines. Missions currently in development and near term SSSC missions are shown in order of approximate launch date. Later missions are listed alphabetically.

SSSC Missions Currently in Development

AIM small Explorer

The primary goal of the Aeronomy of Ice in the Mesosphere (AIM) mission is to resolve why Polar Mesospheric Clouds (PMCs) form and why they vary. In addition, AIM will determine the mesospheric response to solar energy deposition and coupling among atmospheric regions.

AIM will examine the relative contributions of solar and anthropogenic effects that cause change in the upper atmosphere and it will examine long term change. AIM will also make key observations of solar energetic particle induced effects on upper atmospheric composition, in particular of odd-nitrogen compounds and ozone.

AIM is a top priority in view of current heightened scientific and public interest in PMCs and the immediate need to understand how the upper atmosphere responds to variable solar energy inputs such as solar storm events. AIM is scheduled to launch in 2006.

Time History of Events and Macroscale Interactions for Substorms (THEMIS)

THEMIS is a MIDEX Explorer mission that addresses the spatial and temporal development of magnetospheric substorms. The mission consists of 5 identical spacecraft and an array of ground-based all-sky cameras. The cameras are a mission-critical element of THEMIS, providing a global context for the in situ measurements and also detecting auroral substorm onset for mission operations decisions. When the spacecraft are on the day side, it will address the question of solar wind control of the magnetosphere and the coupling of energy across the various dayside boundaries.

THEMIS addresses the issue of onset and evolution of the substorm instability, an explosive yet fundamental mode of the magnetosphere. This was identified by the National Research Council as one of five main strategic questions in space physics.

The mission was selected in the last MIDEX proposal solicitation and is currently in Phase C/D development. The mission is scheduled for launch in 2006.

Solar-B

Solar-B will reveal the mechanisms of solar variability and study the origins of space weather and global change. NASA is a 1/3 partner with the Japanese space agency (JAXA) on this mission to investigate the detailed interactions between the Sun's magnetic field and the corona. High resolution observations of active regions on the photosphere together with an X-ray telescope and imaging spectrograph will help understand the creation and destruction of magnetic fields, variations in solar luminosity, generation of UV and X-radiation, and the dynamics of the solar atmosphere.

Solar B addresses most of the expected achievements in Phase 1: reconnection, the mechanisms of particle acceleration near the Sun, the origins of solar disturbances, understanding of the sources of irradiance variations, causes of the extremes in the local environment, and prediction of space weather. Many Phase 2 topics are also covered.

Solar B complements SDO, STEREO, and SOHO by providing high resolution imaging and understanding of detailed mechanisms of variability. The essential next step in understanding the origins of solar activity requires the high resolution data from Solar B.

STEREO

The Solar-Terrestrial Relations Observatory (STEREO) will determine the 3-D structure and evolution of coronal mass ejections (CMEs) from their eruption on the Sun through the inner heliosphere to Earth's orbit. The mission will employ remote sensing and in situ measurements from two spacecraft drifting in opposite directions away from the Earth at 1 AU to triangulate CME-driven shocks, detect preceding shock-accelerated particles, and analyze in situ CME and solar ejecta signatures. As the spacecraft reach large separations, one spacecraft will observe the propagation of CMEs that will be directly sampled by the second spacecraft to provide a definitive determination of the relation between the white light and in situ features of a CME.

This mission will also provide important information on CME-shock-accelerated particles, contributing to the characterization of the space environment. This mission is a high priority for SSSC science because of the central role of CMEs in determining "space weather."

The Solar-Terrestrial Relations Observatory (STEREO) is nearly complete and ready to be launched in 2006.

Coupled Ion-Neutral Dynamics Investigation (CINDI)

CINDI, a NASA Explorer mission of opportunity will fly on the Communication/Navigation Outage Forecast System (C/NOFS) satellite that is funded by the US Air Force. The CINDI mission will measure the electrodynamics of the low latitude ionosphere resulting from ion-neutral interactions. The ion and neutral motions are key variables in the triggering of equatorial spread-F (ESF) and scintillation, which are space weather events that disrupt radio signal propagation over a wide range of frequencies. CINDI will provide the first simultaneous high-resolution measurements of these parameters, and may lead to the development of a predictive capability for ESF and related irregularities.

CINDI has two separate instruments that measure the three dimensional ion and neutral thermal gas flows in the low latitude ionospheric F region. The Neutral Wind Meter (NWM) and the Ion Velocity Meter (IVM) make continuous measurements of the neutral and ion motions along and perpendicular to the satellite's velocity vector. The spatial resolution of the CINDI instruments is on the order of one kilometer, and the precision is +/- 10 meters/second for the neutral drifts, and +/- 5 meters/second for the ion drifts. An important strength is that the measurements are equally sensitive in sunlit and dark conditions. This will allow accurate measurements of neutral winds and ion drifts near the sunset terminator, where the magnitude of the vertical plasma drift creates the conditions that help to initiate ESF and scintillation events.

The CINDI mission supports a number of Objective H RFA's, and has strong ties to space weather programs funded by NASA, the DoD, and the NSF. For example, diagnostic measurements from the CINDI mission will substantially augment the science return from ground-based observatories such as the Jicamarca Radio Observatory (JRO) in Peru, and the growing global network of GPS receivers. In addition, the polar orbiting sun-synchronous DMSP satellites gather ESF related data at high altitudes along the meridional dimension. The CINDI orbit is ideal for providing comparative data for lower latitudes it cuts through the medium in the zonal direction, thus providing temporal and spatial resolution that is critical to characterizing regions of ESF.

The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS)

TWINS provides stereoscopic viewing of the magnetosphere by imaging charge exchanged energetic neutral atoms (ENAs) over a broad energy range (~1-100 keV) using identical instruments on two widely spaced high-altitude, high-inclination spacecraft. TWINS will enable a 3-dimensional visualization of large scale structures and ion dynamics within the magnetosphere. The first TWINS spacecraft may overlap with the IMAGE mission, providing an early (2005-2006) opportunity for magnetospheric stereo imaging that could evolve into three spacecraft imaging with the launch of the second TWINS in 2006.

TWINS will provide a 3D view of the ring current ions in the magnetosphere. These ions carry much of the energy and most of the mass into and through the magnetosphere. Different from in situ observations, TWINS will provide a dynamic picture of the whole magnetospheric system with a cadence that resolves the radial and azimuthal ion motions. The in situ measurements provided by RBSP, MMS and ITSP, are truth data that can be used to further validate the necessary inversion process that will be applied to the TWINS data to obtain 3D ion flux distributions. These TWINS distributions will provide a global geospace input for space weather models. The 3D ion distributions will enable inferring the inner geospace currents and electric fields which penetrate to low altitudes and high latitudes where they couple energy into the ionosphere-thermosphere system partially driving its space weather.

TWINS supports many of the objectives H and J, as can be seen in the discussion above. TWINS value is greatly enhanced if it is flying simultaneously with RBSP, ITSP and MMS.

Solar Dynamics Observatory (SDO)

SDO will help us to understand the mechanisms of solar variability by observing how the Sun's magnetic field is generated and structured and how this stored magnetic energy is released into the heliosphere and geospace. SDO's goals are to understand the solar cycle, the transfer of energy through the solar atmosphere, and the variable radiation output of the Sun. SDO measures subsurface flows, photospheric magnetic fields, high-temperature solar atmospheric structures, and the extreme ultraviolet spectral irradiance that affects Earth's atmosphere.

Solar magnetism drives the variability that causes most space weather. Helioseismology measures the internal causes of activity. Photospheric and coronal observations trace the evolution of magnetic field structures and the origins of disturbances. The upper atmosphere is highly sensitive to solar EUV variability. SDO's investigations are essential to many phase 1 and 2 achievements relevant to all three SSSC Objectives.

SDO needs to fly in 2008 to provide crucial understanding of solar activity, the solar cycle, and the inputs to geospace. Predictive modeling cannot improve without the improved data SDO will provide. SDO is an essential replacement for the aging SOHO spacecraft.

Interstellar Boundary Explorer (IBEX)

IBEX will remotely sense the global interaction between the solar wind and the interstellar medium, complementing the single point direct measurements now being obtained by Voyager

IBEX places a spinning, Sun-pointing spacecraft in a highly elliptical equatorial orbit with an apogee of 35 RE so that it spends most of its time outside the magnetosphere. The payload includes tightly integrated high and low energy single-pixel neutral atom cameras of very high sensitivity needed to observe the relatively weak but telltale fluxes emitted from the heliospheric boundary region. During the course of a year, the cameras will sweep out the entire sky to form a complete map of the interstellar boundary.

IBEX began development in May 2005 for launch in 2008, which may be in time for correlative operations with Voyager. Voyager 1 recently passed through the solar wind termination shock and into the heliosheath region.

Near-Term SSSC Missions

Radiation Belt Storm Probes (RBSP)

RBSP will focus on the variability and extremes of energetic radiation belt ions and electrons by identifying and evaluating their acceleration processes and transport mechanisms and identifying and characterizing their sources and losses. The RBSP instruments provide comprehensive measurements of the particle phase space densities plus the local AC/DC magnetic and electric fields in the inner magnetosphere where the intense radiation belts reside.

RBSP consist of two small satellites in “chasing” elliptical orbits with low perigees, ~ 5.5 RE , geocentric, apogees and slightly different orbital periods. The different periods generate an orbital evolution that provides both variable radial separations in the same local time frame and local time separations at a range of constant radial distances to separate space-time effects in the radial transport and azimuthal drifts of the particles.

RBSP provides one link in the chain of evidence that tracks the Geospace response to solar and interplanetary sources and variability. ACE, TWINS, SDO, MMS, ITSP and IH Sentinels will fill in many of the other links. Flying together, they would provide a nearly complete picture of geospace, its the external environment and the its responses to solar variability and evolving interplanetary plasma and field structures. RBSP is important to objectives H and J because it provides the observations needed to characterize and develop models of the near Earth space weather. Its data will form the basis for specification of the near Earth radiation environment and its variability on a time scale that meets the needs of the Exploration Visions early operations near Earth.

RBSP data will provide a measure of the magnetospheric energy inputs to the ionosphere and atmosphere important to space station and crew vehicle communications, reentry, and atmospheric drag induced orbit variations. In addition, RBSP observations will also provide new knowledge on the dynamics and extremes of the radiation belts that are important to all technological systems that fly in and through geospace. This includes many platforms that are important to life and society as we rely ever more on space platforms to link us together through communications, to provide Earth resource data and to provide entertainment streams. It is also very important that we understand the space weather in geospace as we resume human exploration because it can impact the many US space assets that play a role in our national security and support human exploration.

Magnetospheric Multi-Scale (MMS)

MMS is the first mission designed from the bottom up to separate space from time at the fine scales needed to understand the reconnection diffusion region. MMS will determine the fundamental physical properties of magnetic reconnection.

MMS is a four spacecraft mission designed to study magnetic reconnection, charged particle acceleration, and turbulence (cross-scale coupling) in key boundary regions of the Earth’s magnetosphere. The primary goal of the mission is to use high time resolution, in situ plasma and fields measurements to determine the micro-scale processes in the exceedingly small (perhaps <100 km thick) diffusion region, where the electrons in a plasma become decoupled from the magnetic field, and the field reconnects. The close spacecraft spacing will also enable exploration of the cross-scale coupling of plasma turbulence in the Earth’s magnetosheath, at the magnetopause, and in the magnetotail. Finally, charged particle acceleration processes associated with magnetic reconnection, turbulence, and electric fields in the outer magnetosphere will be determined using direct measure of the plasma and waves that cause the acceleration. MMS will resolve rapidly moving narrow structures, to yield a full understanding of the factors controlling the rate of reconnection. This will enable a predictive science of space weather, which in turn will allow us to understand energetic processes throughout the solar system.

MMS has recently entered development and its results will be needed as soon as possible as a basis for the predictive models of space weather needed to undertake heliospheric weather prediction in support of Exploration. Magnetic reconnection is a primary source of energy release and particle acceleration in plasmas. No mission has ever been properly instrumented and configured to measure the small-scale features of reconnection in space. Thus, we know little about this fundamental process that drives much of the activity on the Sun, near Earth, and throughout the Solar System.

Ionosphere-Thermosphere Storm Probes (ITSP)

The ITSP mission investigates the spatial and temporal variability of the ionosphere at mid-latitudes. ITSP combines imaging and *in-situ* measurements of the I-T system, and physics based models to inform our understanding. Two LEO satellites, in different local time orbits are required to determine how electric fields, thermospheric winds, and composition vary with local time, and generate dramatic changes of electron density in the main ionospheric layer during storms. An IT imager will fly as a Mission Of Opportunity on another spacecraft to support the LEO measurements by observing global composition changes.

To meet the needs of tomorrow and to go beyond an understanding of the climatalogical behavior of the ionosphere we need to make simultaneous, collocated comprehensive measurements of the global behavior of the IT system. The scientific questions addressed by ITSP have direct relevance to the Vision for Space Exploration and to the needs of society. When we prepare to go to Mars, we must be able to land with precision and communicate with assurance. ITSP informs the design of systems for precision navigation and communication without requiring that we build at Mars the equivalent of the Earth's network of ionospheric observatories. ITSP will allow us to characterize, understand, and predict plasma density gradients that degrade augmented GPS systems, and lead to the mid-latitude ionospheric irregularities which produce scintillation of radio signals.

ITSP was designed to overlap with the SDO and RBSP missions flying in the 2008-2015 timeframe. The current schedule places ITSP at solar maximum and in the declining phase of the solar cycle – times when the ionosphere is both enhanced and disturbed. ITSP will fly during the phase of the solar cycle that is the most stressing both from the standpoint of technical systems and models. ITSP results will be available in time to guide the concept of operations for precision landing on Mars and communications (surface-surface and surface-space).

Under current NASA funding guidelines, GEC would launch in a similar timeframe (2017 with a two year lifetime) to ITSP, so the missions would potentially overlap. The GEC mission is focused on very different scientific objectives in a different altitude and latitude regime from ITSP. Each mission provides scientific insight that is unique. An overlap in the mission timeframes provides synergistic opportunities because GEC measures the high latitude drivers that contribute to the middle and low latitude response measured by ITSP. However, because of the urgency of each of these missions, each should fly as early as funding permits, regardless of any loss of overlap with the other.

Inner Heliospheric Sentinels (IH Sentinels)

The four Inner Heliospheric Sentinel spacecraft flying in various formations will detect how structures change in space and time during the transit. IH Sentinels investigations will discover, model, and understand the connection between solar phenomena and geospace disturbances.

Interactions in interplanetary space make the linkage between point sampled 1 AU measurements and their solar sources difficult or impossible. IH Sentinels science is important to understanding which disturbance will be geoeffective and for developing predictive capability. The interactions relate to particle acceleration, the drivers of space weather and characterization of the extreme conditions near Earth and throughout the heliosphere. Most space weather evolves as it passes through the inner heliosphere. Understanding this influential region of space is required for safe and productive use of space. IH Sentinels should fly in conjunction with SDO and will contribute to understanding gained by the Geospace Storm Probe missions. In an extended mission they will provide essential information about material that eventually reaches SWB or other spacecraft at 1 AU and beyond

Solar Probe (SP)

Solar Probe is the first flight into the Sun's corona, only 3 solar radii above the solar surface. Solar Probe's instruments measure plasma, magnetic fields and waves, energetic particles, and dust that it encounters. They also image coronal structure surrounding Probe's orbit and in polar structures at the coronal base. Probe makes two passes into the corona, separated by 4.5 years, exploring why the corona changes its whole form over the solar cycle.

The corona is heated to millions of degrees by poorly understood processes governed by its magnetic field. The UV radiation from the hot solar atmosphere affects the chemistry of the atmospheres of the Earth and other planets. The boundary where the corona accelerates to the solar wind governs the heliosphere and its interactions with the planets and the interstellar medium. That boundary is also critical to the release of solar disturbances that travel throughout the solar system, to the Earth and other planets, producing energetic particle events and magnetospheric storms. Probe will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity. Accurate prediction of events that disturb the Earth's human systems and deepspace explorers require this understanding.

One factor sets the placement of Solar Probe in the Roadmap: Probe is the most technically challenging mission attempted. It must function in the cold and intense particle radiation of its orbit-shaping flyby at Jupiter, and in the heat and high-speed dust impacts of the solar corona. The path to meet the technical challenges is now well defined and Solar Probe is ready for a mission start. Probe can only be achieved with specific budget augmentation because the work to ensure surviving its difficult environment keeps it more costly than any line mission.

Solar Orbiter (SO)

Solar orbiter is a European Space Agency (ESA) mission with U.S. participation that will fly as close as 45 solar radii to the Sun in order to study the solar atmosphere with unprecedented spatial resolution (~100 km pixel size).

Its science goals are to characterize the properties and dynamics of the inner solar wind, to understand the polar magnetic fields using helioseismology, to identify links between activity on the Sun's surface and coronal disturbances using co-rotating passes, and to fully characterize coronal regions from high inclination orbits. Using Venus gravity assists, the orbital inclination will shift over time providing the first high latitude views of the solar poles. Solar Orbiter will provide key components to NASA's LWS program by understanding the causes of Space Weather and thus will answer science questions of Objective H. It will also provide data to increase our fundamental understanding of particle acceleration and the role of the solar dynamo in structuring the solar magnetic field (Objective F).

Both science areas are essential in developing a short and long term predictive capability for the Exploration Vision (Objective J). Solar Orbiter is positioned to fly in the 2015-2025 (Phase 2) time frame which will coincide with Inner Helisopheric Sentinels to continue the system science of our Great Solar Observatory.

Geospace Electrodynamic Connections (GEC)

GEC will determine the fundamental processes coupling the ionosphere and thermosphere. The upper atmosphere is the final destination of the chains of fields, particles and energy that start at the Sun, transit the heliosphere, and are modified by the magnetosphere and upper atmosphere. To transform and inform our understanding of this fundamental question a formation of 3-4 spacecraft must be sent to resolve the spatial structures and time variations, repeatedly and systematically, into the depths of the atmosphere to this transition region: 130 to 180 km. The spacecraft will have complete instrument packages that measure both the magnetosphere energy/momentum inputs at high latitudes and the atmosphere-ionosphere responses.

GEC will transform our understanding of the chain of events from the sun to the atmosphere by providing for the first time, comprehensive, collocated, simultaneous atmospheric measurements, the models with which to interpret them, and context setting measurements of the Sun, heliosphere, and magnetosphere. This region cannot be understood without actually making the in situ observations. GEC does this using proven technologies, such as formation flying, to unravel the spatial and temporal coupling of the transition region phenomena in a reconfigurable observatory.

GEC will transform our understanding of fundamental processes in the upper atmosphere. It will also enable practical applications relevant to Protecting our Home in Space, and the Outward Journey. Dipping the spacecraft from the collisionless into the collisional regime of the atmosphere provides an analog for aerobraking and aerocapture operations at Mars.

Under current NASA funding guidelines, GEC is planned for launch in 2017, with a two -year prime mission lifetime. It is possible that GEC will overlap with the ITSP mission, with corresponding synergies that are discussed under the ITSP description. However, each mission provides unique measurements and insights, and neither one should be delayed for the sake of overlap.

Intermediate-Term SSSC Missions

Auroral Acceleration Multi-Probe (AAMP)

The Auroral Acceleration Multi-Probe (AAMP) mission is designed for extremely high time resolution measurements of particle distributions and three-dimensional electric and magnetic fields in situ within the Earth's auroral acceleration region. The auroral acceleration region provides a unique laboratory for the study of acceleration processes, both because it reveals many of the critical processes and because it is readily accessible to measurement. Our basic understanding of particle acceleration in parallel electric fields and kinetic Alfven waves, as well as the structures that support parallel fields, have come from in situ auroral observations. To make the progress required for a predictive understanding requires simultaneous measurements both along and perpendicular to magnetic fields. The AAMP four satellite mission is designed to provide the needed conjunctions through a careful orbit strategy.

One of the key goals of Objective F is providing the detailed understanding of the processes that accelerate particles to high energies that will be necessary to predict fluxes of high energy particles throughout the solar system. This predictive capability is the goal of RFA J.3. In addition, by providing a better understanding of energetic particles in the Earth's space environment, AAMP is also important to Objective H because it will enable mitigation of impacts on space assets, and, by quantifying the auroral input to the ionosphere/thermosphere, it will improve models of lower latitude composition and variability of the ionosphere, which affect communications/navigation activities.

The fundamental understanding of acceleration processes is critical to the NASA SSSC goals and, thus, the mission should be flown as soon as possible. Its placement in the mission queue indicates the need to inform activities that occur in the intermediate time frame.

DOPPLER

DOPPLER consists of a suite of small, lightweight, moderate resolution spectral imagers (UV/EUV imaging spectrograph, 2 EUV imagers, and a Magnetograph) to detect, observe and study remotely all of the relevant signatures of solar activity responsible for space weather events and disturbances.

DOPPLER addresses issues directly relevant to supporting the Vision for Exploration by enabling improved nowcasting and future forecasting of solar activity by identifying and developing new precursor signatures of CME initiation and onset, flare eruption, and flare initiated SPEs. The DOPPLER mission enables improved nowcasting and forecasting of solar activity by providing improved understanding of the physical processes and mechanisms of energy storage and release on the Sun. Measurements of motions and changes in nonthermal velocity distributions in the lower corona and chromosphere are crucial to understanding and separating various models of CME initiation and onset. Depending upon the specific physical process, Dopplergrams and other derived data products are likely to be the most reliable indicators that a specific region is about to erupt.

The DOPPLER mission should fly in the early part of Phase 2 (2015-2020), with overlap with SDO to identify and develop new solar activity precursor signatures necessary to protect astronauts during surface EVAs on the Moon (late Phase 2). The small, lightweight instrumentation developed by DOPPLER would then be available for Phase 3 missions required to provide nowcasting and forecasting capability at Mars and beyond.

Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)

GEMINI is a mission that will provide the first 3-dimensional observations of the global Geospace dynamics in response to external solar drivers and internal coupling. Stereoscopic views of the radiation belt associated ring current and thermal ions of the plasmasphere, simultaneous images of the aurora in both hemispheres, and coordinated ground based observations are used to determine the coupling dynamics between the ionosphere, ring current, and plasmasphere and to discover the important feedback and dissipative mechanisms between these regions.

The power of GEMINI is that imaging this complex coupled system to unravel its macro-scale interactions simultaneously provides the global context for correct interpretation of *in-situ* observations. It is to magnetospheric space-weather what the Solar Terrestrial Relations Observatory is to the solar-wind observations. The discoveries from this mission are applicable to understanding fundamental processes at work not only in Geospace but other magnetized planetary systems and thus are important to Objective F. Global Geospace observations are needed to provide the system level context for nowcasting and prediction of the plasma environment where exploration activities are occurring within Geospace. In addition, these results are significantly augmented when coupled with inner heliospheric and solar disk observations. The conjugate auroral observations are essentially the "footprints" of the magnetosphere and therefore provide the magnetospheric configuration to distances beyond the lunar orbit. For these reasons GEMINI is important to Objective J.

Operating GEMINI in conjunction with the RBSP and ITSP missions is ideal as documented in the LWS Geospace definition report. However, even without mission overlap, the system level understanding of the coupling between regions in Geospace that creates, evolves and annihilates radiation belts and how that induces and impacts ionospheric variability is extremely significant to operational space based assets that society has become so dependent on. As such, GEMINI is important to objective H.

Heliostorm (HS)

The Heliostorm mission would measure the solar wind and heliosphere state "upstream" of the Earth and Moon. Through the use of breakthrough solar sail technology, it would fly 50% further from the Earth (farther upstream) than the current ACE measurement at the Earth-Sun L1. A set of *in-situ* measurements then would provide 50% greater warning time (compared to ACE) of CMEs and shock-accelerated energetic particles. In conjunction with other assets outside the Earth's magnetosphere, the mission would determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes.

Heliostorm safeguards our outward journey by providing an input that is absolutely vital to the prediction of space weather in cislunar space. Astronauts on the lunar surface will benefit greatly as the enhanced warning time will permit reaction to actual upstream conditions measured remotely by Heliostorm. The solar wind input to the Earth is required by all models of the Earth's magnetosphere, and would be provided by Heliostorm or a conventional L1 monitor.

Heliostorm could be flown 5-6 years after a successful Solar Sail Flight Validation (Sail Demo). Heliostorm (or a conventional L1 monitor) must be flown in time to replace the current ACE/Wind configuration. This suggests a launch in the 2016-2020 time frame.

HIGO

HIGO will establish the 3-D structure of the interaction region between the heliosphere and the local galactic environment. It will determine the nucleosynthetic status of a present-day sample of the galaxy and explore the implications of this knowledge for big bang cosmology, galactic evolution, stellar nucleosynthesis, and the birthplace of the Sun and solar system. HIGO will characterize the physical state of the local interstellar cloud and the nature of its interaction with the heliosphere, map the location and establish the characteristics of the extended inner source of neutrals in the heliosphere, and set limits on the dust density in the heliosphere. HIGO will search for molecules and the building blocks of life liberated by sublimation of small comets, asteroids and grains, detectable through measurement of pickup particles.

The spacecraft will use a Venus-Earth Gravity Assist to attain a final 1 x 4 AU equatorial orbit. A spin-stabilized spacecraft supports imaging the heliopause and the solar wind termination shock, determination of the isotopic and elemental composition of the neutral portion of the interstellar gas; measurement of the flow direction, speed and temperature of interstellar atoms, and the composition and radial profiles of extended inner source pickup ions. HIGO also will detect time-dependent interactions of large-scale structures with heliospheric interfaces.

HIGO is important for understanding the fundamental interactions of plasmas and neutrals (F.3), the role stellar and interstellar fields play in planetary habitability (H.4), and the variability of galactic cosmic rays (J.1).

HIGO is an important precursor for optimizing the Interstellar Probe flagship mission and will benefit from the knowledge gained by IBEX and Pluto/Kuiper. HIGO is a small mission that should be flown during phase 2.

Ionosphere Thermosphere Mesosphere Waves (ITMW)

ITM Waves is designed to observe the sources and sinks of gravity waves, including modes of interaction between multiple wave sources, as well as modes of interaction with the neutral and ionized constituents of the atmosphere, and with tides and the zonal mean circulation.

The wave processes studied by ITM Waves are fundamental to the coupling between distinct altitude regions, and to the overall dynamics of the Earth's atmosphere. These processes play a key role in the response of the atmosphere to solar storms. Gravity waves are also thought to be a critical factor in preconditioning the ionosphere by contributing to the initial conditions necessary for plasma instabilities to form near the magnetic equator, and perhaps also at mid-latitudes. These unstable conditions can result in the formation of large-scale depletions in the plasma density, coupled with small-scale irregularity formation and severe radio wave disruptions. The ITM-Waves mission will thereby enable further development of the theory and models necessary for comprehensive understanding of the phenomena. Insight into these phenomena in geospace may help to mitigate issues related to aero-braking and aero-capture in the Martian atmosphere, so ITM-Waves is pertinent to exploration mission requirements.

ITM-Waves should follow GEC and ITSP as closely as possible in time because these two missions provide key information on how the atmosphere responds to solar energy, storms, and substorms. Together the three missions are synergistic in that they address the overall goal of understanding the Earth's response to solar energy. If possible, ITM-Waves should overlap in time with the Mars Dynamics mission because additional synergies would be created by studying the responses of both atmospheres to simultaneous solar forcing.

L1-Sentinel

In situ observations from the Earth-Sun L1 point are essential to understanding geospace and provide about one hour of warning of disturbances traveling toward Earth in the solar wind. The essential quantities are plasma, particles and fields measurements. Enhancing capabilities include radio sensing, composition and high-energy particle detection, and even solar observations, though these can often be accomplished from other vantage points.

Without upstream information the state of the magnetosphere cannot be understood. Models of propagation in the inner heliosphere need a reference at 1 AU against which to test their models. Spatial variations in structures around L1 is not well understood. Data from L1 is needed at all times to provide adequate warning for many operational users in addition to NASA scientists.

The timing of this mission depends upon future assets launched by NASA and other agencies and the continued functioning of existing spacecraft. The existing Great Observatory provides L1 observations and some future mission must do the same. Partnerships may be the preferred method for satisfying the need for observations from L1. The possible flight of Heliostorm, an Earth Science L1 mission, or collaboration with the IH Sentinels or SWB missions may provide additional options.

Magnetospheric Constellation (MC)

MC will employ a sensor web of ~36 spacecraft to describe the temporal and spatial structure of complex processes occurring throughout vast regions of the Earth's magnetosphere, including most of cislunar space between the Earth and its Moon. In situ plasma, magnetic field, and energetic particle observations, and possibly imaging, will be used to distinguish between nonlinear internal dynamics of the magnetosphere and global responses to varying solar wind conditions. The data will be provided on spatial and temporal scales sufficient to enable close cooperation with state-of-the-art numerical simulations capable of describing where magnetic flux, mass transport, energy conversion, and dissipation occur. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

MC is the first sensor web for space weather in geospace and is focused on Earth's dynamic magnetotail, the origin of severe storms in geospace. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

Understanding the mass and energy flow in the magnetotail and throughout the rest of the magnetosphere is an unresolved issue of fundamental importance. With the flight of the New Millennium ST-5 mission, many of the technological obstacles of this mission have been addressed. It should be the next STP mission after GEC, which puts it in the Phase 2 mission queue.

Sun Earth Coupling by Energetic Particles (SECEP)

SECEP seeks to understand and quantify the impact on atmospheric composition, in particular of odd nitrogen, odd hydrogen, and ozone, by solar energetic particle precipitation (EPP). EPP is thought to be a significant source of ozone destruction through production of high altitude odd nitrogen and odd hydrogen compounds which can be transported lower in altitude where they will catalytically destroy ozone. In order to understand these processes SECEP will measure the precipitating energetic particle influx as well as the descending odd nitrogen and odd hydrogen compounds and ozone densities. Other relevant parameters which affect these processes such as temperature and winds will also be observed.

SECEP is crucial to SSSC goals because it studies a key link between solar energy and its impact on the habitability of Earth. Dramatic effects of EPP on stratospheric and mesospheric ozone have been demonstrated by recent observations. The impact is greatly magnified by the long lifetime of odd nitrogen compounds at stratospheric altitudes. The decent of the odd nitrogen compounds from the ionosphere where it is created to the mesosphere and stratosphere occurs primarily in the polar night where destruction by photolysis can not occur. Therefore SECEP provides valuable fundamental science on how atmospheric regions are coupled.

Because ozone plays a key role in Earth's habitability by shielding the population from harmful UV radiation, SECEP is a high priority mission. SECEP should follow GEC and ITSP closely in time because these two missions provide key information on how the atmosphere responds to solar energy and the three missions together are synergistic for the overall goal of understanding the Earth's response to solar energy and the effect on the human population.

Solar Energetic Particle Mission (SEPM)

SEPM – the Solar Energetic Particle Mission will determine how, when, and where solar energetic particles (SEPs) are accelerated and help determine how the solar wind is accelerated. A large aperture UV coronagraph-spectrometer and a large aperture visible light coronagraph-polarimeter will observe the corona from 1.15 to 10 solar radii. SEPM instrumentation will be about 100 times more sensitive than current coronagraphs. New diagnostics will determine velocity distributions for electrons and minor ions and derive magnetic field strengths in coronal streamers and coronal mass ejections (CMEs). SEPM will measure critical plasma parameters in pre- and post-shock CME plasmas including suprathermal seed particle populations and it will characterize upstream turbulence which is believed to play a critical role in particle acceleration.

When combined with an integrated theory and modeling program, SEPM measurements will be used to significantly advance our fundamental understanding of energetic particle acceleration (Objective F). Ultimately this understanding will be used to develop a predictive capability for the flux, energy spectrum, and composition of SEP's – thus enabling the Exploration Vision (Objective J) and providing information about the solar sources of Space Weather that affect our home planet (Objective H).

Ideally the remote sensing SEPM spacecraft should fly in concert with a near-Sun spacecraft (e.g. Inner Heliospheric Sentinels or Solar Orbiter) that will detect energetic particles before significant scattering in the interplanetary medium. SEPM should start as early as possible during a period of high solar activity to inform the development of SEP hazard prediction before human explorers return to the moon.

The possible combination of the SEPM and Doppler missions promises a powerful tool for understanding the physical processes of solar energetic particle acceleration and relating SEPs to flares on the disk and to coronal mass ejections that propagate out into interplanetary space.

Solar Polar Imager

Solar Polar Imager will provide critical missing observations need to understand the solar cycle and the origins of solar activity. It is a single spacecraft mission that uses a solar sail to achieve a final 0.48 AU circular orbit with a 75∞ inclination to the ecliptic. The spacecraft carries a magnetograph -Doppler imager for high-resolution helioseismology and surface magnetic field measurements of the polar regions, a coronagraph for polar views of the corona and CMEs, and in situ particles and fields instrumentation for solar wind and energetic particle observations.

This mission is necessary to understand the solar dynamo because the polar orbit enables us to measure the convective surface, subsurface and deep interior flows that control the solar dynamo and to observe the correlation between the flows and solar magnetic field activity and evolution. The rapid four-month polar orbit also allows us to observe the relationship between solar activity and solar wind structure and energetic particles at all latitudes, crucial for characterizing the near-Sun source region of the space environment. In addition, the polar magnetic field measurements are needed to provide the solar surface boundary conditions for the global MHD models used for space weather prediction.

Because this mission requires a solar sail to achieve the near-polar orbit, it has been placed after the Heliostorm mission that will be the first science mission utilizing solar sail propulsion. The Telemachus mission can also address the goal of characterizing the space environment at all latitudes and give some information on the magnetic fields and flows in the polar regions. Thus at some point, the community may choose between Solar Polar Imager and Telemachus, based in part on the maturity of the solar sail propulsion technology.

Solar Weather Buoys (SWB)

SWBs are ~15 small spacecraft distributed every ~20∞ in ecliptic longitude around the Sun at 0.9 AU, identically instrumented with plasma, magnetic field, energetic particle, and hard xray detectors.

The initial function of SWBs is to answer definitively the yet un-resolved basic scientific question: what is the spatial longitudinal extent and evolution of the major Solar Energetic Particle (SEP) and Coronal Mass Ejection events that occur during the maximum of the solar cycle? Their complementary function is to give prompt and unambiguous warning of the injection of biologically damaging doses of high-energy particle radiation for astronauts exposed on the surface of the Moon or in transit to the surface of Mars.

SWBs will attack the fundamental problem (F.2) of bringing our understanding of the acceleration and propagation of SEPs and CMEs from the Sun to 1 AU up to the level of prediction. In its complementary role, it will safeguard our outward journey (J.2) to the surfaces of the Moon and Mars.

By launching in 2022, the 5-year deployment phase will be completed in time to catch the rise-to-maximum phase of the solar cycle (2027-2030). During the remainder of the solar cycle (2031-2036), SWBs will paint a definitive scientific picture of how large SEPs and CMEs propagate from the inner heliosphere (being simultaneously observed by IH Sentinel, Solar Orbiter, and solar imagers) to 1 AU and beyond towards Mars orbit at 1.4 AU. During this time SWBs' prompt warning capability will be honed and perfected so that they will function with high reliability at the anticipated launch time for the manned mission to Mars (2035).

Telemachus

Telemachus will increase our understanding of the changing Sun and its effects throughout the Solar System. It reveals through helioseismology how convection and rotation couple and magnetic flux accumulates in the polar regions. (F.4) It will uncover the mechanisms in the polar regions of the Sun that accelerate the solar wind and energetic particles and expel plasma and magnetic fields (H.1, J.2). From it's high ecliptic latitude orbit, it can exploit the polar viewpoint to examine the distribution of radio and x-ray emission simultaneously from all solar longitudes. The mission will determine the physics of the strongest stream/stream plasma interactions and transient shocks where they are first formed in the heliosphere. (J.3)

Telemachus shares many objectives with the Solar Polar Imager. Telemachus' orbit provides less frequent and more distant coverage of the solar poles than SPI, limiting it's coverage of the events of interest. However, it does not require solar sails for implementation.

Telemachus should fly in conjunction with the Solar Wind Buoys and the SEPM and IH Sentinels missions for optimum effectiveness. Collaborations with either the Farside Sentinel or SHIELDS mission make it's scheduling late in Phase 2 appropriate. Earlier flight would provide crucial information about the Sun's activity cycle sooner.

Future SSSC Missions

Dayside Boundary Constellation (DBC)

DBC will determine the global topology of magnetic reconnection at the magnetopause. It is a network of ~30 Sun-pointing, spinning, small spacecraft, separated by ~1 RE, that skim both the dawn and dusk sides of the dayside magnetopause. The multi-spacecraft provide simultaneous comprehensive observations of boundary phenomena including turbulence over a wide range of latitudes and local times. Three spacecraft are boosted to have apogee outside the bow shock to provide continuous monitoring of the foreshock-preconditioned solar wind input.

This mission addresses critical unresolved questions about the transfer of energy across the magnetopause boundary. It also will robustly measure the global magnetic field topology on the Earth's dayside magnetopause, something which has not been done before.

MagCon is a precursor mission to DBC, as it will have a constellation of spacecraft in the magnetospheric equatorial plane. Therefore, DBC should be in the Phase 3 mission queue.

Farside Sentinel (FS)

Farside Sentinel is a solar observer with a spacecraft placed at 1 AU viewing the far side of the Sun. It will provide new knowledge about the solar dynamo, solar activity, and the dynamic space environment in general. It contains both remote sensing and in situ instruments. Remote sensing instruments include a magnetograph-Doppler imager and a radio science package for coronal sounding. Its location at about 180 degrees from Earth allows, in conjunction with similar observations from near Earth, helioseismological measurements of the deep interior flows that are thought to drive the dynamo. The magnetograph will provide more longitudinal coverage of the Sun so that the evolution of solar magnetic fields and active regions can be observed for longer times. Farside Solar Observer also provides an additional in situ observation post for the space environment. The in situ instrument package would be similar to that on the STEREO spacecraft.

Farside Solar Observer provides information crucial for understanding fundamental processes (Objective F) and for developing the capability to predict the space environment. Farside will aid predictions of space weather and provide inputs for SWB, MARS, and high-latitude solar observatories.

While it would be advantageous to have this (or the SHIELDS) mission earlier, it was placed in Phase 3 because it was considered lower priority.

Inner Magnetospheric Constellation (IMC)

IMC will determine the interaction among the radiation belts, ring current, plasmasphere, and outer magnetosphere. It is multiple spacecraft in at least two ecliptic plane "petal" orbits. Large day/night and dawn/dusk asymmetries exist in the inner magnetosphere and complicate the global specification of particles and fields. Through simultaneous measure of radial and longitudinal variations in the radiation belts, the temporal and spatial asymmetries will be resolved.

The *in-situ* measurements from these multiple positions allow the construction of comprehensive "weather maps" of the inner magnetosphere (1.5-12 Earth radii) that evolve in response to Sun-induced disturbances. This spacecraft fleet focuses on detailed specification of the orbital environment of most spacecraft and manned missions, to determine in detail the origin and evolution of particle populations and their interaction with the evolving electro-magnetic field during magnetic storms.

These observations extend the radiation belt storm probe results by making simultaneous maps of the radial as well as the longitudinal variations in the radiation belts. It should fly after RBSP, and probably after GEMINI, putting it into Phase 3 of the mission queue.

Interstellar Probe (ISP)

Interstellar Probe is the first mission that will leave our heliosphere and directly sample and analyze the interstellar medium. It is a single spacecraft that will use an advanced in-space propulsion system such as a solar sail or nuclear electric propulsion to reach the upstream interstellar medium at a distance of 200 AU within about 15-20 years. This spacecraft will carry the first payload specifically designed to directly determine the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields.

On its way, it will provide only the second opportunity after Voyager to directly observe the thick region of interaction between the solar wind and the interstellar medium, from the termination shock to the heliopause and beyond. This region plays a central role modulating the Galactic Cosmic Ray flux and in the creation of the anomalous component and understanding this modulation will help increase the productive and safety of human explorers. Additional advanced instrumentation used en route could determine the nature and chemical evolution of organic molecules in the outer solar system and interstellar medium and measure the cosmic infrared background (CIRB) radiation normally hidden by the Zodiacal dust.

Because this mission is enabled by advanced propulsion, it has been place in Phase 3. The Solar Polar Imager mission would provide a technology demonstration of the solar sail propulsion system needed for Interstellar Probe. It is expected that additional resources would be needed for this mission because of its 15+ year lifetime coupled with the need for advanced propulsion.

Tropical ITM Coupler (ITMC)

T-ITMC will explore how neutral and plasma interactions distribute energy within and between Earth's low-latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

T-ITMC will improve our understanding of the influence of geospace on Earth (Objective H), explore the fundamental interactions between atmospheric plasmas and neutrals across scales from 1 cm to 1000 km (Objective F), and provide a fundamental database of atmospheric dynamics (winds, gravity waves, and ion drifts) that can be applied to exploration of other planets (Objective J).

It should be flown after the GEC and ITSP missions and should be reconfigured as necessary to address unanswered questions from those missions. In the event of limited flight opportunities, the importance of T-ITMC can be evaluated in light of the GEC and ITSP results.

Magnetic TRAnsition region Probe (MTRAP)

The primary objective of MTRAP is to measure the build up and release of magnetic energy in the solar atmosphere. MTRAP will measure the vector magnetic field from the photosphere to the magnetic transition region, where the solar atmosphere changes from being plasma to magnetic field dominated. MTRAP will also obtain simultaneous plasma diagnostics of the magnetic transition region with UV/EUV imaging spectrograph measurements. MTRAP has two orders of magnitude greater collecting area and one order of magnitude improvement in angular resolution over Solar-B and will greatly improve our ability to follow rapid changes in the magnetic field geometry. MTRAP is centered around a very large solar optical telescope with a 6m aperture, providing over 100 times the collecting area and 10 times the angular resolution (0.05 arcseconds) of Solar-B.

MTRAP addresses fundamentally important questions and issues related understanding magnetic reconnection and micro-scale instabilities in the chromosphere/corona interface on the Sun.

MTRAP should fly early in Phase 3 of the STP line (2025-2035), benefiting from knowledge learned from Solar-B and SDO.

Reconnection and Microscale Probe (RAM)

The Reconnection and Microscale (RAM) mission is a next generation, high resolution solar mission focused on understanding the basic small-scale processes in hot magnetized plasmas that are ubiquitous throughout the universe. In hot magnetized plasmas the physical processes governing the dynamics take place on remarkably small spatial and temporal scales. RAM addresses several fundamental questions such as what are the mechanisms and magnetic topology that lead to reconnection, what micro-scale instabilities lead to global effects and how do magnetic stresses form and release in the solar corona? RAM includes a 0.02 arcsec/pixel EUV imaging telescope, a 0.1 arcsec/pixel UV/EUV imaging spectrograph, and a small x-ray calorimeter to perform simultaneous high resolution imaging and imaging spectroscopy to understand the small scale dynamic processes and mechanisms of reconnection on the Sun.

RAM addresses fundamentally important questions and issues related understanding magnetic reconnection and micro-scale instabilities on the Sun.

RAM should fly as one of the first missions in Phase 3 of the STP line (2020-2025), benefiting from knowledge learned from Solar-B and SDO.

Solar Heliospheric & Interplanetary Environment Lookout for Deep Space (SHIELDS)

Solar Heliospheric and Interplanetary Environment Lookout in Deep Space (SHIELDS) is a new mission concept developed specifically in response to the Vision for Exploration to help ensure the safety and productivity of human and robotic explorers.

SHIELDS places two spacecraft in fixed locations 120° from Earth in order to view the entire solar surface and to determine the direction of propagation of CMEs anywhere in the inner heliosphere. Remote sensing instruments include coronagraphs (for observing CME onset and propagation), magnetographs (to observes evolution of the surface magnetic fields and active regions) and EUV telescopes (to observe flare activity). Observations of the entire solar surface should help enable the predictability of longer periods that are “all clear” of solar activity (Objective J). The spacecraft would also carry in situ instruments similar to those on STEREO and FARSIDE to observe the CMEs and associated solar energetic particles, also in support of Objective J.

This mission could replace the Farside Sentinel by providing the farside views of the Sun. To provide the helioseismology needed to understand the dynamo and origins of solar activity (Objective F), a Doppler-magnetograph would also be needed. This would be a more costly mission than Farside since it uses two spacecraft, and, at some point the community will decide which of the two to pursue. Like Farside, this mission has been place in Phase 3. It will support RAM, SWB, MARS, high latitude solar observations, and provide inputs for studies of impacts on planets other than Earth.

Stellar Imager (SI)

Stellar Imager (SI) is a mission that will obtain the first direct images of surface magnetic structures in sun-like stars. It will image the evolving dynamo patterns on nearby stars by repeatedly observing them with ~1,000 resolution elements on their surface using UV emission to map the magnetic field. SI will achieve at least 30 resolution elements on stellar disks with 1-min. time resolution in one or more broad optical pass bands.

The power of SI lies in its ability to provide information on the dependence of the dynamo on stellar properties, and enable by its population study dynamo model validation within years rather than many decades. It therefore gives solar physicists a unique ‘laboratory environment’ within which to test predictive models of stellar activity. SI thus addresses the goals of the Exploration Initiative under Objective J by improving long-term space weather forecasts throughout the heliosphere to guide vehicle design and mission planning, and forecasts of extended periods for safe construction at Moon, Mars, Earth-Moon L1, Sun-Earth L2, and LEO staging orbits. By observing planet harboring stars and their evolving environments it will also provide an improved understanding of formation of planetary systems and habitability zones of extra-solar planets. Stellar Imager provides crucially needed information for several of the SSSC Objectives by observing patterns of magnetic activity and underlying atmospheric structure of a population of stars to compare with the sun. It supports Objective F by enabling an understanding of the creation and variability of magnetic dynamos, Objective H by promoting an understanding of the causes and subsequent evolution of activity that affects Earth's space climate and environment and how the habitability of planets are affected by solar variability.

SI should fly early in the Phase 3 mission window (near 2025) to provide the information critical to our planned exploration activities as humans head out through the potentially dangerous interplanetary environment whose character is controlled by the sun.

Partnership Missions

Aeronomy and Dynamics at Mars (ADAM)

Aeronomy and Dynamics at Mars (ADAM) will determine the direct, dynamic coupling of a dusty atmosphere with the solar wind. It is a single spacecraft that will orbit Mars, taking in situ and remote sensing data of the upper atmosphere, ionosphere, and solar wind. Instruments will measure the composition, thermal profile, and circulation in the Martian upper atmosphere. Mars Aeronomy will determine the sources and sinks of ionospheric plasma, its coupling to other regions of the atmosphere, and its to the solar wind.

The dynamics, evolution, and fate of the Mars upper atmosphere addresses fundamental science questions as well as providing pertinent information for manned flights to Mars. Aerobraking and aerocapture require a detailed knowledge of the Martian upper atmosphere, as well as an understanding of how and why the atmosphere varies, for hazard prediction and risk mitigation.

This is a high priority mission with direct relevance to the manned flight component of the Vision for Space Exploration. It should be flown as soon as possible in order to allow time for the scientific investigations of the Mars upper atmosphere to progress to a point of transferring the lessons learned from ADAM to the manned flight program with sufficient lead time to impact mission development. Therefore, it should be a Phase 1 or early Phase 2 mission.

Jupiter Polar Orbiter/Juno

JPO places a spinning radiation hardened spacecraft in polar elliptical orbit around Jupiter at 75° inclination. The payload includes fields and particles instruments, planetary imagery and radio science. Measurements will be made of the Jovian auroral acceleration regions and radiation belts, the polar magnetic field and plasma waves. Radio occultations of the ionosphere and atmosphere will determine their characteristics.

JPO will conduct a comparative test of magnetospheric models in a case where planetary rotation is dominant over the solar wind interaction in powering the system.

JPO timing relative to other missions is non-critical but the mission is highly complementary to other missions that support Exploration of the terrestrial planets, for comparative purposes.

L1-Earth-Sun

The L1 Earth-Sun mission will provide the first comprehensive and continuous observation of the Earth's whole day side atmosphere, together with measurements of the contributions to the critical solar spectral irradiance that drive the upper atmosphere.

The Earth-viewing portion of the mission consists of a combination of spectrometers in an extended wavelength range (58 nm to 2.4 mm), with high spatial resolution on the entire sunlit Earth disk. The solar portion of the mission consists of a UV/soft x-ray irradiance spectrometer, an imaging bolometer, and a UV/EUV imaging spectrograph to explain the irradiance phenomena that affect Earth's atmosphere by providing identification and realistic assessment of the contributions of evolving solar activity features to total spectral irradiance. The mission also includes magnetometer capable of high time resolution measurement of magnetic field fluctuations and shocks, and two energetic particle analyzers capable of measuring energy resolved charged particle spectra.

By observing simultaneously the Earth, the Sun, and the solar wind, the L1-Earth-Sun mission will enable the first detailed exploration of the couplings within the Earth-Sun system. It fulfills a fundamental and critical need in the S3C Strategic plan with cross-cutting synergistic objectives relevant to understanding fundamental processes which influence Earth's climate as well as strong relevance to the Vision for Exploration by improving our understanding necessary for solar activity prediction and its impact on the Earth.

The L1-Earth-Sun mission should fly in the early part of Phase 2 in order to maximize overlap with SDO and GEC. SDO provides complimentary information regarding solar energy deposition while GEC provides in situ observations of the Earth's upper atmosphere that strongly compliment and partially validate the L1-Earth-Sun remote observations. Flying L1-Earth-Sun in early Phase 2 also permits the timely replacement of key existing assets at L1.

Lunar Reconnaissance Orbiter

LRO is conceived as an advance exploration of the moon to prepare for a human return there with longer duration visits than previously achieved. It will contain an investigation for monitoring the radiation environment that will be encountered by astronaut-explorers.

LRO measurements will provide important information about the practical consequences of cosmic ray, solar energetic particles, and magnetotail particle acceleration for long term human presence on the moon.

LRO is needed in the near term to refresh and update our knowledge of the moon and its environments. The radiation environment in particular needs to be better documented, particularly for storm events in which potentially lethal radiation levels are expected.

Mars Atmospheric Reconnaissance Survey (MARS)

The Mars Atmospheric Reconnaissance Survey (MARS) mission will provide a robust assessment of the upper atmosphere of Mars to enable safe human space flight to that planet. It will consist of a comprehensive package of in situ and remote sensing instruments to quantify the dynamics and chemistry throughout the Mars atmosphere. It could be one or several spacecraft, depending on what is thought to be needed to resolve the remaining questions about the Mars space environment.

This mission will provide as complete a set of measurements as possible to answer any remaining questions about the Mars upper atmosphere and its interaction with the solar wind before manned flights to Mars begin.

It should fly after ADAM, but before astronauts go to Mars. Therefore, it is part of the Phase 3 mission queue.

Mars Science Laboratory (MSL)

MSL, the next NASA Mars rover mission, is scheduled to launch in 2009 with the overall science objective to explore and quantitatively assess a potential habitat on Mars. The specific objectives include assessing the biological potential of the environment, characterizing the geology of the landing region, investigating planetary processes of relevance to past habitability, including the role of water, and characterizing the broad-spectrum of the surface radiation environment, including galactic cosmic radiation, solar proton events, and secondary neutrons. The MSL Radiation Assessment Detector (RAD) investigation addresses this final objective that is of direct relevance to SSSC research focus areas J.1, J.4, and H.4.

Characterizing and understanding the Martian radiation environment is fundamental to quantitatively assessing the habitability of the planet and essential for future crewed missions. The consequences of both short and long term effects of energetic particle radiation on Mars are severe. Developing ways to mitigate these risks is the single most important challenge to preparing for future human exploration of Mars (Safe on Mars, National Academy of Sciences, 2002). RAD will provide the essential precursor information necessary to develop this mitigation strategy. RAD also addresses the radiation effects on biological potential and past habitability, as well as keys to understanding the chemical alteration of the regolith due to impinging space radiation.


Objective F: Opening the Frontier...
Object
F1
F2
F3
F4
H1
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SSSC Great Observatory
ACE
Cassini
Cluster
FAST
Geotail
IMAGE
Messenger
POLAR
RHESSI
SOHO
TIMED
TRACE
Ulysses
Voyager
Wind
Missions In Development
AIM
CINDI
THEMIS
Solar B
STEREO
TWINS
SDO
IBEX
Near-Term SSSC Missions
RBSP
MMS
ITSP
IH Sentinels
Solar Probe
Solar Orbiter
GEC
Intermediate-Term SSSC Missions
AAMP
DOPPLER
GEMINI
HIGO
HS
ITMW
L1 Sentinel
Heliostorm
MagCon
SECEP
SEPM
SPI
SWB
TLM
Future SSSC Missions
DBC
FarSide
IMC
ISP
ITMC
MTRAP
RAM
SHIELDS
SI
Partnership Missions
ADAM
JPO/JUNO
L1 Earth-Sun
LRO
MARS
MSL
Pluto/Kuiper
SSD

ive H: Understanding Our Home...											Objective J: Safeguarding the Journey...													
	H2		H3			H4				J1			J2		J3			J4				J5	Page No.
	2	2	3	3	3	4	4	4	4	1	1	1	2	2	3	3	3	4	4	4	4	5	
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Chapter 4

Sun-Solar System Connection: Technology Investments

Develop Technologies, Data, and Knowledge Systems to Improve Future Operational Systems

Innovation is the engine that drives scientific progress, through development of new theories, invention of new technologies that lead to improved measurements, and emergence of entirely new capabilities. SSSC must embrace the development, infusion, and study of new technology, both for its stimulating effect on science (enabling and enhancing new missions), and because of the key role that understanding and predicting the space environment presents for the safety and productivity of our global infrastructure that is increasingly space-based and of other NASA missions.

Continuing progress in the characterization, modeling, and prediction of the Sun-Solar System Connection (SSSC) will require technological development in a number of key areas.

Highly desirable capabilities include:

- Simultaneously sampling space plasmas at multiple points with cost-effective means (e.g., MMS, LWS Storm Probes, and Sentinels); measuring phenomena at a higher resolution and coverage in order to answer specific scientific questions (e.g, GEC);
- Achieving unique vantage points such as upstream of the Earth-Sun L1, polar orbit around the Sun, or even beyond the heliosphere;
- Developing the next generation of capable, affordable instrumentation;
- Enabling the return of vast new data sets from anywhere in the solar system;
- Synthesizing understanding from system-wide measurements using new data analysis and visualization techniques.

The highest priority SSSC technology needs follow these key focus areas:

1. Developing compact, low-cost spacecraft and launch systems;
2. Achieving high ΔV propulsion (solar sails);
3. Designing, building, testing, and validating the next generation of SSSC instrumentation;
4. Returning and assimilating large data sets from throughout the solar system;
5. Analysis, data synthesis, modeling, and visualization of plasma and neutral space environments throughout the solar system.

Table 4.1 shows enabling and enhancing technologies for Sun-Solar System Connection missions. The table traces the dependence of these key technologies to high-priority missions and also outlines the importance of other areas such as avionics, formation flying, structures & materials, power, and low cost access to space. The number of spacecraft required versus time is displayed in Figure 4.1 entitled “Sun-Solar System Connection Cluster and Constellation Missions.” Missions with “clusters” of spacecraft (in the range of 2-6 spacecraft) seek lower unit costs, while constellations missions such as Magnetospheric Constellation (30-36) and Solar Wind Buoys (12-15) could be enabled by ST-5 nanosats.

Enabling and Enhancing Technologies for Sun-Solar System Connection Missions

		Missions before 2025																							Missions after 2025												
	Program[1]	Solar Terrestrial Probes									Living With a Star										Partnerships				STP		LWS				Flagship Missions		Other		Partnerships		
		MMS	GEC	Sun-Earth Connection at L1	MC	Doppler	SEPP	AAMP	HIGO	ITM Waves Coupler	SET	RBSP	ITSP	IHS	GEMINI	Heliostorm	Solar Weather Buoys	Solar Polar Imager	Telemachus	Solar Probe	ADAM	SECEP	JPO	MARS	RAM	ITMC	IMC	Farside Sentinel	SHIELDS	DBC	Interstellar Probe	Stellar Imager	MTRAP	SCOPE	Titan	Venus Aeronomy	Io Electrodynamics
Spacecraft	Number of Spacecraft	4	3		30			4				2	2	4	2		15									3	6		2	12		30					
	Avionics											+				E					E		+										E				E
	Formation Flying	+	+					+																								E					
	Structures & Materials		+																	E																	
Power & Propulsion	Solar Sails															E		E												+	E						
	Propulsion																		E																		
	MMRTG																			E											E						E
	Advanced Photovoltaics		+																+																		
Scientific Instrumentation			+		+	E	E	E	E				+	+		+		E	+	+	E	E		+	E				E		E	E	E	E		E	
Communications				E		E[2]			+					+			+	+	+	+	E		+					+	E		E		E				
Data Synthesis, Analysis, & Visualization					E				+					+	E		+	+		+						+											
Low Cost Access to Space											E																										

Technology	Enabling	E
	Enhancing	+
Programs	Solar Terrestrial Probes	(purple)
	Living With a Star	(yellow)
	Flagship Missions	(dark red)
	Partnerships	(orange)
	Other missions	(green)

Notes: 1. Does not include STEREO, Solar-B & SDO (in implementation); Solar Orbiter, Bepi Colombo (ESA).
2. Communications is not enabling for Earth-orbiting Doppler mission, but would be enabling for Doppler mission at Mars

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The following sections give more detail for each of the high-priority technology needs.

1. Developing compact, low-cost spacecraft and launch systems: Because of the complexity and large scale of solar system plasmas, progress requires clusters or constellations of spacecraft making simultaneous multi-point measurements (e.g., Inner Heliospheric Sentinels, MMS, MagCon, and GEC). For multi-spacecraft missions enabling and enhancing technologies include the development of low mass, power, and volume instrumentation as well as low mass, economical spacecraft. These two developments are linked in the sense that smaller, better integrated, spaceflight instrumentation packages could be accommodated on smaller, less expensive launch platforms.

Reducing the unit cost of multiple space systems will require efforts on multiple fronts. Many system issues are wholly unrelated to typical performance-driven technology development. One important area of technology is the development of low-power electronics for space systems and instruments. Flight validation of one LPE component and technique, the CULPRIT Reed-Solomon Encoder on ST-5, is scheduled for 2006. Support for further development was provided by the NASA' Exploration Systems Directorate in 2004 (ECT NRA). Power dissipation at the component level can be reduced by factors of 50-100 over conventional technology. If LPE technology were available system-wide, power consumption on satellite systems could be reduced by up to 70%, enabling system-wide benefits and providing spacecraft designers with greater flexibility reducing weight, size, and cost.

2. Enabling high ΔV propulsion (solar sails): Progress in key areas of SSSC science requires access to unique vantage points both inside and outside the heliosphere. One key vantage point is high-inclination, heliocentric orbit, which would enable unprecedented imaging of the Sun's polar regions. Mission concepts relying on existing technology use either 5 years of solar electric propulsion to reach just a 38° inclination in the inner heliosphere (Solar

Orbiter) or rely on a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (Telemachus).

The solar sail is envisioned as a cost-effective means of propelling spacecraft in the inner solar system to very high velocity ($\Delta v > 50$ km/s). Because sails rely on the Sun's continuous supply of photons to provide low-thrust propulsion, solar sails also enable missions in non-Keplerian orbits that are currently not feasible by other means. Solar sails would enable three important SSSC missions:

- Heliostorm, providing significantly greater warning of energetic particles accelerated by CME's via measurements upstream of the Earth-Sun L1 point;
- Solar Polar Imager, providing remote sensing of solar poles from a near-optimal vantage point--circular, 0.5-AU, 75° inclination heliocentric orbit;
- Interstellar Probe, a cost-effective means of sampling interstellar space.

A solar sail consists of a reflective membrane and supporting structure that is deployed or constructed in space. As a result of development by the In-Space Propulsion Technologies Project, sail technology has advanced considerably in recent years. In 2004, two 10-m systems were tested in vacuum on the ground, followed by two 20-m systems in 2005. This recent development has moved the solar sail from the realm of science fiction to science fact.

Because of the nature of a solar sail—a gossamer and reflective membrane meant for deployment and to fly in space—there are fundamental limits to further validation and maturation on the ground. Building, deploying and flying a hundred-meter-class solar sail for a strategic science mission will first require a solar sail flight validation or "Sail Demo" mission. The sail demo will develop and operate in space a deployable solar sail, one that provides measurable acceleration and that can be steered. The flight experiment will test and validate the models and processes for solar sail design, fabrication, deployment, and flight. Such models and processes can then be used with confidence to design, fabricate, and operate the larger solar sails needed for strategic missions.

A sail demo is a candidate concept for the New Millennium Program's ST9 mission scheduled for 2010. Scale-up of the technology to 100-m lengths needed by Heliostorm could occur 5-6 years after a successful sail demo. After flight of a 100-m-class solar sail and a few years additional development, scale-up to still larger sails such as for Solar Polar Imager (~160-m edge length) are imaginable from there. Three decades hence, the deployment of a truly monumental, high-temperature sail required by a mission like Interstellar Probe (200-m radius) could be facilitated by human crews operating near libration points.

3. Enabling the development of the next generation of SSSC instrumentation: SSSC missions carry a wide range of instrumentation, some designed to make *in-situ* measurements within space plasmas while others make remote sensing measurements of plasma processes occurring at the Sun, near the planets, or out to the edge of the heliosphere. The development of new instruments and instrument concepts is crucial to the future of SSSC science, driven by the need to refine and improve instruments, reduce their mass and power consumption and enable new measurement techniques. Progress in instrument technology development is needed at all technology readiness (TRL) levels, from basic concepts for new detectors (e.g. MEMS-based (microelectro-mechanical systems) plasma detectors that could be used on MagCon) to system level demonstration of improved instruments (e.g. Compact Doppler/Magnetographs for missions such as Doppler). The development of these instruments will proceed from formulation of new ideas and designs (perhaps based on technologies developed in other fields), basic proof of concept, fabrication of test models, laboratory testing, and finally flight validation. It is important to maintain a balanced program that supports all levels of this development, particularly the final stages that enable instruments to be used in-flight. The most costly and time consuming development stages are those directly preceding flight on science missions, largely because of the specialized equipment required.

In order to continue to lead the world in space science research, NASA must support the development and maintenance of space-quality test facilities, including those capable of simulating the particle and radiation environments encountered during spaceflight missions. For some of these applications, NASA's low-cost access to space (LCAS) program provides an ideal avenue for testing and validation. A prime example of this paradigm is the development of top-hat style plasma detectors. These were first conceived for studies of the Earth's auroral regions, and were first flown on sounding rockets. Their successes in this area led directly to instruments being flown on highly successful magnetospheric missions. Another important avenue for assessing the effects of the variable space environment on potential flight instruments (and other technologies) is the LWS Space Environment Testbed (SET) Program.

Specific component technologies that would benefit SSSC missions include: large area, deep well CCDs, active pixel sensors, low-noise micro-channel plates, foil technology for ENA imagers, high performance EUV mirrors, UV blind ENA imagers, low-mass high-voltage power supplies advanced X-ray optics and detectors, thin solid-state energetic particle detectors, compact, accurate magnetic sensors and small dead-layer solid state detectors. At the system level, many payloads on future SSSC missions will be severely mass and power constrained (MagCon and Solar Weather Buoys, for example): Technologies that reduce sensor and electronics mass and power would be particularly useful. In addition to these focused technology needs, missions may benefit from serendipitous use of technologies developed in other fields. For example, the incredible shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and more power efficient ionization sources.

4. Enabling the return of large data sets from throughout the solar system: As our exploration of the Sun-Solar System connection proceeds, SSSC missions will place an increasing demand on NASA's communication resources. Many missions would be significantly enhanced by increased communications bandwidth. High bandwidth communication would benefit missions that image the Sun, such as Solar Polar Imager or Doppler, by allowing high cadence, high resolution imaging in multiple spectral channels. As solar remote sensing missions are deployed beyond Earth orbit, these benefits become more critical: missions such as SHIELDS or the Farside Sentinel will study the Sun from multiple distant vantage points, requiring spacecraft to be operated up to 2 AU from the Earth. Closer to Earth, missions will require multiple spacecraft to explore the geospace environment, separating the effects of variations in time and space and examining the structure of complex boundaries. Large numbers of individual spacecraft (in MagCon, for example) distributed throughout geospace will stretch the capabilities of the current communications infrastructure. As we venture further out in the solar system, with missions such as Jupiter Polar Orbiter (Juno), HIGO and Interstellar Probe, returning the required data places an increasing burden on spacecraft, driving cost and complexity. Considered individually, the above missions may be achievable with current technology, however pursuing system-wide SSSC science goals will be enabled by enhancements to our communications technology.

Several technologies will contribute to the solution to this problem. Planned enhancements to the Deep Space Network (DSN), replacing outdated 70m and 34m antenna with arrays of smaller antenna working at Ka-band, will increase the available bandwidth substantially, while also providing the flexibility to communicate with multiple spacecraft simultaneously. Using 200 such antennas, for example, would enable kilobit per second communications from an Interstellar Probe at 100 AU, providing the type of data provided by the ACE or Ulysses missions throughout the solar system to the edge of the heliosphere. Optical communication would also provide a substantial increase in communication bandwidth and additionally provide the capability for high-bandwidth point-to-point communication for missions monitoring the interplanetary radiation environment. The next generation DSN is expected to provide both enhanced RF and optical communications. Arrays of small antennas plus other RF improvements (transmitters, inflatable antennas, transponders, for example) together with optical communication would provide orders of magnitude increase in science data rates. RF arrays would also enable a significant increase in the number of spacecraft that can be supported, particularly in closely spaced clusters.

5. Enabling the analysis, modeling, and visualization of solar system plasmas: As we continue to explore Sun-Solar System connections, the requirement to effectively model the vast systems we study using sparsely sampled observations becomes more critical. Remote space weather predictive capabilities may even be required for explorers far from Earth. In many missions (e.g. the Inner Heliosphere Sentinels, MagCon, or SEPM) modeling will be a critical element of the mission itself, while other modeling efforts will be required to assimilate the data collected by multiple missions into coherent models. The necessary groundwork for these activities has already begun - examples include NASA's Information Power Grid, a joint effort between government, academia, and industry to provide large scale, distributed computing resources to the scientific and engineering communities. The Columbia supercomputer, uses 10,240 Intel Itanium 2 processors and provides an order of magnitude increase in NASA's computing capability. The goal of producing integrated models, and software frameworks that link these models, is also being addressed, with organizations such as NASA's Coordinated Community Modeling Center (CCMC), the NSF-funded Center for Integrated Space Weather Modeling (CISM) and the Center for Space Environment Modeling at the University of Michigan. These efforts are by definition cross-disciplinary, requiring expertise in numerical analysis, high-performance computational science, and solar, interplanetary, magnetospheric, ionospheric and atmospheric physics. Future modeling and theory programs will need to be expanded to handle the demands of increasingly complex data sets and simulations that encompass the entire solar, heliospheric and geospace environments. As new computer capabilities emerge, SSSC scientists will construct broader ranging and more complex models that will allow us to predict the behavior of solar system plasmas based on the assimilation of data from our SSSC Great Observatory.

One of the great challenges faced by current and future SSSC missions is visualization of complex data sets measured by multiple spacecraft in a simultaneous, coherent fashion. Current efforts include the VisBARD project, funded by NASA's Applied Information Systems Research Program.   In this project, space science data are displayed three-dimensionally along spacecraft orbits that may be presented as either connected lines or as individual points. The data display allows the rapid determination of vector configurations, correlations between many measurements at multiple points, and global relationships. Events such as vector field rotation and dozens of simultaneous variables that are difficult to see in traditional time-series line-plots are more easily visualized with such a tool. Future data sets will be even more extensive requiring ever more sophisticated visualization tools.

In analyzing future spacecraft data and comparing them with data available from the rest of the SSSC Great Observatory, pattern and feature recognition will become increasingly valuable, allowing large datasets to be mined for events, particularly those detected by multiple platforms. Data structures like the Virtual Solar Observatory and Virtual Heliospheric Observatory will allow such mining, enhancing the value of our data repository and making data more accessible to the science community. Visual representation of imaging data is also critical to its analysis and interpretation, as well as providing a ready means to engage the public. A wide range of SSSC image data will be produced: gamma-ray, X-ray, ultraviolet, visible, infrared, radio, and neutral atom instruments will all produce data requiring image visualization. Tools aimed at producing images of these data are an important part of our current technology, however future missions (STEREO, SDO, IBEX, and GEMINI, for example) will continue to place demands on technological capabilities, as image formats increase in size and more complex multi-dimensional data sets need to be visualized.

Part III: Sun-Solar System Connection Impacts

Education and Public Outreach

Linkages with Other NASA Activities

External Drivers of the NASA SSSC Program

Advancing U.S. Scientific, Security, & Economic Interests

Education and Public Outreach

Unique Education and Public Outreach (E/PO) opportunities are associated with Sun-Solar System Connection science. The top-level objectives, research focus areas, and science achievements that constitute the Sun-Solar System Connection Strategic Roadmap for the next 30 years provide powerful opportunities for Education and Public Outreach from the SSSC scientific community.

We recommend that E/PO activities stemming from the science achievements be developed to support the following five themes:

- **NASA keeps me informed about what's going on with the Sun**
- **The Solar System is an astrophysical laboratory for NASA**
- **NASA science helps us protect our society from hazardous space weather**
- **NASA science helps us understand climate change**
- **NASA science helps keep space explorers safe and supports exploration activities**

These messages are of high interest and relevance to the public and they span the range of scientific activity engaged in by the SSSC community. The traceability to the SSSC science and exploration objectives is clear. Chart A shows the logical flow-down outlining how the SSSC scientific objectives and associated research focus areas lead to the five E/PO themes. The themes then inform the implementation of programs of formal and informal education and public outreach.

The anticipated scientific achievements articulated in Part II Chapter 2 for each of the next three decades that relate most clearly to these themes are shown in Table B. The themes and achievements are color coded to show the most direct links. Table B also identifies the missions that are most closely associated with the achievements and themes.

An expanded and invigorated education and public outreach is essential to the achievement of the Vision for Space Exploration (VSE). NASA's Strategic Objective for Education and Public Outreach is to "Use NASA missions and other activities to inspire and

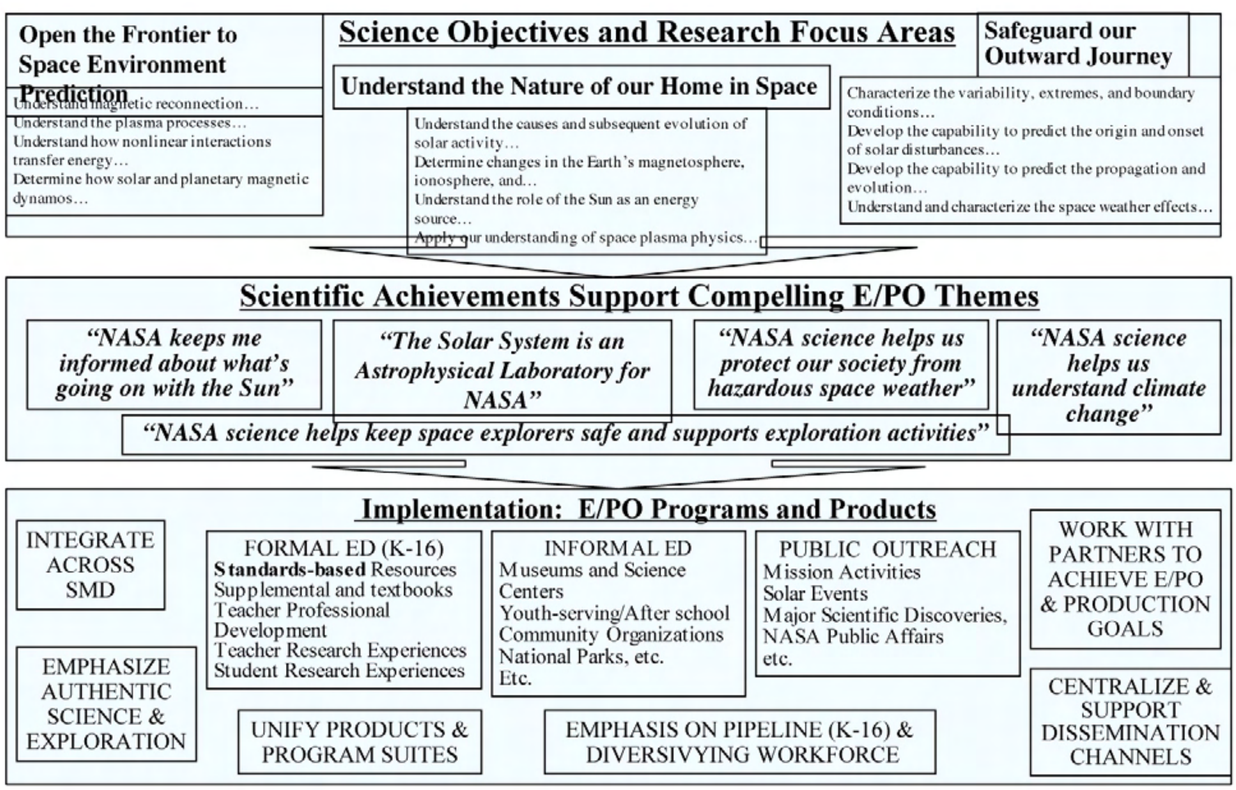


Table B. Science Achievements from the Roadmap support SSSC E/PO Themes

Science Achievements* support SSSC E/PO Themes

SSSC Science Objectives	SSSC E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-beyond
Open the Frontier to Space Environment Prediction	*"NASA keeps me informed about what's going on with the Sun"* *"The Solar System is an Astrophysical Laboratory for NASA"*	Characterize magnetic reconnection at the Sun and Earth Identify key processes that couple regions within and throughout the heliosphere	Understand the magnetic processes that drive space weather	**Predict solar system magnetic activity and energy release** Predict high energy particle flux throughout the solar system
Understand the Nature of our Home in Space	*"NASA science helps us protect our society from hazardous space weather"* *"NASA science helps us understand climate change"*	Identify how space weather effects are produced in geospace Identify the impacts of solar variability on Earth's atmosphere	Determine how magnetic fields, solar wind and irradiance affect the habitability of solar system bodies Identify precursors of important solar disturbances Integrate solar variability effects into Earth climate models	**Provide scientific basis for continuous forecasting of conditions throughout the solar system** Predict climate change
Safeguard our Outward Journey	*"NASA science helps keep space explorers safe and supports exploration activities"*	Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Reliably forecast space weather for the Earth-Moon system; make the first SW nowcasts at Mars	Analyze the first direct samples of the interstellar medium Reliably predict atmospheric and radiation conditions at Mars to ensure safe surface operations
Overarching E/PO Theme: *Scientific progress requires new knowledge systems and innovative use of technology: Measure and Characterize…Development of Models…Predictive Capability; from Sounding Rockets to Solar Sails*				

motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation." The SSSC community emphasizes the connection between achievement of this strategic objective and the Vision for Space Exploration. The development of the workforce needed to achieve NASA's vision requires that E/PO activities engage young people and capture their interest and passion. We need to increase the capacity of our nation's education systems, both in school (Formal: K-16) and out of school (Informal), to prepare students for scientific and engineering careers.

SSSC science and mission activities provide valuable hooks for E/PO. For example, learning to predict the variable radiation hazards and space weather conditions that our astronauts and robots will encounter on excursions to the Moon, Mars, and elsewhere is very exciting scientific work that the public will want to know about. New advances using our Sun and solar system as astrophysical laboratories will fuel the generation of authentic, science-rich education resources that will increase the capacity of the nation's education systems.

Developing the workforce to implement the VSE will require substantial focus on under-represented communities. The current demographic makeup of the science and engineering workforce in the USA is overwhelmingly white. Population projections to 2025 indicate that the percentage of traditionally underrepresented communities will increase. Successful E/PO efforts will benefit substantially by reaching presently under-represented groups.

An exciting example of E/PO targeted at under-represented communities is NASA's Sun-Earth Connection Education Forum's (SECEF) Sun-Earth Day programming for 2005: Ancient Observatories: Timeless Knowledge. This broad program allowed NASA and Native American astrophysicists to share their research into the efforts of ancient cultures to understand the Sun and its affects on their lives, highlighting

Table C. SSSC recommended missions identified with SSSC E/PO Themes

Missions Key to Science Achievements* identified with SSSC E/PO Themes

SSSC Science Objectives	SSSC E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-beyond
Open the Frontier to Space Environment Prediction	***"NASA keeps me informed about what's going on with the Sun"*** ***"The Solar System is an Astrophysical Laboratory for NASA"***	Cluster, TRACE, Polar MMS, Solar Reconnection, RBSP, SDO, Solar-B, STEREO, THEMIS Auroral Imaging, L1monitor Cluster, L1-Monitor ITSP, IBEX, MMS, SDO, STEREO, L1monitor	IBEX, ITImager, MMS, RBSP, SDO, Solar-B, Stereo, THEMIS MagCon, Sentinels, Solar Probe, GEC, ITSP, L1, Solar Orbiter, Orbitals, RAVENS	SHIELDS, SPI, Farside, SWB, SPI , RAM, MTRAP, MagCon, IMC,DBC,Stellar Imager Assumes: ITSP, L1 monitor, SEPP, Auroral Imagers, Solar Sentinels, MTRAP, IMC, MagCon, DBC, AAMP
Understand the Nature of our Home in Space	***"NASA science helps us protect our society from hazardous space weather"*** ***"NASA science helps us understand climate change"***	ACE, Cluster, IMAGE, FAST, Polar, TIMED, GEC, MMS STEREO,ITSP+ITImager, RBSP, SDO, Rocket Campaigns IMAGE, TIMED, AIM, CNOFS ITSP + ITImaging, GEC, SDO, Rocket Campaigns	MSL, **Spitzer** **New:** MAD, TE TE, Lunar Solar Wind History Experiment **Europa Mission** SDO, ITSP, RBSP SP, DOPPLER, SEPP/NE,RAM, SIRA, SHIELDS, Solar Orbiter SECEP, ITMWaves , L1/L2 cont. global obs. RocketCampaigns	Existing: MagCon, AMS, ITM-Waves, GEMINI, Dayside Boundary Con. New:Rocket Campaigns/LCAS, IMC, ITC New?: Solar Polar Imager, TITMC, L1 Monitor (irradiance, particles),SECEP, SHIELD
Safeguard our Outward Journey	***"NASA science helps keep space explorers safe and supports exploration activities"***	TIMED, Soho, ACE, Cassini, Cluster, etc.: SDO, RBSP, ITSP, Inner Sentinels, L1 SW & SEP Monitor, MMS, MSL, Rocket Campaigns	Sentinels, SWB, Heliostorm/L1 Monitor, MagCon, IMC, GEC, GEMINI , DOPPLER, SHIELDS, SEPP, MTO, MAD, SPI	Interstellar Probe, HIGO, Telemachus, Outer heliosphere radio Assumes, results from robotic surveys of Mars and MAD + results from solar-interplanetary and Geospace missions (SDO, DP, HIS, RBSP, ITSP, LRO, Lunar experience etc) +... SCOPE, Telemachus
Overarching E/PO Theme: *Scientific progress requires new knowledge systems and innovative use of technology: Measure and Characterize…Development of Models…Predictive Capability; from Sounding Rockets to Solar Sails*				

the importance of the Sun across the ages. Through programs such as these, SSSC scientists convey NASA's mission and research program activities to diverse audiences. Both English and Spanish language materials have been disseminated.

Integrate messages and utilize best-practice strategies for effective E/PO. Unification of NASA's scientific enterprise into the Science Mission Directorate presents opportunities for science education efforts all across NASA, including SSSC. While each NASA division, mission, and individual contributes unique content and experiences to E/PO; integration into a single science directorate has the potential to be more effective in terms of message and approach. Moving forward, it won't matter if it's Space Science, Earth Science, Solar Physics, Biological Research, or something else – the single 'brand' will be exciting, relevant NASA science. Furthermore, approaches to bring this content to the broadest possible audiences can take advantage of the best strategies of each of the former enterprises to create the strongest possible suites of products and programs. E/PO programs include the development of tools for evaluating quality and impact, in order to identify and disseminate best practices in E/PO.

The SSSC scientific community is vigorously engaged in E/PO and current E/PO efforts align well with SMD's education goals and priorities. SSSC E/PO programs already encourage the scientific community to share the excitement of their discoveries with the public. The programs enhance the quality of science, mathematics, and technology education. Efforts align with NASA's Science Mission Directorate's education goals and priorities to inspire and motivate students to pursue careers in science, technology, engineering and mathematics (STEM) and to engage the public in shaping and sharing the experience of exploration and discovery.

E/PO activities are currently integrated throughout all the SSSC flight missions and research programs. As a result, a significant fraction of the SSSC research community contributes to a broad public understanding of the science and is directly involved in education at the pre-college and college level. Graduate student participation in SSSC research programs are enhanced by the Graduate Student Research Program, a cooperative program between NASA Education and the Science Mission Directorate. Vigorous E/PO programs also stem directly from various science programs within the SSSC community to effectively serve the needs of local communities.

Centralized efforts such as the Sun-Earth Connection Education Forum (SECEF; a partnership between NASA Goddard Space Flight Center and the University of California at Berkeley) strive to facilitate the involvement of SSSC scientists in E/PO activities and to establish strong and lasting partnerships with formal and informal education communities. These centralized efforts seek to develop a national network to identify high-leverage education and outreach opportunities and to support long-term partnerships. SECEF helps provide ready access to the products of SSSC science education and outreach programs. They also promote the participation of under-served and under-utilized groups in the SSSC science program by providing new opportunities for minorities and minority universities to compete for and participate in SSSC science missions, research, and education programs.

Sun-Earth Day

Sun-Earth Day is an annual national program supported by SECEF. Since 2001 the SSSC community has shared the science linking the Sun and Earth with educators, students, and the general public via informal learning centers, the Web, TV, and other media outlets through high-profile, well supported annual events. NASA science is connected to classrooms and museums in real time, and educational resources are disseminated via the Web and through NASA centers. In the context of an overarching emphasis on the Sun-Earth connection, a specific theme is created each year to continue to engage the public.

2001 - Having a Solar Blast

2002 - Celebrating the Spring Equinox

2003 - Live from the Aurora

2004 - Venus Transit

2005 - Ancient Observatories: Timeless Knowledge

2006 – Eclipse In a Different Light

Sun-Earth Day activities have broad reach. For example, the 2004 Sun-Earth Day website received 40 million hits in 40 hours. There were 1000 news reports on various TV channels, including 40 interviews with NASA scientists. More than 12,000 packets of educational materials were distributed to teachers, museums, and amateur astronomers in support of the 2004 Sun-Earth day programming.

As part of the 2005 Sun-Earth Day program, the Ancient Observatories: Timeless Knowledge website (sunearthday.nasa.gov) and the Traditions of the Sun website (www.traditionsofthesun.org) were launched in fall 2004 to allow users to explore Chaco Canyon and other areas. Visited 500,000 times, these websites also highlight NASA research on the Sun and Native American solar practices within a larger historical and cultural context. Formal education programs engaged 75,000 teachers and 225,000 students, with all 10 NASA Centers hosting events. 100 NASA Explorer Schools also participated. Informal education efforts included programs hosted by 24 museums across the country and training for Girl Scout Master Leaders who ultimately engaged some 10,000 girl scouts in Sun-Earth Day activities. The culminating event for Sun-Earth Day 2005 was a live bilingual webcast from Chichen Itza, Mexico that reached thousands of Hispanic and Native American participants.

Examples of Strong Mission E/PO Programs: SOHO & IMAGE

SOHO, the Solar and Heliospheric Observatory mission, runs a vigorous program to disseminate images to informal audiences and to the media, regularly distributing near-real time images of the Sun (LASCO, EIT, and MDI images) on the Web, Weekly to the American Museum of Natural History's AstroBulletin, and to a variety of media publishers, including National Geographic. Sun and space weather 3-D/motion postcards (lenticulars) are a very popular tool for engaging students and the general public. Over 180,000 lenticulars have been distributed.

SOHO sponsors two model collaborations with educators and students. FiMS (Fellowships in Mathematics and Science), a partnership grant with the Pennsylvania Department of Education (in 3 school systems), provides a strong example of the power of working directly with the local formal education system. SOHO educators and scientists work with their local teachers to increase content knowledge and support their ability to develop and implement inquiry-based lessons tied to state standards and the current curriculum. The Endeavour program, a collaboration between SOHO/NASA and 18 school systems, gives teams of students real-life NASA problems to research. Students are supported by teacher team leaders that have been exposed to the content and training through professional development.

Efforts to broaden the reach of SOHO's E/PO efforts, including English and Spanish versions of presentations on the Dynamic Sun CD and of the build-your-own-spectroscope poster, have been very effective. In addition, SOHO brings the science and exploration of our Sun to the visually impaired through their groundbreaking "Touch the Sun" book.

IMAGE, the Imager for Magnetosphere-to-Aurora Global Exploration mission, has been at the forefront of providing teachers with math and space science classroom activities. The IMAGE team works hard to improve public awareness of space weather impacts and to improve student math skills. Its annual space math workbooks have been distributed to over 75,000 teachers through their Space Weather CD and their popular POETRY website (Public Outreach, Education, Teaching and Reaching Youth; image.gsfc.nasa.gov/poetry). The Soda Bottle Magnetometer , designed by POETRY in 1997, has been a popular hands-on activity for millions of students and is a key element in the Student Observing Network (SON).

Recently, IMAGE created a new program called the 'Space Science Problem of the Week' that is distributed electronically to over 5000 teachers. These extra-credit math problems cover the entire gamut of science and engineering problems and give grade 7-12 students a hands-on and authentic math experience in solving key problems in SSSC science. IMAGE also sponsors the INSPIRE project which has allowed students of over 2000 high school teachers from North America and around the world to listen-in to low frequency radio signals called whistlers, that are made by Earth's magnetic field in space.

In informal education, IMAGE has created museum kiosks at the Houston Museum of Science, planetarium programs such as 'Force Five', and has contributed to the SECEF Space Weather museum exhibit, which collectively have brought SEC science and research to over 200,000 people annually.

E/PO Challenges and Recommendations

Strong opportunities exist to extend the power of SSSC science and related mission activities to engage and inspire students in formal education settings, audiences at informal learning centers, and the general public across the nation via the press and other communication outlets. Table C presents a summary of challenges to effective E/PO and a series of recommendations to expand and enhance NASA's E/PO activities.

Table D. Challenges and recommendations to effective E/PO

Challenge	Recommendation
E/PO practices vary widely across NASA. This is a disadvantage for both PIs and for audiences. PIs are often in the position of inventing their own E/PO programs, products and activities and audiences need to constantly relearn how to take advantage of these efforts.	Generate uniform, standards-based product lines with themed content for schools, museums, and science centers, as well as the press and media outlets. Invest production resources in development of core products that can be used appropriately by a range of E/PO partners.
The formal, K-12 science education system needs strong connections with NASA's scientific, engineering and technological enterprises if it is going to play sufficient role in preparing the science and engineering workforce required to implement and achieve the Vision for Space Exploration.	Correlate NASA's activities, enterprise-wide, with national science standards (e.g. National Science Education Standards of the NRC and Benchmarks for Scientific Literacy, Project 2061) to develop a roadmap for infusing NASA resources into the formal K-12 system. Middle School presents a particular opportunity due to the level of concepts mastered; more flexible curricula can be designed for use in High School. Develop templates for products, programs and professional development that, combined with the roadmap, effectively connect NASA's ongoing, authentic activities to classrooms for educators and learners.
Too few undergraduates choose physics-based careers in particular and science and engineering careers in general. Extend focus from K-12 to K-16 to integrate cutting-edge SSSC topics into undergraduate physics courses along with other relevant NASA content.	Broad dissemination is required to achieve impact. Requiring individual PIs and Missions to create their own dissemination channels is burdensome and lessens impact. Expand existing, and develop new centrally supported channels for dissemination that mission and research-based E/PO can use to reach full range of audiences.
There are limited opportunities for undergraduates, graduate students, and early career scientists to obtain the intense hands-on training that is required to design, build, and manage the next generation of space science hardware.	Sub-orbital rocket and balloon payloads are a proven, cost-effective method for "high context" training of space scientists, but resources for these programs have been decreasing. It is imperative to reverse this trend in order to increase training opportunities.
Use of E/PO investments are not maximized due to lack of sustained support and dissemination.	Make sustained investment over time in Web-based dissemination of NASA materials. Use of best-practice templates to create materials will facilitate maintaining currency.

Provide education and professional development resources for formal and informal science education that are consistent and coherent across the entire NASA enterprise. NASA needs to coordinate and centralize its educational outreach to better enable E/PO partners to take advantage of SSSC science to engage their audiences. Educators in the K-12 arena require standards-based educational resources coupled with high-quality professional development offerings to take advantage of NASA's constant stream of fresh, current, authentic scientific discovery and engineering activities. NASA creates resources such as informational websites, animated simulations, sets of data visualizations, teaching guides, sets of standards-based curriculum activities, on line courses, video conferences, interactive modules, posters, opportunities to interact on line and by video with scientists, engineers and technicians, opportunities for student research, and regular updates. These must be coupled with appropriate professional development to ensure that educators always have NASA in their tool-kit for effective science education. Partnership with professional organizations such as the National Science Teachers Association has proven effective for NASA, and should be expanded.

SSSC and other NASA missions and activities likewise provide wonderful springboards for learning in the informal setting. But educators and exhibit planners in informal settings typically find using each NASA opportunity requires a significant effort simply to ramp up, since there is little consistency in what NASA produces, from center to center, or from mission to mission. It would be tremendously helpful for each NASA activity to have a standard set of resources with common interfaces and similar formats that are fairly consistent from activity to activity, e.g., an informational website, an annotated simulation, a set of opportunities to interact with scientists, engineers and technicians, and activities for out-of-school settings. Professional development is also required for informal educators; and current partnership efforts with professional organizations such as the Association of Science and Technology Centers have proven effective, and should be expanded.

Flexibility is, of course, essential. The unique opportunities and requirements of each activity should be exploited, technologies will evolve, and evaluation will inform revision. However, the ability to count on a standard package would likely reduce the learning curve for users and increase the usability and use of the resources. SECEF is a good example of the value of a coordinated national effort to develop and support E/PO activities; emphasis on standardized packages will strengthen this approach.

Promote and support the integration of the SSSC-related content more fully into standards-based K-12 science curricula. National science education standards provide direct opportunity to take advantage of SSSC science specifically and NASA science in general to improve science education on a national level. In this era of standards-based curriculum and high stakes testing, what gets taught is what is required in the curriculum and thus assessed on tests. State science curriculum standards generally map to these national standards, and thus tremendous opportunity exists for current SSSC science content to enrich and infuse these curricula. Influential science education standards such as the National Science Education Standards (National Research Council) and the 2061 Benchmarks for Science Literacy (AAAS) place substantial emphasis on SSSC related science concepts from the earliest grades through high school. The 2061 Benchmarks, for example, posit that in order to achieve scientific literacy students in grades K-2 master concepts such as 'The Sun can be seen only in the daytime, but the moon can be seen sometimes in day and sometimes in night' (4A/2); students in grades 3-5 further expand this understanding to 'Stars are like the Sun, some being smaller and some larger, but so far away they look like points of light' (4A/5); in grades 6-8 they learn that 'The Sun is a medium-sized star located near the edge of a disc-shaped galaxy of stars, …' (4A/1), and that 'Telescopes reveal that the Sun has dark spots' (10A/2); and by high school, that 'Increasingly sophisticated technology is used to learn about the universe. Visual, radio, and X-ray telescopes collect information from across the entire spectrum of electromagnetic waves;

… (4A/3). This progression of understanding highlights the role of understanding the Sun at many levels in developing scientific literacy. SSSC scientific research provides vivid, authentic examples to promote student mastery of these concepts.

The entire NASA enterprise could, for example, be mapped to the Benchmarks for Scientific Literacy, and/or the National Science Education Standards. The result would be a roadmap in itself for integrating NASA science and engineering activities into science curricula across the nation.

Extend focus to higher education in order to ensure adequate numbers of trained scientists and engineers for the SSSC community and the rest of NASA to achieve the VSE. Solar and space physics needs a national effort that relates the exciting applications in our field to specific curricular needs of introductory physics and astronomy – classes with substantial enrollments at just about every college in the nation. The excitement of space science can entrain and encourage more undergraduates through physics, math and engineering programs at the university level. This will compliment current programs geared towards providing early research experience (such as NSF's REU program) that are very important for attracting non-traditional students into the workforce. Attention needs to be paid to how the space physics workforce is developed – where do students come from and why – in order to ensure sufficient numbers for a healthy scientific community able to achieve NASA's goals.

Increase availability of "high context" learning experiences for undergraduates, graduate students, and early-career scientists in order to train the next generation of space scientists. There are multiple ways to provide genuine, practical experience for new experimenters to participate. The Low Cost Access to Space program (see section XX) has historically been an important part of this process and should be strengthened. New program possibilities include a "Hardware Apprenticeship Program" with a competition similar to the NSF Career program. Recent PhDs working at universities could be funded for a 3-5 year hardware development and flight program. This would both train and sustain them during a crucial stage of their space science career. Another possibility is a NASA SMD funded undergraduate/graduate course in Space Research, which would take student teams through the design/construction/flight of a small sub-orbital payload. A program such as this could increase the engineering workforce available to NASA as well as the number of hardware-trained space scientists.

Increases in the cost, complexity, and management of space missions have made it difficult to use them to make any substantive gain in workforce training. The sub-orbital programs are still a cost-effective way of giving future space scientists and engineers a real world experience that contains all of the elements of a full space flight, and therefore provides one of the few methods for widening the scientist and engineer pipeline for NASA

Enhance existing and create new distribution channels for E/PO efforts: products, programs, and messages. It is not realistic or effective to make individual SSSC PIs responsible for building and sustaining their own dissemination relationships. This is not to say that individual PIs should not be encouraged to go into classrooms, make public presentations, or appear in the media. We recommend that NASA develop a spectrum of dissemination options that are supported and sustained centrally. In addition, NASA should support best practice use of World Wide Web for keeping products current and leveraging development efforts over time.

Emphasize unique learning opportunities that SSSC-related content can provide, in particular, the visualization of data, essential for advancing science learning and the nation's scientific capacity. Expand efforts already underway to create high production-value media programs around the scientific assets of NASA, including Sun-Earth System. Fully digital space shows; large-format media projections, television productions, etc. are powerful vehicles for promoting public understanding of complex phenomena and teaching students of all ages critical skills for 21st century science involving collecting, analyzing, visualizing and communicating data and constructing, manipulating and interpreting scientific models and simulations. Increased efforts taking advantage of partnerships with media production groups and distributors will contribute substantially to achieving greater impact for E/PO programs.

Focus on innovative external partnerships to create programs that reach a broad range of the public. Through leveraging partnerships with informal science learning centers (museums, planetaria, science centers); national parks; community groups (Girl Scouts), publishers, and the media, SSSC science can be more widely disseminated by taking advantage of existing channels. For example, NASA has connected very effectively with the National Parks to provide content on the aurora and noctilucent clouds for summer programs in Alaska and information about the Sun in support of educational programs at parks in the southwest. Such programs provide amplified impact by enhancing the capacity of established channels to engage, excite and educate the public with science and engineering content. New avenues should also be explored, for example, products developed with the gaming industry could engage the public, young and old, in the Vision for Space Exploration.

To maximize impact of SSSC science for E/PO, efforts should take advantage of opportunities that exist at the intersection of the "formal" and "informal" education sectors. Too often in education policy and strategy, schools and museums are viewed independently, with isolated objectives and separate strands of efforts. While there are clear differences, substantial connections and overlaps exist. Many informal science education institutions already operate at the intersection of the two sectors – offering substantive professional development for teachers, providing learning experiences and field trips for classes, delivering after-school services, and developing and distributing curriculum materials and resources. A key strength of these institutions is local knowledge. The formal education landscape is highly variable and this local knowledge is key to successful connections between science and engineering-rich agencies, such as NASA, and science and engineering education efforts in the formal setting. NASA E/PO should take advantage of the existing connections and overlap between the formal and informal education arenas.

Develop better coordination with Public Affairs to maximize the effectiveness of E/PO efforts. Consistent messaging is essential to effective communication, and effective communication is key to strong E/PO. More substantial overlap should occur between Public Outreach and Public Affairs (PA). These activities are distinct: Public Outreach from SSSC covers a broad range of topics and targets the public directly, whereas Public Affairs communicates specifically new and current discoveries to the media for dissemination to the public. However, the visual and editorial resources required by the two are very similar, and thus we recommend that Public Affairs team up with the E/PO group early in order to develop the same core messages and visual assets. This will facilitate getting better media coverage of scientific results and publicizing exciting E/PO events. It will also strengthen education programs because they can use the visual and editorial assets developed for Public Affairs and Public Outreach.

E/PO efforts need to focus on outreach, not advertisement. While it is important to raise public awareness of SSSC missions and activities, E/PO funds must be invested in products and programs that go beyond advertisement and truly engage and inform. Thus we strongly discourage the use of E/PO funds for lanyards, pins, etc., that are solely designed to advertise a mission.

Educate the public via outreach through informal and formal channels about the risks inherent in the exploration of space. As NASA pursues Return to Flight and the Exploration Vision, it will be very important for the public to be aware of the risks associated with these activities. In the event that accidents occur that result in tragic loss of life or even setbacks in mission activities, the public will be best able to respond appropriately if they were aware up front of the risks involved.

Shift in management and implementation of SMD E/PO. NASA E/PO has made a remarkable impact through commitment of substantial funds over the past decade or more. The value of having the scientific community intimately involved in the development and implementation of E/PO products and programs cannot be over emphasized. Thus we strongly advocate maintaining the established commitment of funds for E/PO.

For smaller efforts NASA should continue to offer supplements for which individual PIs can apply to support E/PO activities that stem from their scientific research and mission activities. New E/PO activities should map to one of the five themes articulated above. Themes will be modified and replaced as part of future SSSC strategic planning activities. However, rather than expect each investigator to invent a new set of E/PO activities, we recommend that the allocation of E/PO funds ordinarily be linked to a broad portfolio of approved, adaptable E/PO programs and product templates from which the PI may select. Further, NASA should require that dissemination ordinarily be through one or more of NASA's approved and maintained channels.

The portfolio of approved E/PO product and program suites should be developed using existing successful E/PO efforts as models, as well as taking advantage of best practices in formal and informal education. It is very important that these be developed through collaboration between the Science Directorate and the Office of Education. It also very important that investigators funded by the Science Directorate play a significant role in the choice of allocation of their E/PO funds.

At the mission scale, we encourage better coordination between the mission EPO and the overall EPO program. This may include an adaptable selection of approved product and program suites. PIs should identify the SSSC E/PO theme(s) to which their activities map and be required to utilize appropriate dissemination strategies and channels. While individual teams must demonstrate a genuine commitment to E/PO, and teams with particular interest and expertise in developing new types of E/PO should be encouraged and supported, as a general rule PIs should not be burdened with inventing E/PO programs as they are putting together their mission proposals. In essence, science proposals funded by the Science Mission Directorate should continue to be selected on the basis of their scientific merit. Funding for E/PO derived from these scientific missions and programs should then be approved by and selected using agency guidelines, perhaps at the mission confirmation review.

The PIs should manage their own E/PO programs and help oversee the allocation of mission E/PO funds.

Sustained public engagement with, and support of, the VSE will be essential to NASA's success over the next 30 years. The SSSC community is excited to collaborate in the E/PO efforts designed to bring the public along on the VSE. Progress in SSSC science will not only enable the safe and productive transit and landing of human and robotic explorers on other bodies in our Solar System; it will also advance our capacity to mitigate hazardous space weather impacts and global climate change at Earth; and it will continue to open new frontiers of scientific discovery about the Earth, the Solar System, and the Universe.

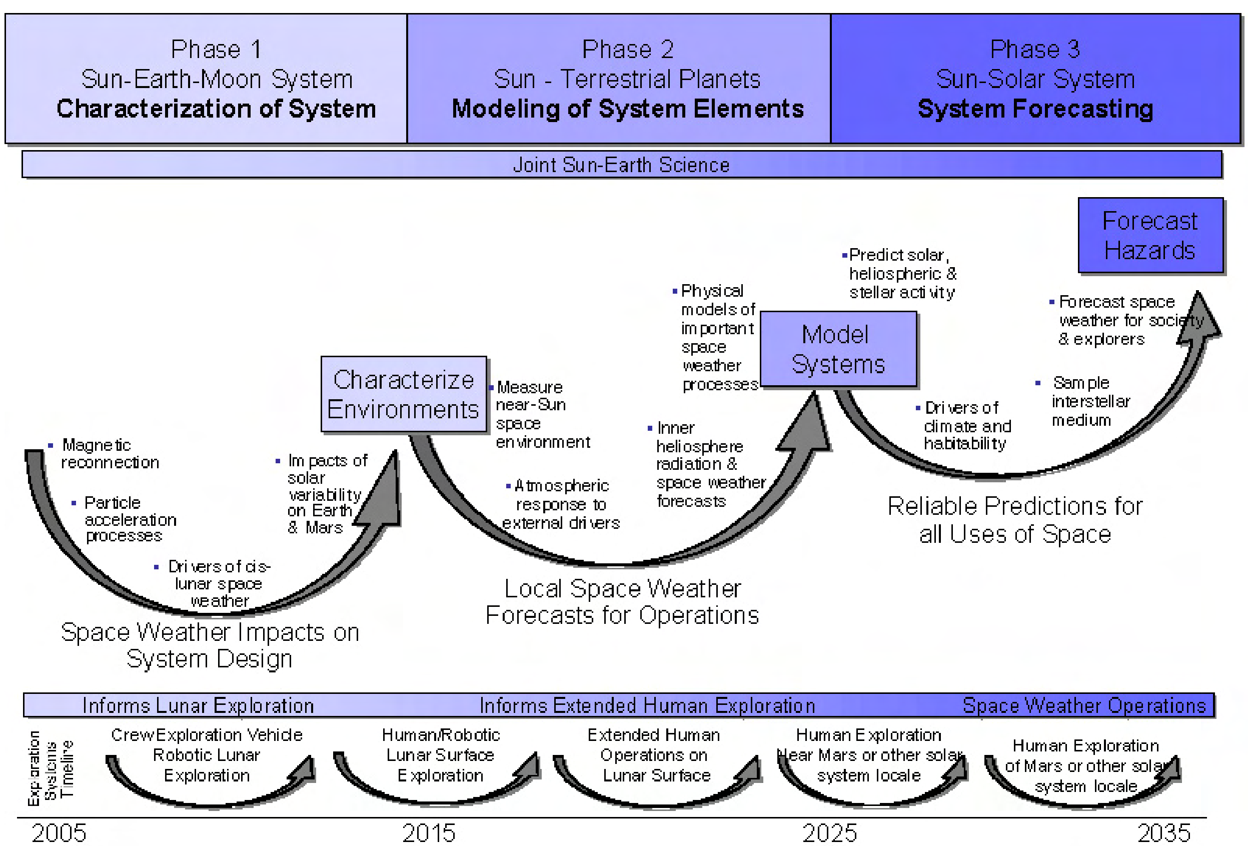
Linkages between Sun-Solar System Connections and other NASA Activities

Linkages Between SSSC Strategic Roadmap and other NASA Strategic Roadmaps:

Sun-Solar System Connection (SSSC) science focuses on space plasma physics in our cosmic neighborhood. It encompasses the Sun and the processes and phenomena that determine the space environment near the Sun, in the Earth-Moon system, in the vicinity of other solar system bodies, and throughout interplanetary space to the very boundary with interstellar space.

To the degree that the space environment matters to people or their technological systems, whether on Earth or in space, SSSC science has application to human activities. Penetrating energetic particles and photons produced by acceleration and radiation processes in space plasmas profoundly and adversely impact any exposed living organism through cellular damage and mutation. They also adversely impact exposed technological systems through episodic and cumulative damage to microcircuits and cumulative degradation of materials. Therefore, the processes that produce and transport energetic radiation are of direct interest to modern humans.

The situation for long-duration space flight is somewhat analogous to deep-ocean operations of naval ships. Vessels are designed to survive in various climatic conditions; yet the weather, which can be extreme, limits operations and determines how vessels should be configured in any situation. Similarly, operations in space will depend on space weather, viz., extravehicular activities (EVAs), maneuvers, operations on lunar and planetary surfaces, and safe harbor. Space weather in the vicinity of planetary bodies affects the state of the upper atmosphere – density and wind distribution – that is critical to vehicle aerocapture, ascent, and descent scenarios as well as the state of the ionosphere – spatial and temporal electron density distributions – that influences navigation systems and high band-width communications. As for terrestrial weather, space weather awareness, understanding, and prediction will be essential enabling activities for space exploration operations. Therefore, we



recognize strategic linkages between the SSSC Roadmap and all three Exploration Roadmaps (Lunar exploration, Mars exploration, and the development of the Crew Exploration Vehicle).

The effects of space weather on Earth's atmosphere are of special interest. Enhanced ozone depletion is a documented consequence of energetic particle precipitation. We are aware of space plasma processes that erode the Earth's atmosphere, removing ~103 kg of hydrogen and oxygen daily, and vastly greater quantities during space storms. We have performed computer simulations that imply even greater loss of atmospheric constituents at Mars, which lacks the shielding provided by an intrinsic planetary magnetic field. The potential role of local space weather and/or solar variability in terrestrial climate change is as yet unknown. The state of the Earth's ionosphere is thought to be subtly modified by terrestrial seismic activity. Quantitative determination of the intrinsic terrestrial magnetic field requires an accurate accounting of field sources external to the solid Earth. These external sources are dominated by electrical currents carried in the space plasmas surrounding the Earth. For these reasons, we also recognize strategic linkages between the SSSC Roadmap and the Earth Science Roadmap.

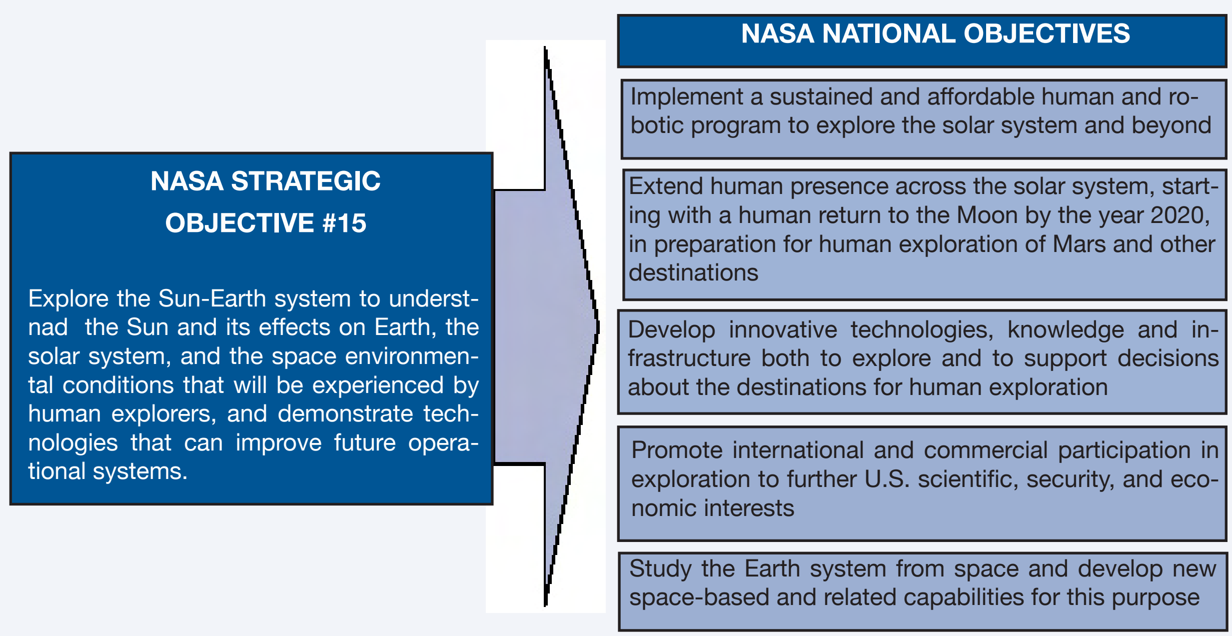
The same processes and phenomena that drive space weather in our solar system also shape environments throughout the universe. We have a typical, variable, main sequence star (the Sun) in our cosmic back yard. We live on a habitable planet that is largely protected from hazardous elements of our local space environment by a magnetic shield (the magnetosphere), a feature not shared by all astronomical, or even planetary bodies. As we try to understand the remote universe and its potential to evolve life, it is imperative that we take as full account as possible of the lessons we learn from the specimens we can virtually touch with our hands. Therefore, we recognize important linkages between the SSSC Roadmap and other Science Roadmaps that seek to understand nearby planetary systems (SRM03) and the larger universe (SRM08) and also between the SSSC Roadmap and the Roadmap to search for other habitable planets (SRM04).

Linkages Between SSSC Strategic Roadmap and NASA Capability Roadmaps:

Continued progress in Sun-Solar System Connection (SSSC) science requires new capabilities based on the development of new technology. Future technology needs are driven by diverse requirements. Cluster and constellation missions are required to simultaneously sample large-scale space plasmas at multiple points (Magnetospheric Constellation, Inner Heliospheric Sentinels, Solar Weather Buoys, Dayside Boundary Layer Constellation, Inner Magnetospheric Constellation). Highly focused missions require improved measurement resolution and sensitivity (MMS, GEC, RAM, MTRAP, GEMINI, DOPPLER). Missions with special orbital requirements will need in-space propulsion. Examples include requirements to dwell at a point farther upstream in the solar wind from the L1 libration point (Heliostorm), to achieve a polar heliocentric orbit (Solar Polar Imager), or to escape from the solar system (Interstellar Probe). As the missions in our roadmap are developed, they will require new technologies in instrumentation, data visualization, communication, and analysis systems. Future SSSC technology needs fall into several focus areas.

Propulsion and Power: A number of SSSC missions will study solar system plasmas from unique vantage points. Propulsion systems that can supply a larger delta-V than conventional rocket engines, or that can provide large delta-V without a large mass or power penalty, can enable such challenging missions. For high-performance, cost-effective propulsion in the inner solar system, or for exiting the solar system in timely fashion, solar sails are the ideal choice. Significant ground demonstrations of solar sail technologies have been performed already. We encourage continued development of this technology and support the idea of a flight demonstration during Phase 1 of this Roadmap (CY 2005 – 2015). We also encourage renewed capacity to produce RTGs that have low-EMI, high-efficiency power conversion.

Micro-spacecraft: Owing to the large scale and complexity of solar system plasmas, future discoveries will depend on deployment of spacecraft in clusters and constellations, making simultaneous multi-point measurements within the plasmas under study. Enabling technologies will include low mass/power/volume



NASA's Advanced Planning and Integration Office (APIO) developed the statement of NASA Strategic Objective #15 for the Sun-Solar System Connection division to support NASA's Guiding National Objectives (in NASA's Direction for 2005 and Beyond, NASA HQ, February, 2005)

instruments, and low-mass, low-cost spacecraft.

DSN: NASA's Deep Space Network (DSN) is evolving to meet the communication and navigation needs of the agency's increasingly complex, data-intensive missions. Analysis of Sun-Solar System Connection Roadmap missions suggests that, over the next 25 years, downlink rates will need to increase by a factor of at least 1,000, even from the more distant regions of our solar system. The trend toward multi-spacecraft missions will likely cause a large increase in the number of required supportable links back to Earth. Near-Earth missions should use and cultivate the continued evolution of commercial space networks.

Advanced Computing: Advanced supercomputing is a vital capability for enabling space weather model development and innovative data analysis and visualization. Examples of successful innovation in this area include Project Columbia and the VisBARD project.

Instrumentation: Many future SSSC missions will require development of new scientific instrumentation, including large focal plane arrays, large-scale adaptive optics, and solar-blind energetic particle and photon detectors. The development of hyperspectral and three-dimensional detectors are needed for solar and geospace remote sensing. Miniaturization of high voltage power supplies will relieve mass and volume resource constraints. Increased quantum efficiency of UV and EUV detectors will enable significant savings in mass as small but sensitive instruments can be developed. The shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and power efficient ionization sources. Conductive polymers and other exotic materials and coatings may lead to development of solar blind detectors, new and better dust analyzers, and miniature mass spectrometers. It is important to develop and maintain ground test facilities for simulating particle and radiation environments in space. Radiation test facilities will be particularly important as technological innovations and the push to develop more power efficient instruments results in smaller electronic instrumentation. Ground testing is extremely valuable, but NASA's low-cost access to space (LCAS) program is required for complete testing and full validation of advanced instrumentation. Imaging is an area of instrumentation where we should place significant development effort. Remote imaging provides more information than any practical number of single-point measurements. Imaging is crucial to understanding the complex interacting set of systems that make up the Sun-Solar System well enough to develop the properly constrained and accurate predictive models that are critical to support exploration, including a sustained human presence in space. The three primary imaging tools include Energetic Neutral Atom (ENA), Radio Tomography, and Photon Imaging, Photon imaging includes x-ray, extreme ultraviolet (EUV), far ultraviolet (FUV), visible (VIS) and infrared (IR).

Space Environment Testbeds (SET): The LWS SET technology development project performs spaceflight experiments of new approaches for mitigating the effects of the dynamic space environment that are driven by solar variability. Its investigations validate new hardware, methods, models, and tools, all geared toward mitigating the effect of the space environment on systems.

External Cost Drivers Beyond Our Control

Scientists and engineers working on Sun-Solar System Connection science have overcome many of the problems of building, flying, and operating space missions. But our science is affected by factors beyond the control of the community. Each is founded on rational decisions made by groups in the larger society within which we work. Like St. Francis, we need "the serenity to accept the things [we] cannot change, the courage to change the things [we] can, and the wisdom to know the difference."

Space Launch Cost in the Free Market

The single largest cost in most space missions is the launch vehicle. Unlike other technologies, the cost to orbit a kilogram has remained nearly constant over the past decade.

Why is the cost so high? Space launchers are the most difficult challenges in engineering and manufacture because the forces and energies present in a launch vehicle are so great that they prevent graceful failures. From 1988 to 1999, 4% of launches failed in ways that required their destruction to insure public safety. As an Aeronautics and Space Engineering Board report states "Destruct commands are often superfluous because vehicles explode or break up because of dynamic forces." In the early years of spaceflight, NASA solved this problem by building duplicate satellites, so that one might succeed if another failed. Today the response of the users has been to emphasize reliability of a small number of satellites.

The commercial space market provides about half of the global demand for launch vehicles. The 2004 FAA/COMSTAC forecast of commercial demand shows that the launch rate is static at ~22 per year from 2000 until 2013. The principal change has been the demand for very large satellites, with the average mass per satellite growing from 2,400 kg in 1993-94 to 4,100 kg in 2003-04. The recent development of EELVs by the DoD suggests that their needs are similar to those of the commercial market. Some of the other Federal space activities, including NASA, also need large spacecraft and launchers. Taken together, the manufacturers of space launchers have good reason to focus on larger vehicles. The constant, small numbers of launches prevents economies of scale. To recoup the high development costs of new launchers, it is desirable to stop the production of older, smaller vehicles. Opportunity for small, simple, inexpensive, or risky payloads is absent when only large, expensive vehicles are available. Only large, expensive spacecraft make commercial economic sense.

Yet, many NASA science missions can be accomplished with much smaller, less costly spacecraft. The SMEX, MIDEX, Discovery, ESSP, and New Millennium mission lines are all highly productive and depend on smaller vehicles.

Public Trust and Risk Tolerance

NASA provides the visible demonstration of the value of American technological society to solving grand problems. The inspiration provided by a great success such as the Mars Rovers is matched by the disappointment and concern attached to failures of other missions. Success and failure are visible and owned by the American public.

Personal freedom is one foundation of American society. We accord individuals the right to pursue activities that have significant risk of failure, even injury or death, as a price of that freedom. These private risks, taken voluntarily, are accepted. Risk in systems supported or controlled by tax funds is not accepted. Public safety and fiscal responsibility require detailed investigation to determine causality and future improvement. Examples include airline or other controlled transportation accidents, military accidents, and NASA accidents.

NASA missions are growing in size, cost, and complexity. Growing complexity drives a compounding of levels of risk management, including detailed process control, frequent reviews, and greater requirements on project management. Risk management seeks to minimize avoidable failures, which imposes delay and unplanned costs on all missions because they share common technologies independent of their science focus. As with other complex aspects of our society, the cost of risk management is an increasing fraction of the total.

Yet, risk is a critical part of the process of learning to succeed. NASA fosters future success by offering broad range of projects and missions to permit new generations to learn through trial and error, and help the best progress to larger projects. The desire to minimize risk must be tempered by a desire to maximize long-term success.

National Security

Space technology provides unique contributions to national security, in reconnaissance, navigation, and communication (and space weather effects on such systems). American technological advantages over potential adversaries drives restrictions on civilian space interactions with foreign collaborators. Recent increases in these restrictions, founded in the International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR), apply even to scientific interactions with friendly nations. NASA has accorded Principal Investigators (PI) freedom to involve foreign collaborators. The cost of these positive foreign interactions is increasing in order to insure the required compliance with ITAR/EAR restrictions. One result is decreased opportunities for the cost-sharing of space missions.

Yet, foreign contributions, such as the Huygens lander on the Cassini mission, have immeasurably improved the quality of many science missions. Strengthening the technical teamwork between the U.S. and our partners permits activities that could not be achieved separately.

NASA and External Factors

These problems are opportunities for NASA leadership. Fiscal responsibility, scientific and technological opportunities are strong arguments for working to maintain a range of launch vehicles, both large and small. This is a capability important to NASA.

The public and future scientists are inspired by spaceflight because it challenges us to advance the limits of our abilities. Engaging the public in the challenges and inherent risks of pioneering spaceflight and exploration is an opportunity for E/PO on these issues in modern systems. NASA's work with its communities to develop the most cost-efficient methods for appropriate risk management of complex space projects is a capability that can improve many areas of our technical society and economy.

Foreign collaborations add value that advances America's space goals. Aiding its projects to achieve cost-effective compliance with ITAR rules is a capability important to NASA. Continued dialog and negotiation between NASA and the other relevant agencies to develop and clarify more appropriate rules for space research missions will enhance the capability of those agencies for dealing with other critical technical issues.

Advancing U.S. Scientific, Education, Security, and Economic Interests

The **International Heliophysical Year** (ihy.gsfc.nasa.gov): The U.S. House of Representatives Science Committee approved House Con. Resolution 189: Celebrating the 50th anniversary of the International Geophysical Year (IGY) and supporting an International Geophysical Year-2 (IGY-2) in 2007-08. The resolution calls for a worldwide program of activities to commemorate the 50th anniversary of the most successful global scientific endeavor in human history - the International Geophysical Year (IGY) of 1957-58. The resolution also calls for an "IGY-2" that would be even more extensive in its global reach and more comprehensive in its research and applications.

U.S. External Partnerships and Relationships

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious. The nation's efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, and planetary environments as a single connected system. External constituencies requesting and making use of new knowledge and data from NASA's efforts in this area include the Federal Aviation Administration (FAA), the Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA), the power industry, and the industry of satellite manufacturers and operators.

Constituencies within NASA include the Exploration Systems Directorate, the Space Operations Directorate, the Deep Space Network, and the various satellite operations centers.

International Cooperation

International Living with a Star: In January 2002, the Interagency Consultative Group (IACG) established the International Living With a Star (ILWS) program. The IACG consists of the heads of the space science programs of the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), the National Aeronautics and Space Administration (NASA), and the Russian Aviation and Space Agency (RASA). The charter for ILWS is to

NASA Constituencies	real-time space weather data	space environment specification	satellite anomaly diagnosis	navigation, radar, communication, transmission media error corrections	spacecraft subsystem technology transfer	models of space processes for use in nowcasting and forecasting
Satellite Operation Centers	●		●			
Space Operations Directorate	●	●				●
Exploration Systems Directorate		●				●
DSN/TDRSS/other communications	●			●		●
External Constituencies						
NOAA/NWS	●	●				●
FAA	●			●		
DoD	●	●	●	●		●
Commericial Satellite Operators	●	●	●		●	
Power Industry	●					●
Communication Industry	●			●		●

Table 1: NASA and external constituencies requesting and making use of new knowledge and data from NASA's Sun-Solar System Connections group.

"stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity". More than 20 contributing organizations are listed at http://ilws.gsfc.nasa.gov.

Currently Operating SSSC Missions with significant International participation:

Solar Heliospheric Observatory (SoHO)	partnership with ESA
Geotail	Partnership with Japan/JAXA
Cluster	partnership with ESA
Ulysses	partnership with ESA

SSSC Missions in Development with significant International participation:

Solar-B	partnership with partnership with Japan/JAXA, ISAS, PPARC
STEREO	contributions from CNES, Switzerland, DLR, PPARC, ESA, Hungary
THEMIS	contributions from Canada, CNES, DLR, and Austria
MMS	contributions from recently-selected international partners
AIM	agreement with British Antarctic Survey, Australia
TWINS	contributions from DLR

Near-term Mission Concepts:

Solar Orbiter	possible partnership with ESA
LWS/ Geospace	possible contributions from to-be-selected international partners
LWS/Sentinels	possible contributions from to-be-selected international partners

Appendices

A. 2005 Sun-Solar System Connection Roadmap Teams

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Al Diaz, *NASA Headquarters*
Timothy Killeen, *National Center for Atmospheric Research*
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Committee Members:

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Scott Bailey, *University of Alaska*
Thomas Bogdan, *National Center for Atmospheric Research*
Cynthia Cattell, *University of Minnesota*
Scott Denning, *Colorado State University*
Gregory Earle, *University of Texas at Dallas*
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B. Bibliography of Key Agency and NRC Documents

Key Agency Documents

A Journey to Inspire, Innovate, and Discover, June 2004 (the Aldridge Commission Report).

The Need to Transform the Structure and Management of NASA, Report of the Roles, Responsibilities And Structures ("Clarity") Team, June 24, 2004.

A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report, January 30, 2004 (the Diaz Report).

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Space Science Enterprise Strategy, October 1, 2003.

Sun-Earth Connection Roadmap, 2003-2028, January 2003.

Enhancing Mission Success -- A Framework for the Future, A Report by the NASA Chief Engineer and the NASA Integrated Action Team, January 2001.

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Solar and Space Physics and Its Role in Space Exploration, Committee on the Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, Space Studies Board, National Research Council, 2004, ISBN 0-309-09325-2.

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Issues and Opportunities Regarding the U.S. Space Program, Summary report of a workshop on National Space Policy, National Research Council, 2004.

The Sun to the Earth -- and Beyond: Panel Reports, Solar and Space Physics Survey Committee, Committee on Solar and Space Physics, National Research Council, 2003, ISBN 0-309-08972-7

Assessment of NASA's Draft 2003 Space Science Enterprise Strategy, a letter report, May 29, 2003

Assessment of NASA's Draft 2003 Earth Science Enterprise Strategy, a letter report, July 31, 2003

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Review of NASA's Earth Science Enterprise Applications Program Plan, Task group report, 2002

Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data, task group report, 2002.

Assessment of Mars Science and Mission Priorities, Committee on Planetary and Lunar Exploration, 2001, ISBN 0-309-08917-4.

NRC Bibliography (Past 5 Years) - *continued*

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Assessment of Mission Size Trade-offs for NASA's Earth and Space Science Missions, Space Studies Board Ad Hoc Committee on the Assessment of Mission Size Trade-Offs for Earth and Space Science Missions, Space Studies Board, National Research Council, 2000, ISBN 0-309-06976-9.

The Role of Small Satellites in NASA and NOAA Earth Observation Programs, SSB, 2000

Radiation and the International Space Station: Recommendations to Reduce Risk, Committee on Solar and Space Physics and Committee on Solar-Terrestrial Research, National Research Council, 2000, ISBN 0-309-06885-1.

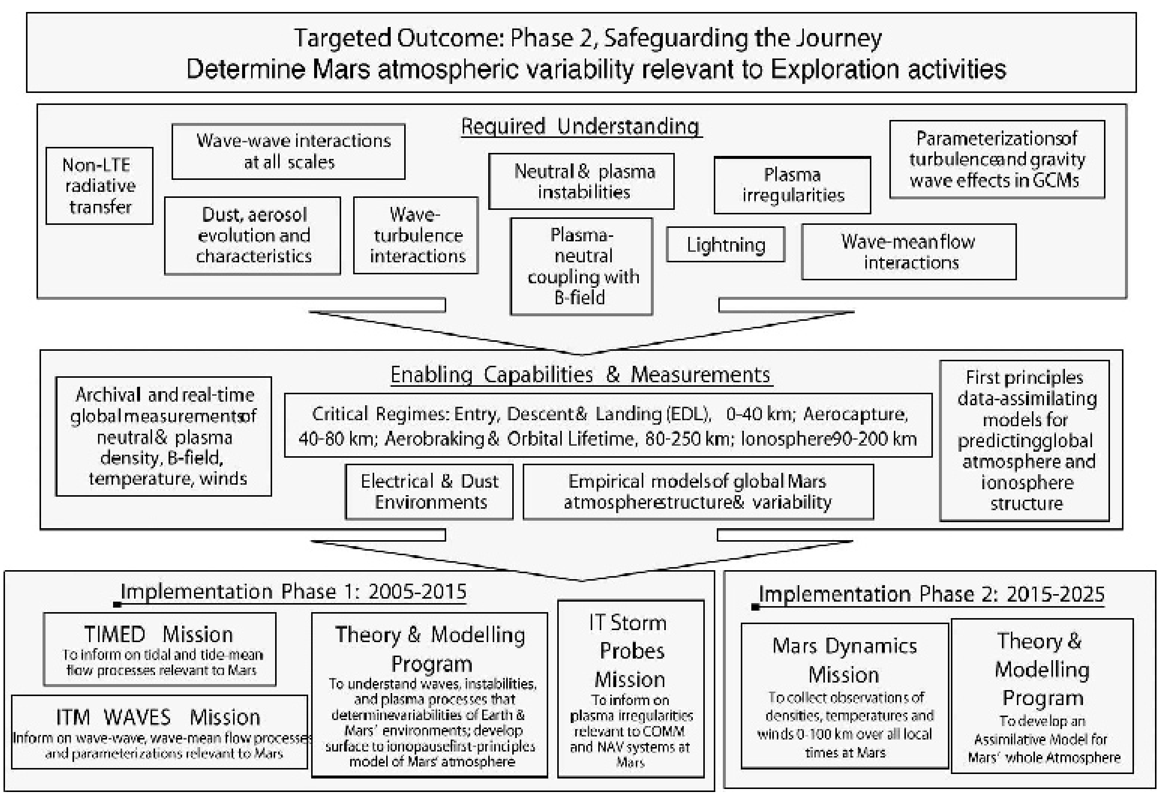
C. Reconciling the Roadmap and Decadal Survey Approaches & Results

Recognizing that a 'business as usual' approach was not likely to be effective, this Roadmap has taken a different approach to prioritizing the SSSC strategy. Beginning with the NASA strategic objective assigned to the new Sun-Solar System Connection division, the Roadmap Committees performed a complete requirements-driven derivation of a program to meet the nation's needs. The committee was supplied by the reports developed by the NRC, including the Decadal Survey and the update to that survey. The committee was also informed by community input in form of formal reports, white papers, through a community workshop, and through personal contacts.

The three top SSSC objectives were broken down into research focus areas that support the achievement of the top-level goal. The focus areas in turn led to two somewhat independent, more detailed breakdowns of effort – investigations and targeted outcomes. This contrasts with past efforts that have been constructed essentially from the bottom up based primarily on scientific priorities and opportunities as well as the perceived needs of the users of SSSC science.

The investigations present the more familiar scientific approach to organizing the efforts, one that lays out a logical progression toward addressing the broad topics outlined in the research focus areas. The investigations are enumerated in Part II Chapter 1 with the descriptions of the research focus areas for each objective. With each investigation it was relatively straightforward to identify missions and supporting elements of the program required to made real progress. Setting priorities was more difficult.

The targeted outcomes provide an alternate basis for constructing a program; one that the Roadmap Committees found helpful for assigning priority to various components of the program. We identified for each research focus area the achievements that should be completed during each of the next three decades. The achievements are shown in Part II Chapter 2. Each achievement resulted in a flow-down chart listing first the required understanding, then the enabling capabilities and measurements, and finally the implementation linked to missions and other supporting program elements. One sample chart is shown in the accompanying figure.



The timing of the achievements was driven first of all by what is required to support the new Vision for Space Exploration with which NASA has been tasked. With an ambitious, though not fully developed, schedule for returning humans to the Moon for an extended period followed by human mission to Mars, certain information is critical for defining and designing a safe and productive exploration program. SSSC science contributes crucial information to inform and enable that phased effort and we have ordered our programs to provide the necessary information at the appropriate time. Of course exploration is more than human spaceflight and the program emphasizes robotic exploration in pursuit of transformational knowledge as well.

Second, the scientific development of the program requires a logical progression of discovery, understanding and prediction. While these go hand-in-hand and different parts of the program are in different stages, this criterion is similar to the drivers used to formulate our strategic plans in the past. The difference this time is that the scheduling is driven by more than just the simple desire to pick the questions that show the most promise for progress. This time we were looking for progress in particular areas.

Our final criterion was to define a program that is possible to achieve – both technically and financially. This was a real challenge with the reduced funding available in both the Explorer and STP programs. Many important topics are deferred, put aside, or left for implementation in the Explorer program. The optimized plan restores many synergies lost in the realistic plan.

How did the resulting program compare to earlier recommendations provided in the decadal survey and previous SEC Roadmaps and NASA Enterprise Strategy?

The NRC and roadmap committees ended up in remarkably similar places. The science and exploration objectives, the research focus areas, investigations, and achievements match very well. There is a somewhat broader scope in this road map because of the connections with Earth science, the new emphasis on the journey of exploration, and the longer time period considered. The missions proposed include all the top priorities of the 2002 NRC Report The Sun to the Earth - and Beyond for NASA. Together with the completion of STEREO, Solar-B, and SDO and the continued operation of the SSSC Great Observatory, these include Solar Probe, MMS, RBSP & ITSP, JPO/Juno, IH Sentinels, GEC, LCAS, MMS, L1/Heliostorm, GEMINI, L1 Monitor, Solar Orbiter, Explorers, and all of the relevant recommendations for vitality as well. (A few mission names have changed). Table B2 gives a detailed comparison between the 2002 Decadal Survey Science Challenges and the Research Focus Areas described in Part II, Chapter 1.

How can this be? 1) The basic science needed to predict conditions for safe and productive exploration is the same understanding required to handle the affects of the space environment on society. The requirements for the outward journey have been largely anticipated by LWS. 2) The strategy laid out in the past was robust, in the sense that the long-term objectives transcend most immediate changes in emphasis. Understanding of the entire system was crucial and remains crucial. The science questions and the order in which they must be addressed remain the same in order to open the frontier to space weather prediction. The STP missions fly at a slower rate, but the basic science they will provide serves the most important needs of the NASA vision. 3) With reduced resources the missions already initiated will take the remainder of the decade to complete. In our realistic scenario no mission will launch before 2015 that has not already begun and this time frame goes beyond the end of the decadal survey. Because these missions support the vision, the program looks very much the same in the near term as it did three years ago.

There are some important changes to the intermediate and long term program. The importance of the inner heliosphere through which disturbances propagate has increased. New missions to understand energetic particles have been identified and we have recommended increased collaboration with Earth science colleagues to understand the terrestrial radiation budget. There is also increased emphasis on the contributions our discipline can make to understanding the Martian atmosphere and the role space weather effects have on planetary habitability. Decision points have been set where choices need to be made about the direction of the program based on evolving priorities and what is learned in the mean time. As in previous Roadmaps, a suite of unfunded flagship and partnership missions has been identified to address problems that cannot be handled in the existing mission lines; however, some of the partnership missions have changed. The importance of L1 observations has increased. And, unfortunately, many of the intermediate term missions from the last Roadmap have been pushed farther into the future.

Comparison of the 2005 SSSC Strategic Roadmap Primary Science Objectives Research Focus Areas the 2002 Decadal Survey Science Challenges

2005 SSSC Strategic Roadmap Primary Science Objectives & Research Focus Areas		2002 Solar and Space Physics Decadal Survey Science Challenges				
Objective F: Open the Frontier to Space Weather Prediction *Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium*		1. Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of solar cycle, the causes of solar activity, and the structure and dynamics of the corona	2. Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium	3. Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences	4. Understanding the basic physical principles manifest to processes observed in solar and space plasmas	5. Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in the Earth's magnetosphere
RFA F1: Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms	F1	X		X	X	
Research Focus Area F2: Understand the plasmas processes that accelerate and transport particles	F2	X			X	
RFA F3: Understand the role of plasmas and neutral interactions in nonlinear coupling of regions throughout the solar system	F3	X	X	X	X	
RFA F4: Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments	F4	X	X		X	
Objective H: Understand the Nature of Our Home in Space *Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields*						
RFA H1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment	H1	X		X	X	X
RFA H2: Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects	H2			X	X	X
RFA H3: Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving atmospheric and climate change	H3	X				X
RFA H4: Apply our understanding of space plasmas physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability	H4	X	X	X	X	
Objective J: Safeguarding our Outward Journey *Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space*						
RFA J1. Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers	J1			X		X
RFA J2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather	J2	X				X
RFA J3: Develop the capability to predict the propagation and evolution of space weather disturbances to enable safe travel for human and robotic explorers	J3		X			X
RFA J4: Understand how space weather affects planetary environments to minimize risk in exploration activities	J4		X	X		X

D. SSSC Mission Studies:

The following Roadmap Mission Quad Charts were prepared to provide a summary level description of the missions identified in the 2005 Roadmap. Additional mission quad charts identified as * are included to archive community ideas and missions identified in previous roadmaps that were actively discussed but not included in the 2005 Roadmap narrative. The level of study maturity for these roadmap missions varies from a quad chart concept and description, to engineering concept and Vision Mission studies conducted during and between roadmaps, and finally to missions in pre-formulation and science definition team study, formulation and implementation. The current SSSC Explorer, STP and LWS missions in formulation and implementation are included to connect the present program through science objectives and achievements with the missions described in this Roadmap. The evolution of mission priorities derived from the NASA Strategic Planning and Budget process provides the direction and pace of additional studies for selected missions to raise their study maturity level in support of this process.

Alphabetical Listing of Quad Chart Summaries

Aeronomy of Ice in the Mesosphere (AIM)
Auroral Acceleration Multi-Probes (AAMP)
Aeronomy and Dynamics at Mars (ADAM)
Bepi-Colombo (BC)*
CINDI
Dayside Boundary Layer Constellation (DBC)
Doppler
Farside Solar Observer
Geospace Electrodynamic Connections (GEC)
Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)
Geospace System Response Imager (GSRI)*
Heliospheric Imager and Galactic Observer (HIGO)
Heliostorm
Interstellar Boundary Explorer (IBEX)
Inner Heliospheric Sentinels (IH Sentinels)
Inner Magnetospheric Constellation (IMC)
Interstellar Probe
Io Electrodynamics
Ionosphere Thermosphere Mesosphere (ITM) Waves
Ionosphere-Thermosphere Storm Probes (ITSP)
Janus*
Juno
L1 Diamond*
L1 Earth-Sun
L1 Mars
L1 Mission
L1 Solar-Climate Connection Explorer
Lunar Imaging Radio Array (LIRA)*
Magnetic TRAnsition region Probe (MTRAP)
Magnetosphere-Ionosphere Observatory (MIO)*

Magnetospheric Constellation (MC)
Magnetospheric Multiscale (MMS)
Mars AeronomyMars Atmospheric Reconnaissance Survey (MARS)
Mars Dynamics*
Mars GOES
Near Earth Solar Coronal Explorer (NESCE)*
Neptune Orbiter
New Horizons (Pluto)*
Radiation Belt Storm Probe (RBSP)
Reconnection and Microscale (RAM)
Solar-B
Solar Connection Observatory for Planetary Environments (SCOPE)
Solar Dynamics Observatory (SDO)
Solar Energetic Particle Mission (SEPM)
Solar Heliospheric & Interplanetary Environment Lookout for Deep Space (SHIELDS)
Solar Imaging Radio Array (SIRA)
Solar Orbiter
Solar Polar Imager
Solar Probe
Solar Sail Flight Validation (Sail Demo)
Solar-TERrestrial RElations Observatory (STEREO)
Solar Weather Buoys (SWB)
Space Environment Testbeds (SET)
Space Physics Package and Interface*
ST-5 Microsat Technology Constellation Validation
Stellar Imager
Sun-Earth Coupling by Energetic Particles (SECEP)
Sun-Earth Energy Connector (SEEC)
Telemachus
Time History of Events and Macroscale Interactions During Substorms (THEMIS)
Titan*
Two Wide-Angle Imaging Neutral-Atom Spectrometeres (TWINS)
Tropical ITM Coupler
Venus Aeronomy Probe
Whole Sun Sentinels*

Mission	Mission Study Status	Concept Maturity	2000 RN Study	2002 RN Study	2004 RN Study	2003-4 IRN	Vision Mission	2002-3 RN	SDT	Perform	Formulat	Implement	Comments	Planned Launch
	Near-Intermediate/Pre Lunar (2005-2016)													
	STP Missions													
[illegible]	[illegible]	H		D	D							STP		2008
[illegible]	[illegible]	H		D	D							STP		2008
[illegible]	[illegible]	H		D	D						STP		[illegible]	2013
[illegible]	[illegible]	M-H		D	D				STP				[illegible]	
[illegible]	[illegible]	M-H		D	D				STP				[illegible]	
[illegible]	[illegible]	L	RN	RN	D									
[illegible]	[illegible]	L	RN	RN	RN									
[illegible]	[illegible]	LM	RN	RN	D	IRN							[illegible]	
	LWS Missions													
[illegible]	[illegible]	H		D	D							LWS		2008
[illegible]	[illegible]	H		D	D					LWS			[illegible]	
[illegible]	[illegible]	H		D	D					LWS			[illegible]	2015
[illegible]	[illegible]	M-H	RN	RN	D				LWS				[illegible]	2013
[illegible]	[illegible]	D			D									
[illegible]	[illegible]	D			D									
[illegible]	[illegible]	LM	RN	RN	D	IRN							[illegible]	
[illegible]	[illegible]	H			D							LWS		
[illegible]	[illegible]	LM		RN	D	IRN							[illegible]	
[illegible]	[illegible]	M-H		D	D				LWS				[illegible]	
	Explorers													
[illegible]	[illegible]	H										EXP		2008
[illegible]	[illegible]	H			D							EXP		2008
[illegible]	[illegible]	H			D							EXP		2008
[illegible]	[illegible]	H			D							EXP		2008
[illegible]	[illegible]	H			D					EXP			[illegible]	2008
	[illegible] Missions													
[illegible]	[illegible]	H										NF		2008
[illegible]	[illegible]	M	RN	RN	D						NF		[illegible]	
	Other Missions													
[illegible]	[illegible]	H			D				SDT		ESA		[illegible]	
[illegible]	[illegible]	H		D	D	IRN			SDT	ESA			[illegible]	
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	H			D							NMP		2008
[illegible]	[illegible]	LM			D					NMP				2010
	Long Term/Mars (2017-2034)													
	STP Missions													
[illegible]	[illegible]	L	RN	D	D									
[illegible]	[illegible]	L		RN	D									
[illegible]	[illegible]	L	RN	RN	D									
[illegible]	[illegible]	L		RN	RN									
[illegible]	[illegible]	L	RN	RN	D									
[illegible]	[illegible]	D		D	D									
[illegible]	[illegible]	LM	RN	RN	D	IRN							[illegible]	
[illegible]	[illegible]	LM		RN	D	IRN							[illegible]	
[illegible]	[illegible]	M	RN	RN	D		VM						[illegible]	
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	D		D	D									
[illegible]	[illegible]	L		D	RN									
[illegible]	[illegible]	M	D	D	D		VM							
	LWS Missions													
[illegible]	[illegible]	LM		D	D	IRN							[illegible]	
[illegible]	[illegible]	D		D	D									
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	L		D	RN									
[illegible]	[illegible]	D			D									
[illegible]	[illegible]	L	RN		D									
[illegible]	[illegible]	D		D	D									
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	L			RN								[illegible]	
	[illegible] Missions													
[illegible]	[illegible]	L	RN	D	D									
[illegible]	[illegible]	M					VM						[illegible]	
[illegible]	[illegible]	M	D	D	D		VM						[illegible]	
[illegible]	[illegible]	L	RN	D	RN								[illegible]	
[illegible]	[illegible]	L	RN		D								[illegible]	
[illegible]	[illegible]	L			RN									
[illegible]	[illegible]	D			D								[illegible]	
	Other Missions													
[illegible]	[illegible]	M	RN	RN	D		VM						[illegible]	

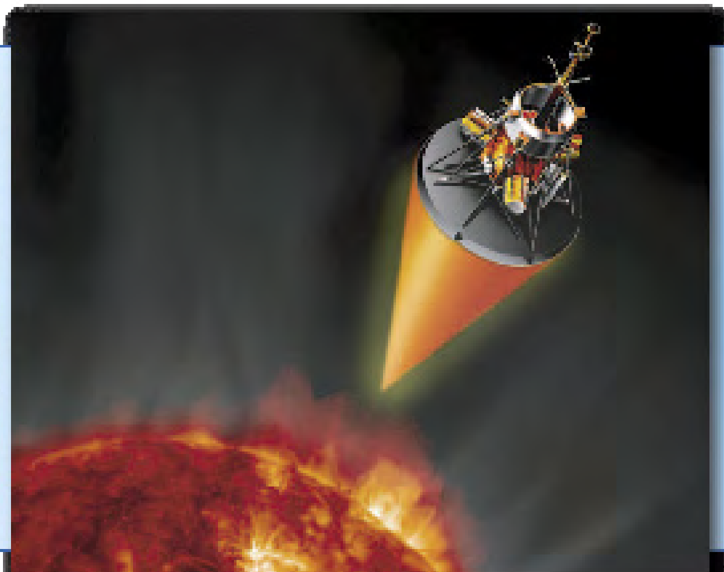
Notes

[illegible]

Insert Mission Quad Charts here - 2 per page

SSSC Landmark Discovery Missions

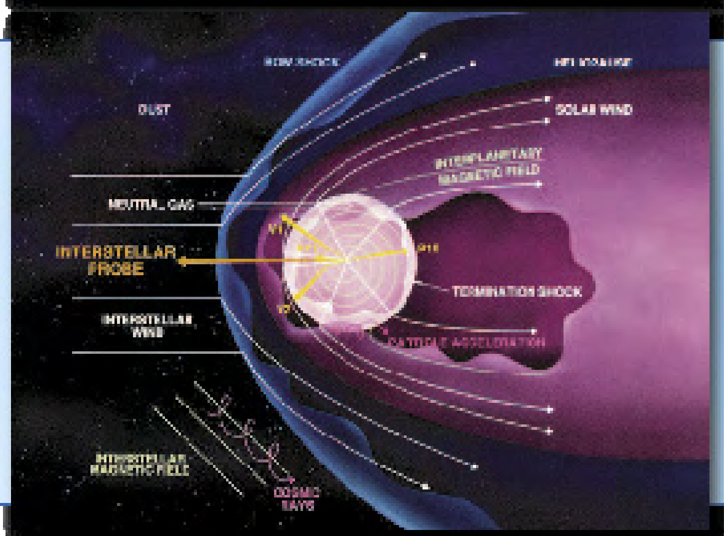
NEAR-IMMEDIATE TERM



Solar Probe

- Measure magnetic reconnection at the Sun
- Thermal shielding protection for in situ solar wind measurement at 4Rs

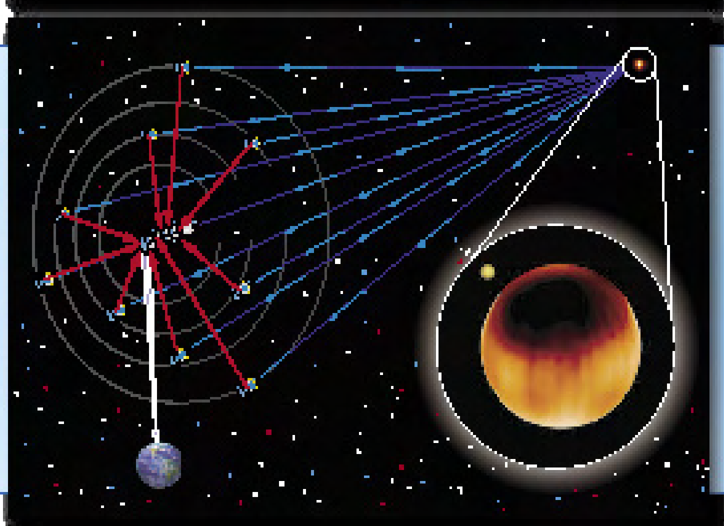
LONG-TERM



Interstellar Probe

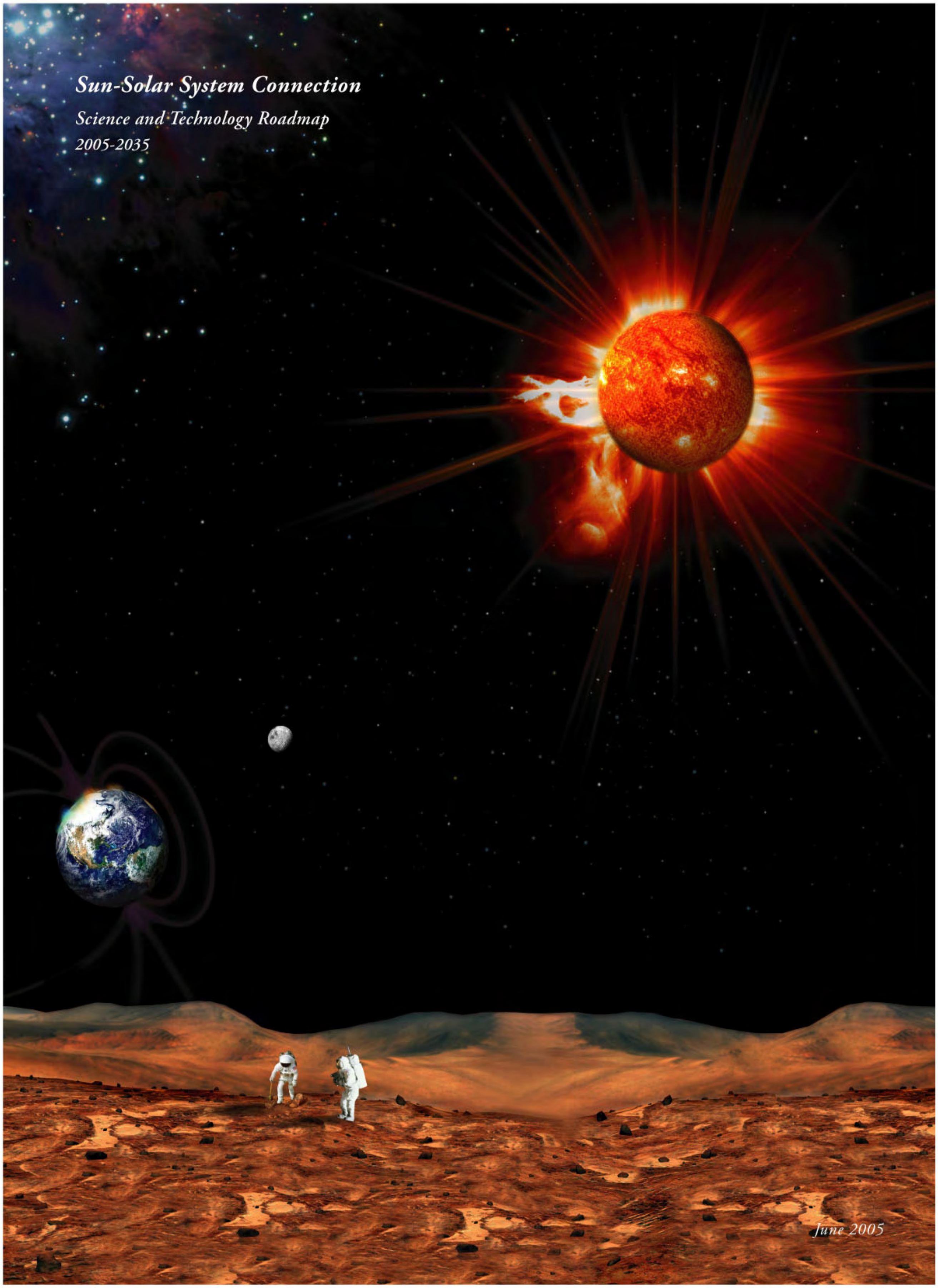
- Analyze the first direct sample of the interstellar medium
- Advanced propulsion for 200Au in 15 years

FAR-TERM



Stellar Imager

- Image activity in other stellar systems
- UV interferometry in space with precision formation flying autonomous constellation


Sun-Solar System Connection
Science and Technology Roadmap
2005-2035
June 2005