Chapter 2. Sun-Solar System Connection: The Program

Principles and Policies

The strategy presented in this document has been derived from the NASA Objective for SSSC to address the vital, urgent, and compelling needs of the nation. The community based SSSC Roadmap committees have solicited input from the constituents 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.

Implementation Strategy

The science and exploration program described in the previous chapter occupies a valuable niche in the NASA Science Mission Directorate. SSSC research will develop knowledge that transforms our 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 enable the science of the division.

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.

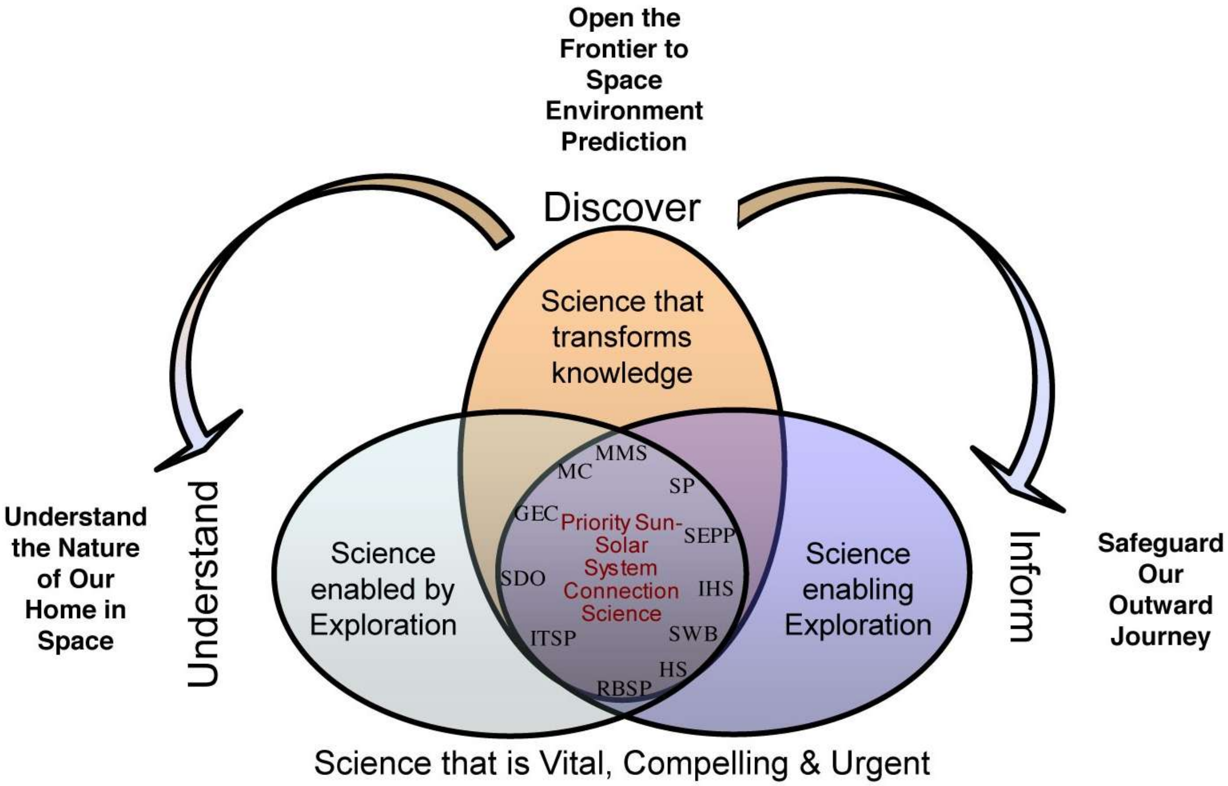
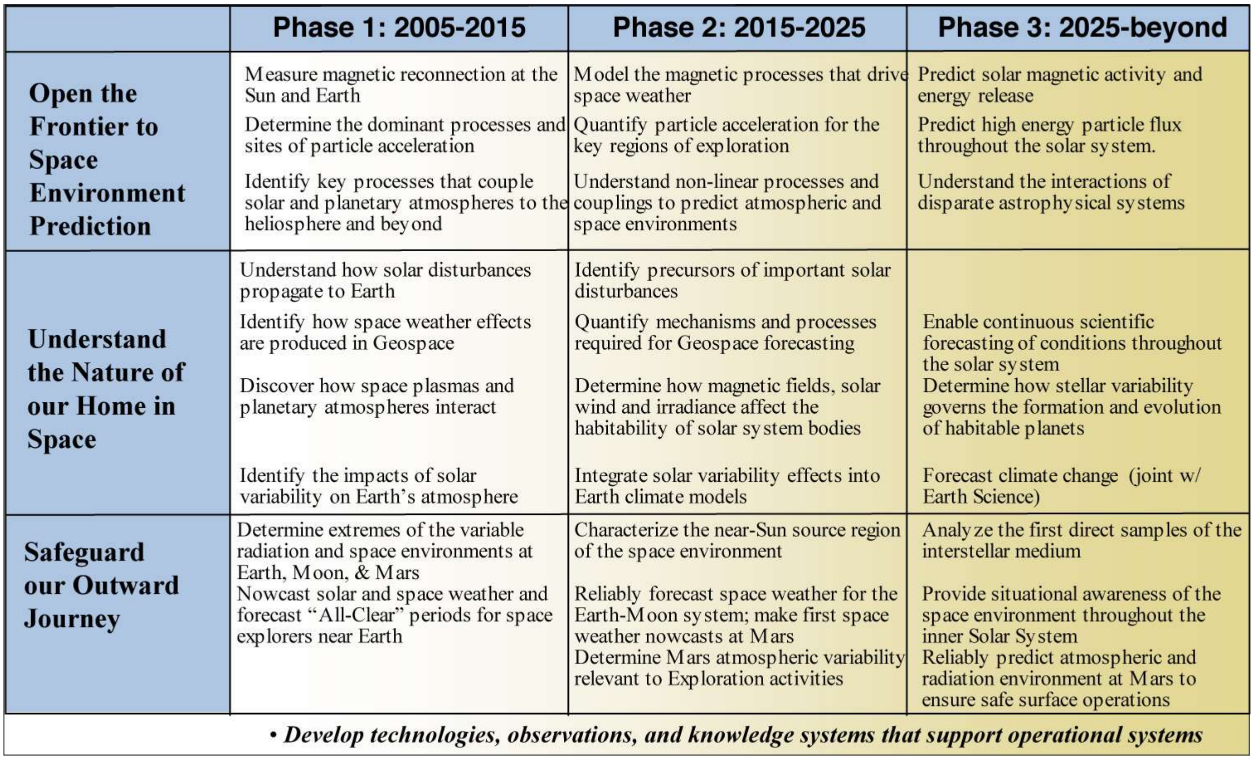


Figure Caption: The intersecting ovals illustrate the intersection of three categories of science: discovery science that is enabled by exploration, science that transforms our understanding, and science that informs to enable exploration. At the intersection is the 'sweet spot' where the highest priority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

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 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.



	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 Determine the dominant processes and sites of particle acceleration Identify key processes that couple solar and planetary atmospheres to the heliosphere and beyond	Model the magnetic processes that drive space weather Quantify particle acceleration for the key regions of exploration Understand non-linear processes and couplings to predict atmospheric and space environments	Predict solar magnetic activity and energy release Predict high energy particle flux throughout the solar system. Understand the interactions of disparate astrophysical systems
Understand the Nature of our Home in Space	Understand how solar disturbances propagate to Earth Identify how space weather effects are produced in Geospace Discover how space plasmas and planetary atmospheres interact Identify the impacts of solar variability on Earth's atmosphere	Identify precursors of important solar disturbances Quantify mechanisms and processes required for Geospace forecasting Determine how magnetic fields, solar wind and irradiance affect the habitability of solar system bodies Integrate solar variability effects into Earth climate models	Enable continuous scientific forecasting of conditions throughout the solar system Determine how stellar variability governs the formation and evolution of habitable planets Forecast climate change (joint w/ Earth Science)
Safeguard our Outward Journey	Determine extremes of the variable radiation and space environments at Earth, Moon, & Mars Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Characterize the near-Sun source region of the space environment Reliably forecast space weather for the Earth-Moon system; make first space weather nowcasts at Mars Determine Mars atmospheric variability relevant to Exploration activities	Analyze the first direct samples of the interstellar medium 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 thoroughly considered. 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.

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; low cost access to space for unique science, community health, and instrument development needs; technology development; 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 confront major road blocks to future progress. Flagship missions have great promise for scientific advance, but may cost four or more times as much as an Explorer. Missions of this scope cannot be accomplished within the current resource limits of the program without fatally compromising the rest of the program. Flagship missions are identified separately as top priorities for additional funding.

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. Achievements identified in Table 2.1 correspond fairly well to these phases.

Our Phase 1 program presumes the continued operation of missions in the Great Observatory. The baseline Phase 1 program includes only new missions that are already in development or whose announcement is expected in the very near future. STEREO, Solar-B, and MMS in the STP program, SDO and RBSP in the LWS program, and the selected Explorers: AIM, THEMIS, and IBEX. Additional Explorers will close gaps in the program. The 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 the first plunge through the 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 and some of the missions identified for early in Phase 2. The multiple synergies and comprehensive views afforded by the 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 questions.

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 - the Inner Heliosphere Sentinels and ITSP. These rely on 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. 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 section 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.

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. Rockets and balloons provide low-cost rapid access to space. The fleet of existing missions makes up a Great Observatory that evolves as new missions are launched and new combinations of observations are made. 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.

Solar Terrestrial Probes

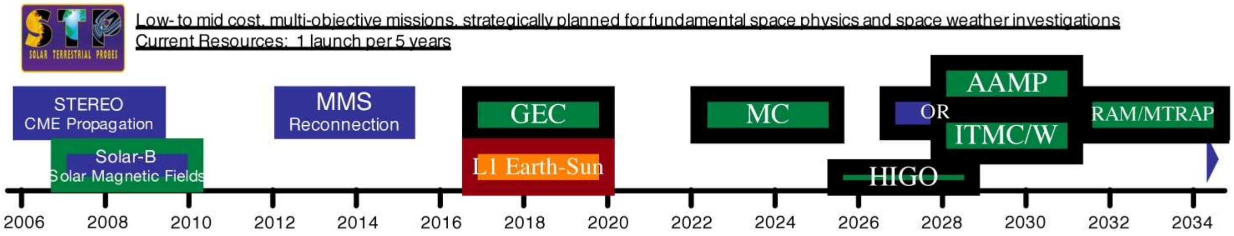
The Solar Terrestrial Probe investigations focus on specific scientific areas required to advance our fundamental understanding of the Sun – Solar System Connection. Subsequent missions target the ‘weakest links’ in the chain of understanding. STP missions are strategically defined and investigations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

STP is one of two strategic lines for the Sun-Solar System Connection. Strategic mission lines afford the space physics community the opportunity to plan specific large 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 mesophere 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 poorly observed region just below stable satellite orbits where the interactions of the charged and neutral components of the atmosphere become more important – the linkage between 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 Section.

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.



The figure shows the STP missions identified for flight through 2035 in our current budget projection. Blue boxes represent anticipated SSSC resources, in units of medium sized missions. Mission names in blue boxes indicate that these resources are committed and development is underway. Green boxes represent new missions assigned here to blue box 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. Orange boxes represent Flagship or Partnership missions dependent upon anticipated resources from outside current SSSC Programs.

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

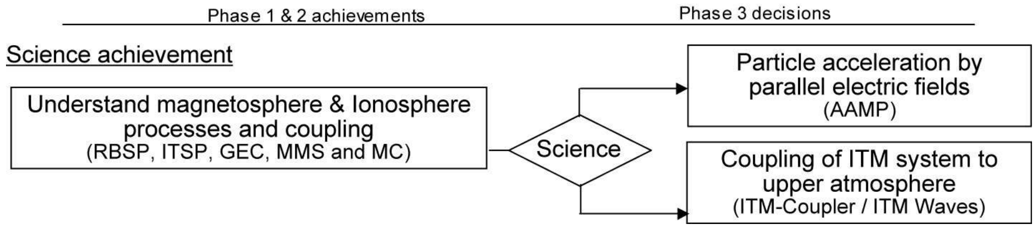
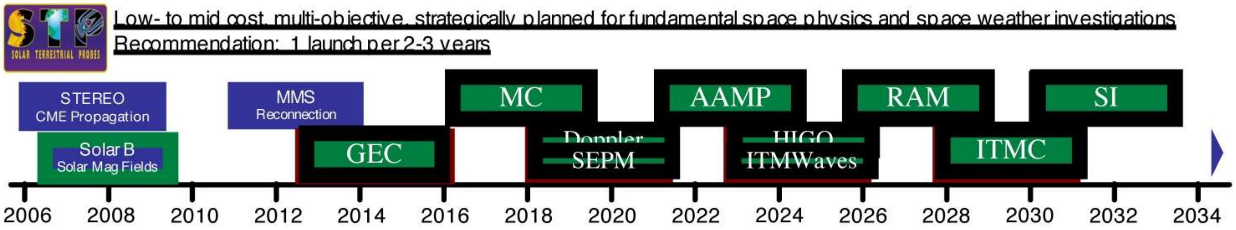


Figure Caption: Schematic illustrating a decision point for selecting a future mission.

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.



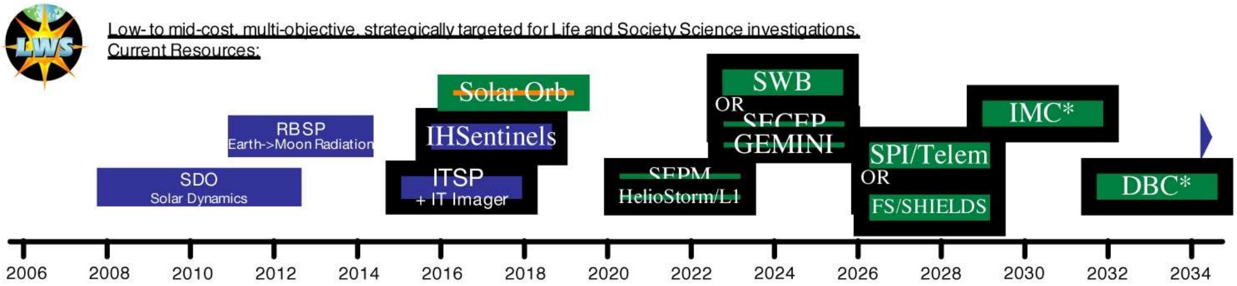
The figure shows the mission identified for flight through 2035 in our optimized scenario. The synergy of mission is apparent.

Living with a Star

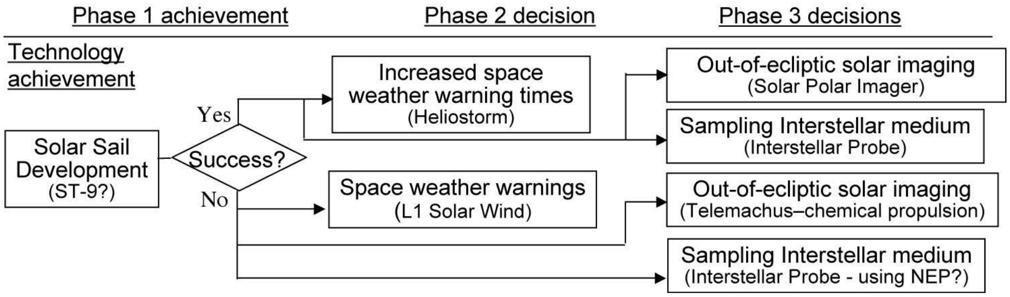
The Living With a Star program emphasizes the science necessary to understand those aspects of the space environment that affect life and society. The ultimate goal is to provide a predictive capability for the space weather that affects us. LWS missions have been formulated to answer specific science questions needed to understand the linkages among the interconnected systems that affect 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 missions are currently in development or about to be announced: 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. Two pairs of geospace storm probes complement SDO to measure the terrestrial environment at the same time. 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. The second, the Ionosphere-Thermosphere Storm Probes (ITSP) also includes a separate imaging instrument.

Our Roadmap concurs with earlier recommendations that the next two LWS missions should complete the geospace storm probes by launching ITSP and explore radial evolution of structures with the Inner Heliosphere Sentinels (IHS) mission. The priority of the ITSP mission is driven by the very practical need to aid communications and navigation; ITSP will survey the global distribution of ionospheric and thermospheric densities, ionospheric irregularities, and geomagnetic disturbances as a function of varying solar and geospace conditions. The Exploration Initiative raises the priority of the IHS mission because hazardous space weather near Earth cannot be understood without it. In our realistic scenario for LWS these two missions are launched within a year of each other in 2015 and 2016. Our optimized scenario moves these missions up to increase 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 IHS in situ measurements and will provide solar observations from a different vantage point.



The next LWS missions in Phase 2 address understanding energetic particle production near the Sun with the Solar Energetic Particle Mission (SEPM) and better measurement of the solar wind and energetic particle inputs to geospace with Heliostorm or an L1 Mission. These two missions can be smaller in cost than typical strategic missions. The choice between Heliostorm and an L1 mission is complex. Heliostorm would use solar sails to hover another hour or two upstream of the L1 point in the solar wind; this mission depends on a timely demonstration flight of solar sail technology. 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.



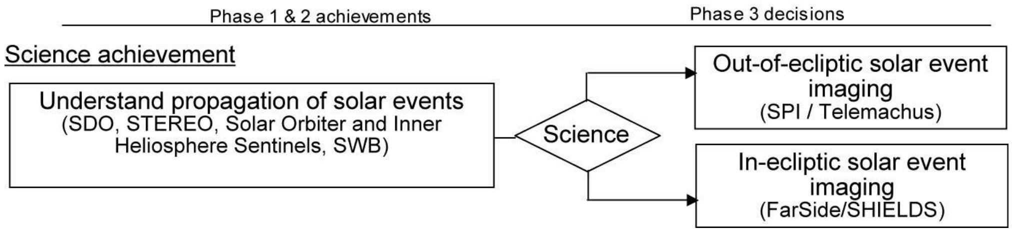
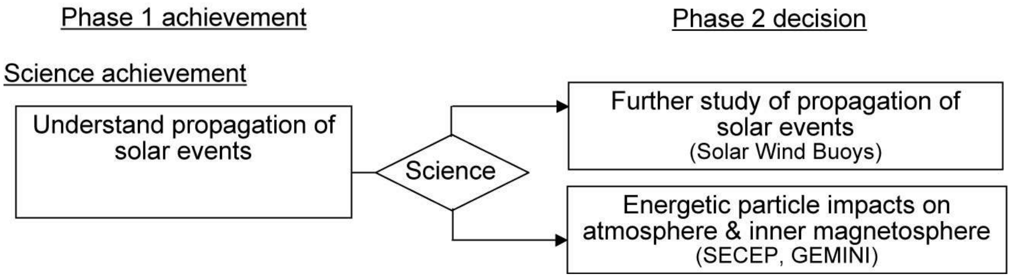


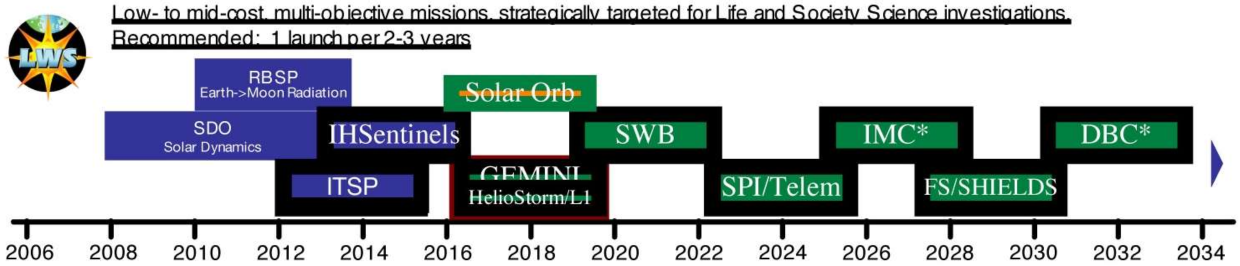
Figure Caption: The diagrams suggest decision points for future missions based on technology or science criteria.

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 IHS 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 proscribed 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 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.

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.

[[[[INSERT FLAGSHIP/PARTNERSHIP TIMELINE HERE]]]]

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 IHS, 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.

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

The strategic objective addressed in this roadmap is intrinsically one of *connections*, of influences extending over vast distances to produce dramatic effects throughout the solar system. Because these connections are generally mediated extremely locally by largely invisible agents -- plasmas and magnetic fields -- the science of Sun-Solar System Connections must rely on multi-point *in situ* measurements and remote sensing measurements from platforms deliberately distributed throughout the solar system.

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." Our Great Observatory is a fleet of solar, heliospheric, geospace, and planetary spacecraft 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 remote sensing, in situ measurements, data analysis, and models to provide physical understanding and predictive capability for space weather. 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 help predict tomorrow’s space weather. The measurement capabilities include imaging the Sun; sensing *in situ* and remotely the disturbances in interplanetary space; and measuring particles, fields, and radiation in geospace, remotely and *in situ*. Continuing and evolving this distributed observatory to meet the needs of the Vision for Space Exploration is one of the community’s highest priorities.

The very large “Halloween Solar Superstorms” described in the next section demonstrate the unique and powerful capability of the SSSC Great Observatory to view a system of systems. The effects of the solar storms from the Sun to the Earth and beyond were observed simultaneously in key regions and from specific vantages. It would not have been possible to link the consequences of these superstorms at Earth and Mars to the solar drivers without this collection of satellites and the human and computational resources to interpret the data. The power of the Great Observatory comes from the combination of multiple operational assets, focused and large-scale models, and associated data analysis. Many of the spacecraft are SSSC missions, but additional “observation posts” are provided by spacecraft 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 these responses were different in order to meet the needs of the Vision for Space Exploration.

The Great Observatory is vital to explain fundamental physical processes at work throughout the complex, coupled system that is the Sun-Solar System. For example, magnetic reconnection between the interplanetary and terrestrail magnetic fields is the critical physical process determining the size of a geomagnetic storm. We have greatly increased our understanding of the role of this process by relating upstream solar wind measurements to *in situ* data near the small dayside reconnection site and to satellite-based images of the corresponding ionospheric airglow emissions. Similarly, using assets spread throughout the solar system, we have significantly improved our understanding of how solar activity modulates galactic cosmic rays. These discoveries about the foundational physics of our solar system were made possible by the combined resources of our Great Observatory: the coupled observations, the detailed data analysis, the extensive modeling efforts, and the knowledge of the underpinning theory. 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 MO&DA) 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 by the community to maximize the return on the agency investments. The 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 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.

New missions are 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 meet the new needs of the Vision for Space Exploration as articulated in this road map, new missions will be needed in order to characterize, understand and predict the dynamic environmental conditions in space to maximize the safety and productivity of both human and robotic space explorers. 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.

The SSSC Great Observatory in Action: The 2003 Halloween Solar Storms

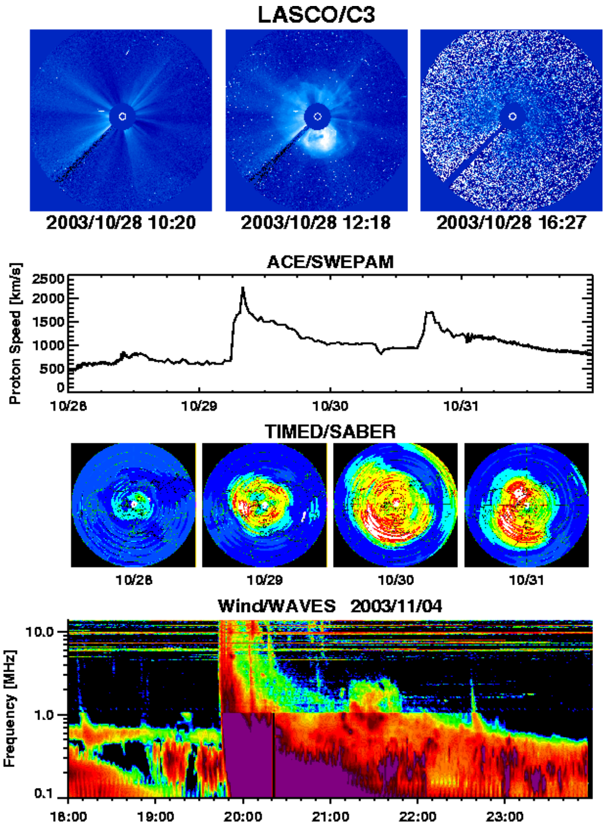
The violent solar eruptions of late October and early November 2003 are the best observed outbreak of intense solar activity to date. These events, referred to as the 2003 Halloween Storms, are extreme events in terms of both their source properties at the Sun and their heliospheric consequences. The plasma, particle and electromagnetic consequences of these events were felt throughout the heliosphere thanks to the distributed SSSC Great Observatory.

Disturbances associated with two of the solar eruptions arrived at Earth in less than 24 hours, providing benchmark data for space weather purposes. Historically, there have been only 13 such events, including the historic Carrington event of September 1, 1859. Several characteristics of the Halloween Storms displayed extreme behavior, including active region size and potential energy, flare occurrence rate and peak intensity, CME speed and energy, shock occurrence rate, solar energetic particle (SEP) occurrence rate and peak intensity, and the geomagnetic storm intensity.

About 59% of the reporting spacecraft and about 18% of the onboard instrument groups were affected by these storms. Electronic upsets, housekeeping and science data noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation, and proton heating were observed. Most earth-orbiting spacecraft were put into safe mode to protect from the particle radiation. Significant impacts also affected society: about 50,000 people in southern Sweden (Malmoe) experienced a blackout, where the oil in a transformer heated up by 10 degrees; surge currents were observed in Swedish pipelines; numerous occurrences of degradation and outage of GPS systems were reported; and several teams on Mount Everest experienced interference in high-frequency radio communications.

The solar energetic particle event on October 28, 2003 caused a significant ozone depletion between 50 and 80 km from the ground. A ten-fold enhancement in the ionospheric total electron content over the US mainland occurred during October 30-31. Extraordinary density enhancements in both the magnetosphere and ionosphere coinciding with intervals of southward IMF and high-speed solar wind were observed.

When the storms arrived at Mars the MARIE instrument on board the Mars Odyssey succumbed to the onslaught of radiation. The storms continued past the orbits of Jupiter and Saturn as detected by Ulysses and Cassini, respectively. Wind, Ulysses and Cassini radio instruments at widely different vantage points also observed a radio burst resulting from colliding CMEs on November 4, 2003. Finally, after about 180 days, the disturbances reached Voyager 2, piled up together as a single merged interaction region (MIR), which led a large depression in cosmic ray intensity, lasting more than 70 days. Although it is not that unusual for such solar eruptions to occur during the declining phase of the solar cycle, these events bench mark the level of understanding we have on the behavior of the sun over different time scales. The fleet of spacecraft in the Great Observatory helped us not to be taken by surprise by the Halloween Storms.



Caption: *The solar corona from SOHO before, during and after the fast halo coronal mass ejection (CME) on October 28, 2003 (top row). The image taken after the CME is seriously degraded by the energetic particles from the CME. This CME and the next one on October 29 resulted in record solar wind speeds as measured by the Advanced Composition Explorer near L1 (second row). Outgoing energy flux radiated by atmospheric nitric oxide at 5.3 micron as measured by TIMED increased drastically during the October 2003 storms (third row). The fastest CME of this period occurred on November 4; shortly thereafter it collided with a preceding CME and produced an intense radio signature detected by the Wind spacecraft (bottom). This signature was also detected by Ulysses and Cassini spacecraft from distant locations in the heliosphere.*

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. 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), 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), 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 will begin 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 to improve 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 question 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 research 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 be 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 small levels that might otherwise be overlooked. NASA should also seek to expand current partnerships with industry, universities, and other agencies. For example, current successful EPO efforts tend to focus on K-12 levels without adequate resources for the critical later years when college students are making career decisions and may need additional inspiration to continue toward a career in space physics.