National Aeronautics and Space Administration

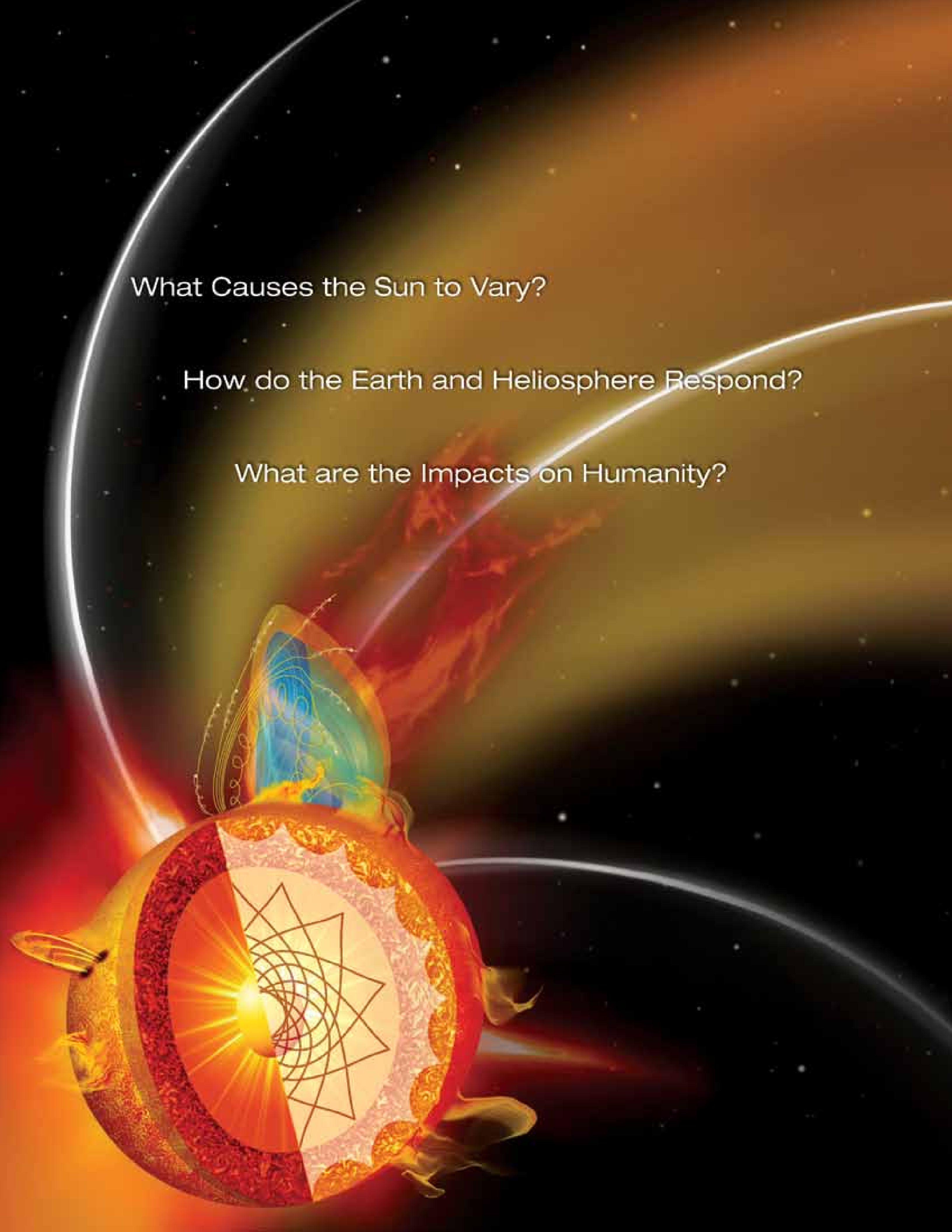
Heliophysics

THE SOLAR AND SPACE PHYSICS OF A NEW ERA

Recommended Roadmap for
Science and Technology 2009–2030

2009 Heliophysics Roadmap Team
Report to the NASA Advisory Council
Heliophysics Subcommittee
May 2009

heliophysics


What Causes the Sun to Vary?
How do the Earth and Heliosphere Respond?
What are the Impacts on Humanity?

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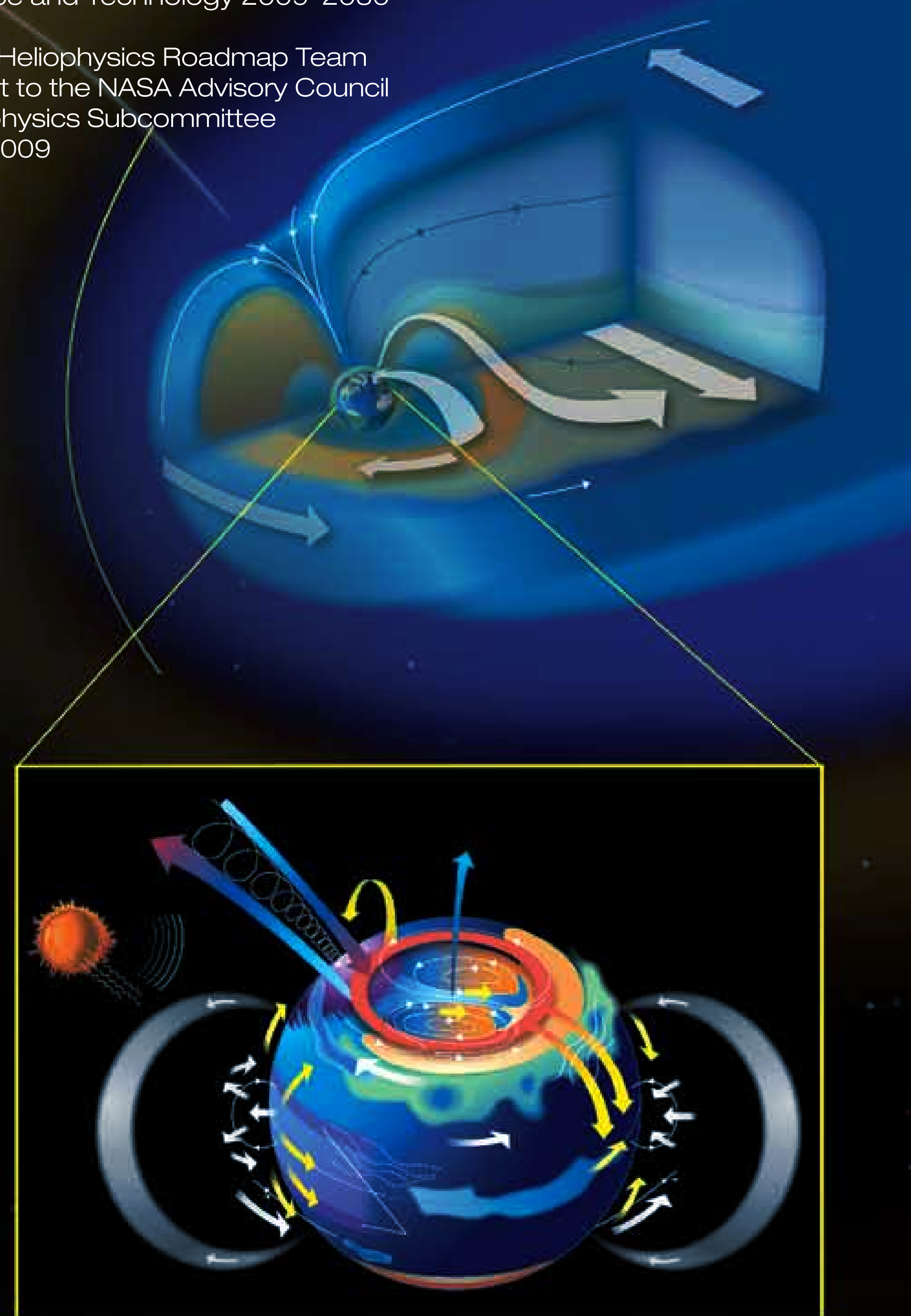

Cover Image Caption:

Heliophysics is a science that studies the linked phenomena in the region of space influenced by the Sun. It seeks to understand the influence of the Sun throughout the solar system and, in particular, its connection to the Earth and the Earth's extended space environment. Key in this endeavor is the study of the fourth state of matter: plasma. A plasma is a conducting body of electrically charged electrons and ions. In space, plasmas are controlled by the gravitational and magnetic fields of the Sun and the bodies within the solar system. Plasma processes are expressed in the Sun, the Sun's atmosphere, interplanetary and interstellar space, and in planetary magnetospheres and ionospheres. The aurora is a widely known, visible manifestation of plasma processes on Earth. Ultimately, the habitability of the Earth is governed by the sum total of such gravitational and magnetically controlled events in the evolution of the solar system.

2009 Heliophysics Roadmap Team

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Center Co-Chair: Dr. O.C. St. Cyr, NASA Goddard Space Flight Center
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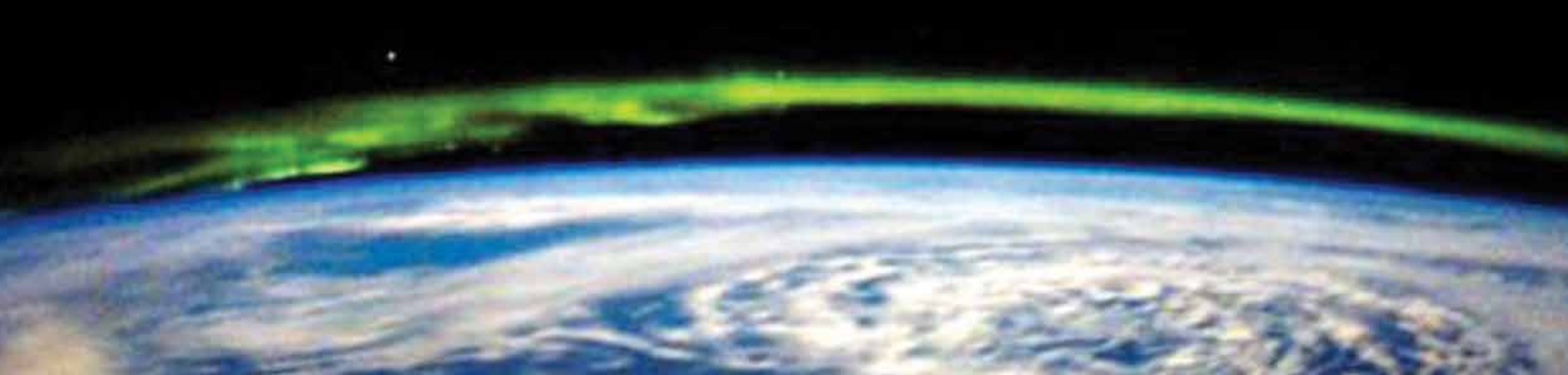
Table of Contents

The drive to understand the world around us is a basic part of our humanity. Research in fundamental science provides the ideas and discoveries that form the long-term foundation for science and technology as a whole, which in turn drive the global economy and our very way of life. In 2005, a panel of nationally recognized experts from across the spectrum of science and society, chaired by Norman Augustine, retired chairman and chief executive officer, Lockheed Martin Corporation, produced "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." To quote from the report:

> *"Since the Industrial Revolution, the growth of economies throughout the world has been driven largely by the pursuit of scientific understanding, the application of engineering solutions, and the continual technological innovation. Today, much of everyday life in the United States and other industrialized nations, as evidenced in transportation, communication, agriculture, education, health, defense, and jobs, is the product of investments in research and in the education of scientists and engineers."*



Executive Summary

Heliophysics: The Solar and Space Physics of a New Era

Our planet is immersed in a seemingly invisible yet exotic and inherently dangerous environment. Above the protective cocoon of Earth's lower atmosphere is a plasma soup composed of electrified and magnetized matter entwined with penetrating radiation and energetic particles. The Earth's magnetic field interacts with the Sun's outer atmosphere to create this extraordinary environment.

Our Sun's explosive energy output, which varies on time scales from milliseconds to billions of years, forms an immense structure of complex magnetic fields. Inflated by the solar wind, this colossal bubble of magnetism, known as the heliosphere, stretches far beyond the orbit of Pluto, from where it controls the entry of cosmic rays into the solar system. On its way through the Milky Way, this extended atmosphere of the Sun affects all planetary bodies in the solar system. It is itself influenced by slowly changing interstellar conditions that in turn can affect Earth's habitability. In fact, the Sun's extended atmosphere drives some of the greatest changes in our local magnetic environment affecting our own atmosphere, ionosphere, and potentially our climate.

This immense volume is our cosmic neighborhood; it is the domain of the science called heliophysics.

Heliophysics helps us understand the Sun, our own protective magnetized environment, and their effects on the Earth and solar system. In fact, a robust heliophysics research program is critical to human and robotic explorers venturing off our planet and into space. A well planned science approach can enhance our ability to predict the extreme, highly variable conditions surrounding us and through which explorers must travel. An effective plan incorporates studying the Sun, heliosphere, and planetary environments as elements of a single interconnected system — one that contains dynamic space weather and one that evolves in response to solar, planetary, and interstellar conditions.

Systems Science Approach

It is time for a strategic commitment to systems science — to seek understanding of fundamental processes and interconnections across disciplines. In concert with the other NASA science divisions (Planetary Science, Astrophysics, and Earth Science), heliophysics shares the responsibility for learning about the Earth, our solar system, the universe, and their interrelationships. We must have this kind of comprehensive knowledge if we are to reach beyond the confines of our planet and navigate safely across the vast ocean of space.

Heliophysics brings to the table an ability to directly explore the local cosmic environment—an environment not unlike that of many stellar systems in the universe. This is our only "hands-on" laboratory—one that we can study up close. By studying our own tiny corner of the immense universe, we can learn about phenomena that shape a solar system and may affect the habitability of a planet. How is it, for example, that on Earth we enjoy a beautiful and mild climate as contrasted to the icy desolation of Mars or the fiery-furnace climate of Venus?

Image Caption:

On March 21, 2008, an STS–123 Endeavour crewmember captured the glowing green beauty of the aurora borealis from the International Space Station. Looking northward across the Gulf of Alaska, over a low-pressure area (cloud vortex), the aurora brightens the night sky. The aurora is the most obvious sign of the Sun-Earth connection.

Roadmap Purpose

The U.S. scientific community is committed to a long-term, sustained effort toward understanding our space environment — its past, present, and future exemplified by models of the Sun-Earth-planet system and consistent within all areas of space science.

Toward that goal, this document represents an input of the U.S. heliophysics science community into the strategic planning process for the NASA Science Directorate for the period 2009–2030. NASA Headquarters charged the roadmap team with crafting a sustainable science program achievable within NASA's resources. With flexibility as a guiding principal and input from the community, including a Town Hall meeting in May 2008, we charted a roadmap to enable first-rate science and encourage new discoveries and partnership opportunities. Our plan is designed to withstand changes in available funding, implementation costs, and limits in launcher availability. It incorporates the healthy launch cadence needed to address the end-to-end system science.

This roadmap articulates a paradigm change by presenting a prioritized science queue with a recommendation to defer specific mission implementation approaches until the time of mission formulation. By presenting a science queue rather than a mission queue, our roadmap is closer to a true strategic plan. Specific mission architectures and implementation tactics will be determined within the context of constraints at the time of mission formulation. We believe our plan has the greatest potential to achieve the vision for heliophysics set forth in the 2003 National Research Council (NRC) Decadal Survey.*

This roadmap also specifies how heliophysics program elements should work together to help us understand the interconnected phenomena of our cosmic neighborhood.

We began developing our science queue by adopting the 2006 roadmap science objectives and structure that originated with national and decadal survey objectives. That structure was organized by three general goals: Frontier (F), Home in Space (H), and Journey of Exploration (J). Each goal included four research focus areas and a set of priority investigations. The new roadmap includes these divisions along with a set of "Open Science Questions" for each investigation. We refer to this flow down of science objectives as our Science Traceability Matrix.

Science Targets

The Science Traceability Matrix helped identify science areas not adequately addressed by operating or planned missions. We believe these "science targets" warrant consideration as future investigations. We do not yet call them missions because we have not specified mission architecture, satellite specifics, or instrument configurations. Rather, for each science target, we articulate a science objective that would, for example, appear as the mission objective in a future Announcement of Opportunity issued by NASA. We also prioritize the targets and place them in a launch queue consistent with the FY 2009 President's budget.

Six new and exciting science targets are suggested as the basis for critical, cost-constrained missions as new additions to the Heliophysics System Observatory (HSO) constellation of operating heliophysics missions. These science targets will address the most urgent and compelling science issues in heliophysics and provide opportunities of discovery as these targets explore fundamental processes in novel ways. The targets will uncover new relationships in and broaden understanding of the Earth's neighborhood. The individual missions will have an even greater impact through collaboration with the HSO fleet as new ground-based processing and collaborative facilities become more widely employed.

The three targets that address fundamental processes were assigned to the Solar Terrestrial Probe (STP) mission line; the other targets address significant interconnection science issues and were assigned to the Living With a Star (LWS) mission

* The Sun to the Earth — and Beyond,
A Decadal Research Strategy in Solar and Space Physics, ISBN 0-309-08509-8

line. All targets are scoped to fit within the NASA small or medium cost category. The cost of individual missions is to be constrained to these categories — as defined by NASA Procedural Requirement (NPR) 7120 — so as to meet the launch cadence recommendation. Strict limits on individual mission scope and cost containment will allow deployment of assets frequently enough to address the entire range of urgent scientific problems and advance a system-level understanding of heliophysics in a timely fashion.

The science targets and their objectives are listed below.

Solar Terrestrial Probes Science Queue

- **Origins of Near Earth Plasma (ONEP):** Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.
- **Solar Energetic Particle Acceleration and Transport (SEPAT):** Understand how and where solar eruptions accelerate energetic particles that reach Earth.
- **Ion-Neutral Coupling in the Atmosphere (INCA):** Understand how neutral winds control ionospheric variability.

Living With a Star Science Queue

- **Climate Impacts of Space Radiation (CISR):** Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on nitric oxide (NO) and ozone.
- **Dynamic Geospace Coupling (DGC):** Understand how magnetospheric dynamics provide energy into the coupled ionosphere-magnetosphere system.
- **Heliospheric Magnetics (HMag):** Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

Leveraging Resources for the Science Targets

We assume continued support of existing space assets, the launch of missions in development, and availability of timely Explorer Program missions. To realize the HSO's full potential, the strategy must be bolstered by a robust foundation of supporting research, data analysis, modeling and theory, and technology development. This combined effort will produce a broader and deeper understanding of the heliophysics realm. Our Nation will reap the benefits both economically and intellectually.

The Explorer Program constitutes a tremendous potential to increase launch frequency for heliophysics research. We are hopeful that NASA will restore funds to the Explorer Program based on the program's demonstrated value toward meeting NASA objectives. Small satellites, including Small Explorer (SMEX) missions, launched under the Explorer Program can address many open science issues identified in this roadmap. We anticipate that NASA will solve the launcher availability issues attendant to the loss of medium class Delta II launch vehicles, which provide a vitally important resource to heliophysics.

Missions in Formulation/Development

This roadmap strongly endorses the acquisition and launch of the following missions in development that address key program objectives:

- The **Solar Dynamics Observatory (SDO)** is scheduled for launch this year, set to explore the fundamental nature of solar magnetism and how it produces the solar cycle effects that influence Earth.
- The **Radiation Belt Storm Probes (RBSPs)** will explore processes that control the acceleration of space plasma to hazardous levels.

- **Magnetospheric Multiscale (MMS)** will seek to understand the fundamental process of magnetic reconnection, which taps the energy stored in a magnetic field and converts it to heat and kinetic energy.
- **Solar Probe Plus (SP+)** will orbit closer to the Sun than any previous spacecraft to learn why the solar corona is so much hotter than the photosphere and how the solar wind is accelerated.
- The **Solar Orbiter (SO)** collaborative mission with the European Space Agency (ESA) will explore the magnetic connections of the Sun-Heliosphere system.

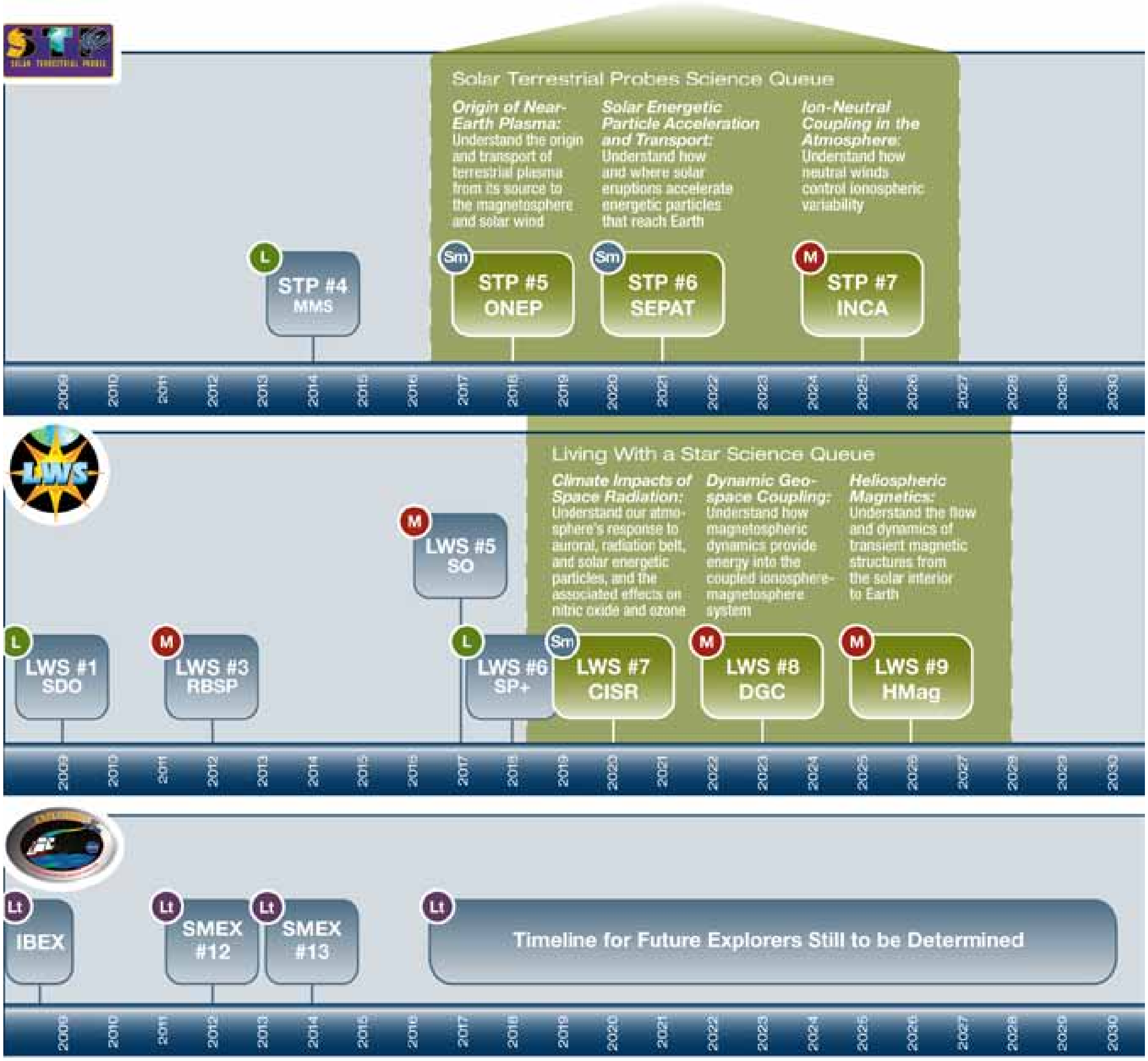
Summary of Prioritized Recommendations

1. Implement a science target queue to address the most urgent heliophysics science problems facing the Nation. *(pp. 24, 64)*
2. Strive to meet a launch frequency of two to three per decade for each of its STP and LWS strategic lines, allowing the entire range of most urgent scientific problems to be addressed and advancing a system-level understanding of heliophysics. *(pp. 24, 103)*
3. Reduce cost growth to help meet launch frequency requirements of the science. *(pp. 24, 105) Methods include the following:*
   - **a.** Peer review competition at the time of formulation be used to define the implementation of strategic missions to best address the recommended science goals within the resources available. *(pp. 26, 105)*
   - **b.** The time span between mission definition and procurement be minimized. Procure what is planned and implement what is procured. *(p. 105)*
   - **c.** Establishment of policies and procedures to minimize and control implementation costs during all phases of mission formulation and development. Avoid a “full mission science regardless of cost” mentality. *(p. 105)*
4. Pursue a restoration of the Explorer program to reestablish a desired mission cadence of 18 months with an equal number of SMEX and Mid-Size Explorer (MIDEX) opportunities. This recommendation is in recognition of the value of the Explorer program to meeting NASA objectives. *(p. 44)*
5. Continue preparation and launch of the current missions in development. *(p. 48)*
6. Continue the existing NASA efforts that transition new scientific knowledge in heliophysics to operational use. *(p. 84)*
7. Ensure that the existing supporting research programs be robustly supported, that the interdependence of each element be optimally defined and that funding of all efforts reflect the interdependence and the complementary aspects of each element. *(pp. 24, 52)*
8. Plan with other agencies for the eventual loss of capability in space to measure conditions in the solar wind critical to both operational and scientific research. *(p. 83)*

In conclusion, our plan is intended to address the most critical open science issues and is flexible enough to be executed within current and prospective NASA resources. It will direct us on a journey deep into the physics of magnetically and gravitationally dominated plasmas, from the Sun to our own magnetosphere and ionosphere and across the vast reaches of space to the outer limits of the solar system. Our travels will lead us to confront the fundamental processes upon which the behavior of the whole is built and ultimately expand our vision of the cosmos.

Science queue for heliophysics mission lines 2009–2030. Missions awaiting launch and those in formulation/development are shown with current mission names. New strategic science targets are identified by their science objective and centered on anticipated launch dates. Explorer launches are indicated and specific science content will be competed. Potential partnership and leveraged missions are also indicated. Within currently known implementation assumptions and constraints. This queue is achievable within the President's FY 2009 budget.

Recommended Science Queue



Cost Definitions for Missions

- N Nominal
- Lt Light: <$250M
- Sm Small: $250M–$500M
- M Medium: $500M–$750M
- L Large: $750M–$1B

Per NPR 7120.5 D

Potential International Partnerships

- Lt SOLAR-C (JAXA)
- N ORBITALS (CSA)
- Lt Cross-Scale/Scope (ESA/JAXA)
- Sm Interstellar Mission

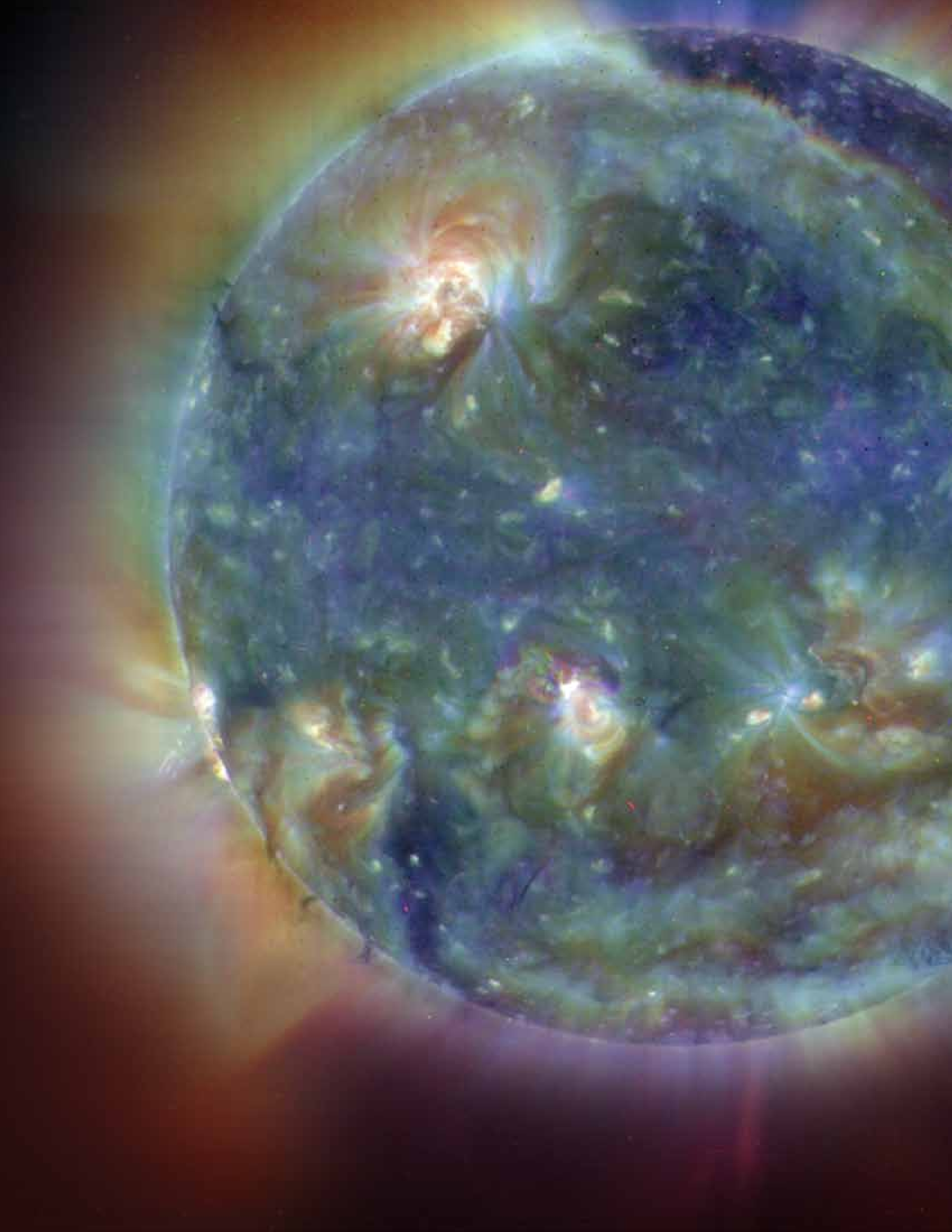
Color of button indicates size of NASA contribution. Funding is not reflected in roadmap budgeting and would require additional resources.

Intra-NASA Partnerships

- JUNO
- Mars Atmosphere and Volatile EvolutioN (MAVEN)
- Mars Science Laboratory (MSL)
- Lunar Reconnaissance Orbiter (LRO)
- Lunar Atmosphere and Dust Environment Explorer (LADEE)

No contribution of funds is anticipated.

Note: LWS #2 and LWS #4 are the Space Environment Testbeds (SET) and the Balloon Array for RBSP Relativistic Electron Losses (BARREL) suborbital project, respectively.



Chapter 1

HELIOPHYSICS: THE SCIENCE

NASA has charged the Heliophysics Division to "develop an understanding of the Sun and its effects on Earth and the solar system." Working from this directive, the formulation of a strategy for heliophysics research begins with a clear exposition of the scientific goals that flow down from this and other high-level NASA and Decadal Survey goals to an articulation of science objectives that can be addressed by flight missions. We call this cascade of science objectives a Science Traceability Matrix (Appendix A) that culminates with a set of open science questions lying at the level of mission objectives. The intermediate levels follow the structure of the 2006 Heliophysics Roadmap with the F, H, and J objectives as stated below, to 12 research focus areas (RFAs), to 18 priority investigations (summarized on page 29), and then to many open science questions. The open science questions are used to identify gaps in our science program leading to recommended prioritized science targets. The targets are the mission objectives for future Solar Terrestrial Probes (STPs) and Living With a Star (LWS) strategic mission lines and candidate objectives for future Explorer missions and potential partnership missions.

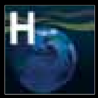
Chapter 1 is organized around the science in the following three broad and interconnected scientific and exploration objectives:

- F **Open the Frontier to Space Environmental Prediction.**
- H **Understand the Nature of Our Home in Space.**
- J **Safeguard the Journey of Exploration.**

RFAs and priority investigations are the second and third tier objectives. The RFAs are mapped to the challenges articulated in the National Research Council (NRC) 2003 Heliophysics Decadal Survey. The full panel of open science questions for each of the priority investigations are given in Appendix A.

Understand the Sun and its Effects on Earth and the Solar System

Open the Frontier to Space Environmental Prediction
Understand the fundamental physical processes of the space environment—from the Sun to Earth, to other planets, and beyond to the interstellar medium.



Understand the Nature of Our Home in Space
Understand how human society, technological systems, and the habitability of planets are affected by solar variability interacting with planetary magnetic fields and atmospheres.

Safeguard the Journey of Exploration
Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space.

The science of heliophysics seeks understanding of the interaction of the large complex, coupled system comprising the Sun, Earth, and Moon; other planetary systems; the vast space within the solar system; and the interface to interstellar space. Heliophysics is a bold enterprise of space exploration that seeks to understand the connections that govern the solar system and the implications for our home in space, to predict the hazards of exploration, and to understand the impact of the space environment for the habitability of other worlds.

Research Focus Areas

F1 Magnetic reconnection

F2 Particle acceleration and transport

F3 Ion-neutral interactions

F4 Creation and variability of magnetic dynamos

Open the Frontier to Space Environmental Prediction

The Sun, our solar system, and the universe consist primarily of plasma. Plasmas are more complex than solids, liquids, and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate particles, sometimes to very high energies, and the magnetic fields guide their motions. This results in a rich set of interacting physical processes, including intricate exchanges with the neutral gas in planetary atmospheres.

Although physicists know the laws governing the interaction of electrically charged particles, the collective behavior of the plasma state leads to complex and often surprising physical phenomena. As the foundation for our long-term research program, we will develop a comprehensive scientific understanding of the fundamental physical processes that control our space environment.

The processes of interest occur in many locations, though with vastly different magnitudes of energy, size, and time. By quantitatively examining similar phenomena occurring in different regimes with a variety of techniques, we can identify the important controlling mechanisms and rigorously test our developing knowledge. Both remote sensing and in situ observations will be utilized to provide the complementary three-dimensional, large-scale perspective and the detailed small-scale microphysics view necessary to see the complete picture.

Research Focus Areas

H1 Causes and evolution of solar activity

H2 Earth's magnetosphere, ionosphere, and upper atmosphere

H3 Role of the Sun in driving change in the Earth's atmosphere

H4 Apply our knowledge to understand other regions

Understand the Nature of Our Home in Space

Humankind does not live in isolation; we are intimately coupled with the space environment through our technological needs, the solar system bodies we plan to explore, and ultimately the fate of our Earth itself. We regularly experience how variability in the near-Earth space environment affects the activities that underpin our society. We are living with a star.

We plan to better understand our place in the solar system by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. We plan to characterize and develop a knowledge of the impact of the space environment on our planet, technology, and society. Our goal is to understand the web of linked physical processes connecting Earth with the space environment.

Even a casual scan of the solar system is sufficient to discover that habitability, particularly for humankind, requires a rare confluence of many factors. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are subjects of immense interest to heliophysics. Lessons learned in the study of planetary environments can be applied to our home on Earth, and vise versa, the study of our own atmosphere supports the exploration of other planets.

Research Focus Areas

J1 Variability, extremes, and boundary conditions

J2 Capability to predict the origin, onset, and level of solar activity

J3 Capability to predict the propagation and evolution of solar disturbances

J4 Effects on and within planetary environments

Safeguard the Journey of Exploration

NASA's robotic spacecraft continue to explore the Earth's neighborhood and other targets in the heliosphere. Humans are expected once again to venture onto the surface of the Moon and one day onto the surface of Mars. This exploration brings challenges and hazards. We plan to help safeguard these space journeys by developing predictive and forecasting strategies for space environmental hazards.

This work will aid in the optimization of habitats, spacecraft, and instrumentation, and for planning mission operation scenarios, ultimately increasing mission productivity. We will analyze the complex influence of the Sun and the space environment, from origin to the destination, on critical conditions at and in the vicinity of human and robotic spacecraft. Collaborations between heliophysics scientists and those preparing for human and robotic exploration will be fostered through interdisciplinary research programs and the common use of NASA research assets in space.

Open the Frontier RFA F1:

Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, the solar wind, and in magnetospheres

Reconnection is a topological change in a magnetic field configuration that releases stored magnetic energy to a plasma. Reconnection can accelerate particles to very high energies, and it can dramatically alter the regions of space accessible to those particles. It is responsible for the energy release in solar flares. In the corona, reconnection can sever large clouds of dense plasma from the magnetic fields that anchored them. Reconnection at the front side of the magnetosphere and in the magnetotail is responsible for the coupling between the solar wind and the Earth's magnetosphere that drives the aurora and geomagnetic storms. The consequences of reconnection can be devastating to space assets, voyaging humans, and communication systems on Earth.

Reconnection is fundamentally a multiscale process. The large-scale configuration of the magnetic field creates the conditions under which reconnection can occur, but the explosive conversion of magnetic energy originates in a region called the diffusion region, which is very small in comparison. For example, reconnection at the Earth's magnetopause (the boundary separating the solar wind and terrestrial magnetic fields) occurs in the diffusion region with an area on the order of hundreds of square kilometers, compared to a total magnetopause surface area of approximately 60 billion square kilometers. Current solar imaging techniques are insufficient to resolve the diffusion region associated with solar flares and coronal mass ejections (CMEs). While there have been a few encounters with the diffusion region in the near-Earth environment, systematic study of this phenomenon is just beginning. The physical processes that initiate and control reconnection remain to be measured.

Most of our basic theoretical understanding of reconnection comes from a magnetohydrodynamics (MHD) perspective. Although this approach has provided important insight, it is inherently limited in that it cannot address the very small scales on which ions and electrons decouple from the magnetic field or the detailed particle energization process. Important questions remain unanswered both observationally and theoretically: What initiates the reconnection process? What are the kinetic processes that occur and what is their role? What is the range of scale sizes of the region over which reconnection occurs in different regimes? What determines if reconnection is quasi-steady or bursty? What mechanisms or boundary conditions control the spatial and temporal scales? What is the three-dimensional structure of the reconnection region and how does this structure affect particle acceleration?

Priority Investigations:
What are the fundamental physical processes and topologies of magnetic reconnection?

How are plasmas and charged particles heated and accelerated?

How are mass and energy transferred from the heliosphere to a planetary magnetosphere?

Decadal Survey Challenges:
Challenge 4: "Understanding the basic physical principles manifest in processes observed in solar and space plasmas."

Open the Frontier RFA F2:

Understand the plasma processes that accelerate and transport particles

Priority Investigations:
How are plasmas and charged particles heated and accelerated?

How is solar wind plasma accelerated?

How are planetary thermal plasmas accelerated and transported?

How do solar wind disturbances propagate and evolve through the solar system?

What are the roles of mass and energy flows in the behavior of planetary magnetospheres?

Decadal Survey Challenges:
Challenge 4: "Understanding the basic physical principles manifest in processes observed in solar and space plasmas."

Challenge 5: "Developing a 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 Earth's magnetosphere and ionosphere."

High-energy particles accelerated at the Sun and within interplanetary space and cosmic rays from outside the solar system pose a serious hazard to human and robotic exploration. Energetic particles produced or trapped within planetary magnetospheres can have deleterious effects on important technological assets in those locations. Predicting these effects requires a fundamental understanding of where and how particles in space can be accelerated and how they are transported.

More than one mechanism can operate to produce a given energetic particle population at a given location. Moreover, energetic particles are accelerated both at localized sites (solar flares, planetary bow shocks, magnetotail reconnection sites, auroral acceleration regions, and radiation belts), and globally (coronal and interplanetary shocks, corotating interaction regions and global merged interaction regions in the solar wind, and the termination shock in the heliosheath). Important processes for near-term investigation include quasi-static electric fields parallel to the background magnetic field, wave electric fields, stochastic (Fermi) acceleration, and the drift of particles along a component of the electric field such as that occurring in shocks and the magnetotail.

Specific examples of phenomena that, upon investigation, should yield a deeper understanding of plasma processes that accelerate and transport particles are the aurora, CMEs, and the solar wind termination shock. The Earth's aurora provides a unique opportunity to understand acceleration by parallel electric fields and waves. Particle acceleration at CME shock fronts is a leading candidate for the production of gradual solar energetic particle (SEP) events. New observations at the solar wind termination shock suggest that suprathermal ion populations dominate the kinetic energy of the plasma in the heliosheath, which changes our views of how particle energizing occurs in the outer heliosphere.

An understanding of the acceleration of thermal plasmas is also vital as these may form seed populations for subsequent energization or mediate the transport and acceleration of energetic particles. In terrestrial and planetary magnetospheres, for example, thermal plasmas can be accelerated to sufficiently high energies to form ring currents and radiation belts. The solar wind transports energetic particles and provides acceleration regions through its interaction with magnetospheres, the termination shock, stream interaction regions, and interplanetary CMEs. The origin of the solar wind is not well understood and represents a large gap in our knowledge of fundamental processes.

Open the Frontier RFA F3:

Understand the ion-neutral interactions that couple planetary ionospheres to their upper atmospheres and solar and stellar winds to the ambient neutrals

There are many locations throughout the solar system where interactions between charged and neutral particles strongly affect the behavior of the system. Charged and neutral species respond to different forces but interact through collisions. These collisions result in chemical reactions and transfer energy and momentum between the populations. Most important for near-term study is to understand the large-scale balance between gravitationally and magnetically controlled components of the system.

Planetary atmospheres, including that of the Earth, are affected directly by ultraviolet (UV) and infrared radiation from the Sun. Charged particles are produced when this radiation is absorbed and energy is produced that can be redistributed in a variety of ways before being reradiated to space. The charged particles may also be influenced by a magnetic field. The Sun's interplanetary magnetic field can produce a stress known as mass loading. The presence of a planetary magnetic field prevents direct interaction of an atmosphere with the solar wind and produces a magnetosphere providing additional pathways for redistributing the energy from the Sun.

In the case of Earth, the upper atmosphere is also subject to energy and momentum inputs from below, produced by tropospheric processes and mountainous geographic features. Variations in these inputs can change the large-scale temperature and composition in the middle and upper atmosphere. Such processes may also operate in the atmospheres of Venus and Mars.

When charged and neutral particles exist in the presence of a magnetic field, the mobility of the magnetized plasma becomes anisotropic and drag forces between the plasma and the neutral gas produce complex electrodynamic interactions. Such interactions dramatically affect the spatial distribution of the plasma, and the resulting instabilities lead to structures spanning a wide range of sizes. In the case of the Earth, large-scale plasma structures accelerate or decelerate the neutral atmospheric gases and change circulation patterns. Smaller scale plasma structures influence the propagation of radio waves and affect communications and navigation systems.

These and other interactions between charged and neutral species feed the nonlinear, seemingly separate behavior of both species. It is not possible to specify the state of the entire system from only instantaneous knowledge of a single component or from simple monitoring of external drivers. Rather, both initial states and the evolutionary time scales must be understood over a wide spectrum of scales. Meeting these requirements represents our primary challenge to future progress.

Priority Investigations:

What governs the coupling of neutral and ionized species?

How do coupled middle and upper atmospheres respond to external drivers and to each other?

What is responsible for the dramatic variability in many of the state variables describing the ionosphere-thermosphere-mesosphere (ITM) region?

How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

How do the heliosphere and the interstellar medium interact?

Decadal Survey Challenges:

Challenge 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."

Challenge 3: "Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences."

Challenge 4: "Understanding the basic physical principles manifest in processes observed in solar and space plasmas."

Chapter 1

Open the Frontier RFA F4:

Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary, and stellar environments

The generation of cosmic magnetic fields is a fundamental physical mystery that underlies a wide range of phenomena in the Sun-Earth system, the solar system, and indeed the universe beyond. In addition, magnetic fields control and influence many events that affect the technological functions of our society.

For example, the Sun's variable magnetic field is the energy source for solar particle acceleration, and the structure of the field controls the entry of galactic cosmic rays (GCRs) into the solar system as well as the strength of geomagnetic storms. Helioseismic data from the Solar and Heliospheric Observatory (SOHO) and ground-based observatories have revolutionized dynamo theories of magnetic field generation by placing the main solar cycle dynamo action at the base of the convection zone in the rotationally sheared layer known as the tachocline. Estimates of the correct characteristics of the meridional circulation are thought to be key ingredients for determining the length of the solar cycle. Recently, models have been created that use the meridional flow patterns from previous cycles to estimate the length and amplitude of the next cycle. However, while these dynamo models may be able to forecast the cycle length, they may not capture all of the relevant physics of such models. In addition, details, such as whether the cycle will be double peaked, are still not within our predictive capability. We know even less about activity cycles on other stars though comparative stellar dynamo studies should reveal much about the long-term behavior of stars and the Sun. Developing the understanding of the dynamo process to enable this kind of prediction is important for long-term planning for solar activity and would have obvious applications in trying to understand past and future periods of abnormal solar activity and concomitant effects on terrestrial climate and planetary habitability.

Closer to home, magnetic reversals and other large variations of the Earth's magnetic field can lead to periods of reduced protection from the harsh radiation environment of space. The process responsible for the existence and behavior of these magnetic fields—again, the dynamo—involves the twisting and folding of weak fields so as to change and amplify them. Solving the problem of just how dynamos operate in such widely different environments, from the liquid metal of planets to the gaseous plasma of stars, will allow better predictions of the effects of magnetic field changes at both the Earth and the Sun. This understanding is essential to describing the coupled Sun-solar system connection and has important implications for the exploration of our solar system.

Priority Investigations:
How do planetary dynamos function and why do they vary so widely across the solar system?

What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?

What are the precursors to solar disturbances?

How are mass and energy transferred from the heliosphere to a planetary magnetosphere?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

What is the magnetic structure of the Sun-heliosphere system?

Decadal Survey Challenges:
Challenge 1: "Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona."

Challenge 3: "Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences."

Challenge 4: "Understanding the basic physical principles manifest in processes observed in solar and space plasmas."

Our Home in Space RFA H1:

Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment

The climate and space environment that affects Earth are determined by the plasma, particle, and electromagnetic radiation outputs from the Sun. The solar output varies on many time scales from explosive reconnection on scales of microseconds, to convective turnover taking minutes to hours, to solar rotation over a month, to the 22-year solar magnetic cycle, and to century-long irregular fluctuations, such as the Maunder minimum. This high degree of variability is a consequence of the emergence of the magnetic field from below the photosphere, its transport and destruction on the solar surface, and the intermittent eruption into the heliosphere of energy stored in the atmosphere as flares and CMEs. The heliosphere also modulates the propagation of incoming GCRs on large spatial scales that are on the order of the size of the solar system. In addition, longer term changes that can affect Earth's climate include variations in the solar total and spectral irradiance.

As the solar wind is emitted from the edges of coronal holes, it carries embedded fluctuations of magnetic field, density, and temperature, as well as energetic particle populations. All of these phenomena evolve as they travel through the heliosphere. Shocks accelerate the particles and interact with the other irregularities. CMEs can interact with each other. Particles collide and redistribute energy. The result is an ever-changing background of electric fields, magnetic fields, and charged particle radiation bombarding the Earth and near-space environment. Understanding the three-dimensional, time-varying propagation of solar disturbances is one of the greatest challenges facing us. Understanding the internal configuration of the structures is another.

Precursors can provide useful information about solar and interplanetary events; however, more complete predictive models based on physical principles are necessary if we are ever to usefully assimilate the information. As with terrestrial weather, it is not yet clear how long in advance solar activity can be predicted. Improved and continuous observations of the solar vector magnetic field, at multiple heights (e.g., photosphere, chromosphere, transition region, and corona), along with high-resolution multispectral observations of the atmosphere are as critical for resolving this question as helioseismology is for revealing the subsurface conditions.

Priority Investigations:
What are the fundamental physical processes and topologies of magnetic reconnection?

What are the precursors to solar disturbances?

How do solar wind disturbances propagate and evolve through the solar system?

How do the heliosphere and the interstellar medium interact?

Decadal Survey Challenges:
Challenge 1: "Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona."

Our Home in Space RFA H2:

Understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects

Priority Investigations:

How are planetary thermal plasmas accelerated and transported?

How are mass and energy transferred from the heliosphere to a planetary magnetosphere?

What are the roles of mass and energy flows in the behavior of planetary magnetospheres?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

Decadal Survey Challenges:

Challenge 3: "Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences."

Earth's space environment is a complex, strongly coupled system energized by an amazing range of inputs that originate with the Sun. One important input is the magnetized solar wind rushing past Earth at a million miles per hour, interacting with Earth's magnetic field to produce the magnetosphere, which accumulates and releases that energy in powerful bursts. This process accelerates magnetospheric plasma into Earth's auroral regions and heats the upper atmosphere, a well known effect of the aurora. Auroral heating sets the upper atmosphere into motion and modifies its composition and chemistry. Embedded in the atmosphere is the ionosphere, the density of which is usually driven by solar extreme UV radiation. However, its density can be strongly affected by auroral-induced changes in the atmosphere, and thus by solar wind conditions. The electric fields that develop in the magnetosphere during solar wind-induced disturbances can also strongly modify the ionosphere, drawing high-density plasma from low to high latitudes in great plumes, further enhancing the strength of geomagnetic disturbances by adding to magnetospheric pressure through high-latitude ion outflow.

The short description above shows how solar wind energy initiates a magnetic storm, with subsequent effects in the atmosphere and ionosphere that, in turn, may modify the magnetic storm strength itself. The flow of energy and mass in this strongly coupled system is an intensively studied problem with broad implications for our technologically advancing society and for basic understanding of plasma processes in planetary environments. Individual parts of the system have been the target of many focused studies, yielding a new understanding of processes occurring on a wide range of temporal and spatial scales. Equally important is to understand how these processes couple across the broad range of spatial and temporal scales in our geospace system.

New nonlinear pathways for energy coupling have recently been discovered in geospace. Recent research indicates that the response of the atmosphere to auroral forcing depends on the total energy input and the width of the auroral curtains. Daily tropospheric precipitation in equatorial rainforests releases such a prodigious amount of heat that the tides of atmospheric energy propagating upward from these storms dramatically change the ionosphere. These tides interact with other waves on many scales. These processes involve nonlinear diffusion and wave interactions that are critical for understanding the large-scale behavior of the geospace system.

Our Home in Space RFA H3:

Understand the role of the Sun and its variability in driving change in the Earth's atmosphere

Solar energy in the form of photons and particles drives the chemical and physical structure of Earth's atmosphere. For example, UV radiation and X-radiation deposited globally throughout the mesosphere and thermosphere are responsible for formation of the ionosphere. Also, while particles primarily deposit their energy at high latitudes, the resulting ionization, dissociation, and excitation of atoms and molecules can have a global effect due to dynamical processes that transport energy. Ultimately, these processes combine to drive the temperature and chemical composition of the entire Earth's atmosphere. A key example of how atmospheric modification by the Sun affects life is stratospheric ozone, which acts as a human UV shield. The very existence of the ozone layer is a direct result of solar energy deposition. Nitric oxide created at higher altitudes by processes involving solar and auroral energy may be transported to lower altitudes where it can destroy ozone. Solar energetic particles have been linked to episodic stratospheric ozone depletions, and it is possible that radiation belt particles play a role as well. GCRs are modulated by the solar cycle, but their possible effects on cloud nucleation and, hence, albedo remains controversial. Because life depends on the atmosphere and its climate, study of solar energy-driven atmospheric variations is critically important. Despite this, the strength and variability of atmospheric solar energy deposition remain poorly understood. In addition, coupling processes that spread effects of energy deposition in altitude and latitude are not well understood. Addressing these issues requires high time-resolution spectral observations of solar energy, measurements of the atmospheric response, as well as theory and modeling of dynamical processes that distribute effects of solar energy.

Priority Investigations:
What governs the coupling of neutral and ionized species?

How do coupled middle and upper atmospheres respond to external drivers and to each other?

How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

How do long-term variations in solar energy output affect Earth's climate?

Decadal Survey Challenges:
Challenge 3: "Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences."

Our Home in Space RFA H4:

Apply our knowledge of space plasma physics to understand other regions of the solar system, stars, and the galaxy

Plasmas and their embedded magnetic fields affect the formation, evolution, and destiny of planets and planetary systems. The heliosphere shields the solar system from galactic cosmic radiation. Our habitable planet is shielded by its magnetic field, protecting it from solar and cosmic particle radiation and from erosion of the atmosphere by the solar wind. Planets without a shielding magnetic field, such as Mars and Venus, are exposed to those processes and evolve differently. And on Earth, the magnetic field changes strength and configuration during its occasional polarity reversals, altering the shielding of the planet from external radiation sources.

How important is a magnetosphere to the development and survivability of life? The solar wind, where it meets the local interstellar medium (LISM), forms boundaries that protect the planets from the galactic environment. The interstellar interaction depends on the raw pressure of the solar wind and the properties of the LISM (density, pressure, magnetic field, and bulk flow). These properties, particularly those of the LISM, change over the course of time, and change dramatically on long time scales (1,000 years and longer) as the solar system encounters interstellar clouds. How do these long-term changes affect the sustainability of life in our solar system?

Understanding the nature of these variations and their consequences requires a series of investigations targeting the structure of the heliosphere and its boundaries and conditions in the LISM. Planetary systems form in disks of gas and dust around young stars. Stellar UV emission, winds, and energetic particles alter this process, both in the internal structure of the disk and its interaction with its parent star. The role of magnetic fields in the formation process has not been fully integrated with other parts of the process. The study of similar regions in our solar system, such as dusty plasmas surrounding Saturn and Jupiter, will help explain the role of plasma processes in determining the types of planets that can form and how they later evolve.

Priority Investigations:
What are the fundamental physical processes and topologies of magnetic reconnection?

How are plasmas and charged particles heated and accelerated?

How do planetary dynamos function and why do they vary so widely across the solar system?

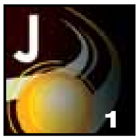
What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?

What is the composition of matter fundamental to the formation of habitable planets and life?

Decadal Survey Challenges:
Challenge 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."

Challenge 3: "Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences."

NRC Astrophysical Context:
Understanding the Sun, heliosphere, planetary magnetospheres and ionospheres as astrophysical objects and in astrophysical context.



Safeguard the Journey RFA J1:

Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers

The Sun is a variable star. Beginning with the invention of the telescope more than 400 years ago, it has been found that the Sun shows quasi-periodic behavior in sunspot occurrence, and that the Earth is susceptible to solar variability. The solar activity cycle, linked to sunspots, is approximately 11 years long. Historical records show that not all solar cycles are the same. The variations we have seen within the 50 years of the space age do not reflect the full extent of solar variability and extremes. Archival records of events in ice cores and specific modeling of the infamous 1859 Carrington event indicate that more severe space weather has frequently occurred. It is important to collect long-term records of space weather events and space climate. Even the ongoing and benign solar cycle minimum is unusual compared to all cycles spacecraft have encountered so far; it lasts longer, and at the same time, the solar polar magnetic field is significantly weaker than in the three previous solar minimum periods. As a result, the Earth's ionosphere has reached its coldest state ever recorded, and the solar wind output of the Sun, which has waned over the course of the past decade seemingly independent of solar activity, has reached an historic low. Recognizing the importance of space measurements, the Heliophysics Division has put in place new rules that will ensure preservation and open access of the data collected by past and currently operating spacecraft. Thus, future research into the extremes of the space environment can utilize effectively what this generation of robotic explorers has gathered and can fit this information into the overall context of solar and space environment variability.

The significance of characterizing extremes in heliophysics derives from its impact on our technological society. NASA, in particular, develops robotic explorers and plans to send humans beyond low-Earth orbit, where they are more vulnerable to space weather hazards. A primary hazard to assets and humans in space are SEPs accelerated at or near the Sun, trapped particles in radiation belts around the Earth (see J4), and GCRs. SEPs represent a transient but high-intensity threat to space hardware and the safety of astronauts. Knowledge of occurrence rate and range of intensities is critical for system design purposes.

The extremes of solar events combined with the drive toward ever lighter and more compact space flight hardware frequently have caused problems for instrumentation, preventing the accurate characterization of the extremes. In some cases, postevent analysis allowed successful recovery of data. However, in order to prepare missions toward data reliability that feed a modeling environment in near-real time, new and robust technologies have to be developed. These developments will pave the way for exploring key mechanisms and regions through which extreme space weather events arise.

Priority Investigations:
How is solar wind plasma accelerated?

What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?

What are the roles of mass and energy flows in the behavior of planetary magnetospheres?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

Decadal Survey Challenges:
Challenge 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."

Challenge 5: "Developing a 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 Earth's magnetosphere and ionosphere."

Safeguard the Journey RFA J2:

Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and safe intervals

Dramatic and rapid changes in space weather that can affect humans and technology anywhere in the inner heliosphere are associated with solar particle events. Recent space weather research has shown that, in a worst-case scenario (J1), unprotected astronauts who are suddenly exposed to solar particle radiation in space can reach their permissible exposure limits within hours of the onset of an event. Such events are a direct effect of the rapid release of stored magnetic energy at active regions on the Sun.

Accurately predicting when safe intervals will occur, or the exact times of sudden releases of radiation at the Sun, poses major challenges to the system science of heliophysics. The time scales involved span several orders of magnitude: minutes and hours are associated with high-energy particle propagation from the Sun to the Earth, days are associated with arrival of solar wind plasma, and months to years for the full development of the heliospheric consequences of solar explosive events.

The largest potential impact on exploration would derive from the ability to predict "all clear" periods. This capability could improve safety by optimized scheduling of manned launches and extravehicular activities (EVAs). In recent years, several observational tools and methods have been developed and are currently being validated that would greatly improve forecasting. Early successes are (1) the capability to image active regions on the far side of the Sun with helioseismology, to be vastly improved with the expected launch of the Solar Dynamics Observatory (SDO); (2) the nowcasting of light-speed particles from prompt particle events that can give up to a 1-hour warning of hazardous SEP arrival; and (3) Solar Terrestrial Relations Observatory (STEREO) heliospheric imaging that can give 1- to 2-days warning of the arrival of energetic storm particles and magnetic disturbances at distances where human and robotic explorers might venture. These advancements have improved our predictive capability. However, much remains to be understood that will enable a significant increase in warning times.

Successful forecasting of space weather depends on (1) complete identification and observational coverage in real-time of critical solar disturbance parameters, (2) the development of observational tools and improved instrumentation that is alert and fully functional even in the midst of severe space weather, and (3) the advances in physical understanding (F and H) as a basis for theoretical and computational modeling of the Sun-Earth-inner heliosphere system. These are all necessary conditions for a heliophysics science enterprise that would fulfill its responsibility for NASA embarking on next-generation exploration activities.

Priority Investigations:
What are the fundamental physical processes and topologies of magnetic reconnection?

How do planetary dynamos function and why do they vary so widely across the solar system?

Decadal Survey Challenges:
Challenge 1: "Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona."

Challenge 5: "Developing a 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 Earth's magnetosphere and ionosphere."

Safeguard the Journey RFA J3:

Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers

Mission success of a lunar landing depends on the productivity of astronauts deploying instrumentation and collecting scientific samples in the surroundings of their landing sites. Solar activity can severely disrupt science activities for a period equivalent to short mission duration, in particular, in scenarios in which the evolution of the solar event is not sufficiently predictable.

The impact of space weather events on humans and technology in space critically depends not only on the intensity of the solar event but also on the site of interest in the solar system and other properties of the outburst. CMEs, for example, propagate away from the slowly rotating Sun on a near-radial trajectory. Thus, whether or not the disturbance interacts with the Earth-Moon system depends mostly on the direction and width of the expanding CME.

The radiation environment in the heliosphere depends on the propagation and transport of the particles in the solar wind and on the radial evolution of, and interaction with, solar disturbances. The behaviors are complex. Some solar particle events can increase radiation intensity to critical levels very rapidly, others rather slowly or not at all. At times, even two maxima can be reached originating from a single solar event; and, in extreme events, the particles tend to fill the inner heliosphere.

Heliophysics has recently made progress to better characterize the extent of solar particle events through observations from distributed vantage points. However, the observational basis for these studies needs to be improved. Despite the value of remote sensing, the regions of the outer corona that provide the interface between the inner corona and the heliosphere (solar wind) can only be fully understood with direct in situ measurements. The Solar Orbiter (SO) and Solar Probe Plus (SP+) missions now in formulation will provide critically needed data from the inner heliosphere.

GCRs are modulated globally over the solar cycle but also locally through propagating transient disturbances. The outer heliosphere is thought to shield us from much of the nearly continuous GCR flux, perhaps by as much as 90 percent at 100 MeV/nucleon, although recent observations by the Voyager spacecraft show that the barrier, if it exists, is not in the inner part of the heliosheath. The sensitivity of the GCR flux to approaching solar disturbances has provided a valuable tool for predicting space weather hazards for spacecraft.

Priority Investigations:

How is solar wind plasma accelerated?

How do solar wind disturbances propagate and evolve through the solar system?

How do the heliosphere and the interstellar medium interact?

What is the magnetic structure of the Sun-heliosphere system?

Decadal Survey Challenge:

Challenge 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."

Challenge 5: "Developing a 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 Earth's magnetosphere and ionosphere."

Safeguard the Journey RFA J4:

Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities

Exploration activities are inherently risky. Beyond the technical challenges, human and robotic explorers across the solar system will be affected by the planetary plasma environments that respond to solar- and heliosphere-driven space weather. The "near-planet" radiation environment, applicable to Earth and all other planetary systems, is of particular concern for exploration activities as this is where exploration will take place for extended periods of time. Space weather at planets can intensify and restructure radiation belts. An effective strategy that minimizes the accumulative dose, from this hazard in particular, includes avoidance through advance warning. The key role that heliophysics occupies is to develop understanding of the physical processes that create and drive the radiation environments near planetary bodies. In the meantime, improved characterization of these environments and identification of parameters that indicate changes will reduce risk to exploration activities to the extent possible.

The ionospheres, thermospheres, and mesospheres impact exploration activities in those planetary environments. These layers provide a means for long-range communication through ionospheric reflection of radio signals. However, surface-to-orbit and surface-to-surface communications are sensitive to heliophysical processes. Aerobraking is a novel technique that utilizes the thermosphere and mesosphere instead of costly propellant. Spacecraft control in low orbits and in aerobraking parking orbits depend on the knowledge of upper atmosphere neutral density. Neutral density variability at aerobraking altitudes is partially controlled by dynamical influences from the planetary atmosphere.

Lunar dust interacts with the solar radiation and wind output. The plasma and UV radiation environment at the Moon's surface contributes to recognized problems with lunar dust. Dust grain adhesion on astronaut suits and instrumentation is not fully understood or resolved.

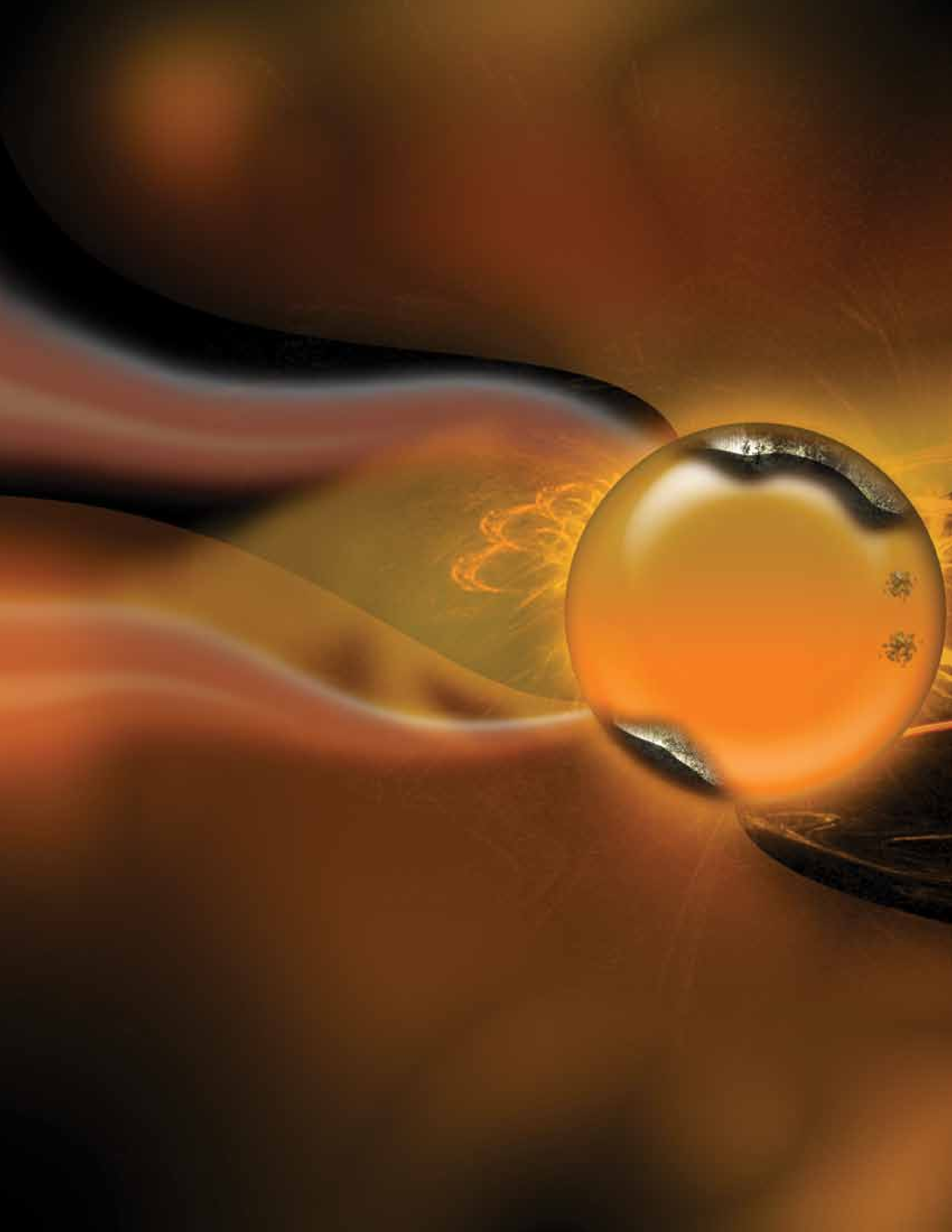
Heliophysics science reduces risk for exploration by directly addressing the issues mentioned above. The Radiation Belt Storm Probes (RBSP) mission in development will measure the variability of the Earth's radiation belts. ITM missions, including Aeronomy of the Ice in the Mesosphere (AIM) and Coupled Ion Neutral Dynamic Investigation (CINDI) in operation, investigate the effects of space weather on the Earth's outer atmosphere and at Mars, and the Artemis missions will utilize two spacecraft to investigate the solar wind and dust interaction near the Moon. Heliophysics, as an interdisciplinary science, will potentially benefit from planetary exploration as planets and the Moon hold unique archival clues on the distant past of solar terrestrial processes that will allow us to understand the system in more depth and detail.

Priority Investigations:
How do coupled middle and upper atmospheres respond to external drivers and to each other?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

Decadal Survey Challenges:
Challenge 3: "Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences."

Challenge 5: "Developing a 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 Earth's magnetosphere and ionosphere."



Chapter 2
HELIOPHYSICS: STATE OF THE DISCIPLINE

The heliophysics discipline has been highly productive and successful in meeting the science goals established for the Heliophysics Division at NASA. The Decadal Survey and roadmaps have been key elements in continuing the productivity of the discipline. Strength from continuity of purpose derives from building the new strategy on the foundation of previous roadmaps, taking into account new scientific discoveries and reassessing the landscape of the discipline. These are the starting points for building this roadmap, which lays out a prioritized set of science targets for future heliophysics missions. Consideration of the integrated support of all program elements led to a launch queue for the highest priority science targets as described in Chapter 3.

Investment Returns 2006–2009:

Recent Discoveries Pose Challenges for a New Era in Heliophysics

Scientific research leads to new insights, increased understanding, and eventually to predictive capabilities and useful applications. The roadmap team assessed progress in heliophysics research to build upon advances made since the 2003–2013 Decadal Survey of Solar and Space Physics. The team identified several developments over the past few years that have led to new directions and posed new challenges for our science discipline.

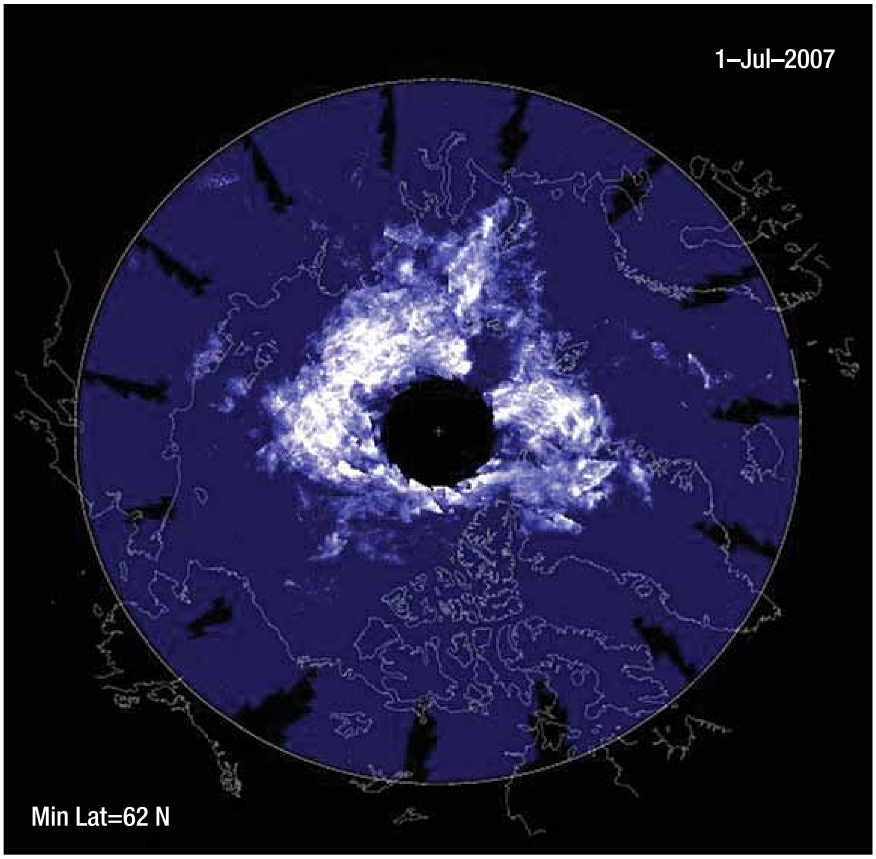
Since the publication of the Decadal Survey, our network of heliophysics spacecraft has both gained and lost observational capabilities. The gains enable new science topics to be addressed, and the losses potentially leave gaps in our ability to make progress for other topics.

We have seen the launch of missions covering a broad scientific range, from the origins of noctilucent clouds (NLC) in the upper atmosphere using Aeronomy of the Ice in the Mesosphere (AIM), the origins of substorms using the Thermal Emission Imaging System (THEMIS), the three-dimensional structure of the magnetosphere using Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS), the three-dimensional structure of the corona and interplanetary space using the Solar Terrestrial Relations Observatory (STEREO), and the fine-scale structure of the solar surface (Hinode). This launch rate was made possible by making extensive use of smaller Principal Investigator (PI)-led Explorer missions, Missions of Opportunity, and foreign partnerships. Similar arrangements will be important for maintaining an adequate rate of further progress.

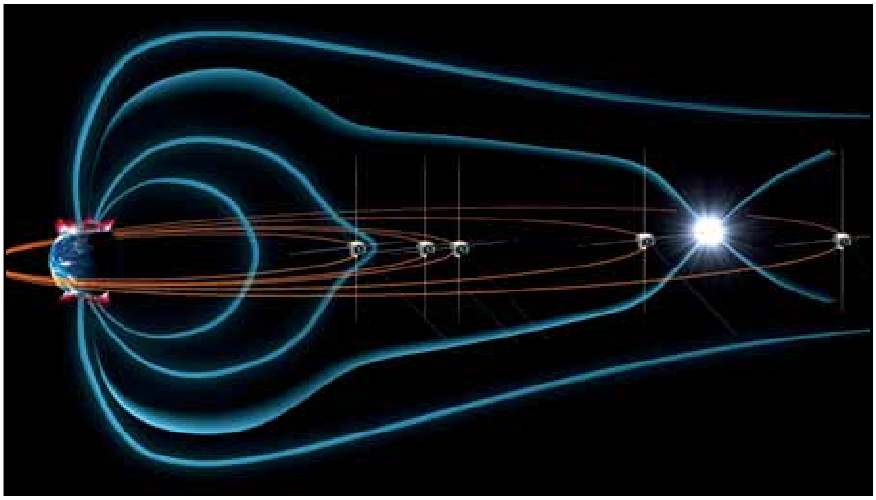
During this same period, the team took note of the loss of observational capability attendant to the loss of several observational platforms, including Interplanetary Monitoring Platform 8 (IMP–8), Imager for Magnetopause-to-Auroral Global Exploration (IMAGE), FAST, Polar, and Ulysses and critical instrumentation on the Thermosphere-Ionosphere-Mesosphere Energetic and Dynamics (TIMED) missions. We reviewed the scientific literature and the assessments of the senior review panels. Scientific results were identified and mapped to the research focus areas (RFAs). Initial results were presented at the roadmap community meeting and further input was solicited. The study produced several highlights. First, magnetic reconnection and particle acceleration remain the dominant fundamental research topics in our field. The last few years have brought direct observations of reconnection occurring within the magnetosphere, the solar corona, and, surprisingly, in the solar wind. Reconnection research is ready to transition from an exploration and discovery phase into detailed understanding of the mechanisms that trigger and moderate it. Our second observation is that the primary breakthrough area for solar terrestrial system science is at the boundaries or interfaces between regions. For example, recent observations with the Coupled in Neutral Dynamic Investigations (CINDI) instrument on the Communications/Navigation Outage Forecasting System (C/NOFS) spacecraft have revealed an unexpected drop in the density of the ionosphere—effectively lowering Earth's boundary with space—as a result of the long period of minimal activity on the Sun during the past solar minimum.

Following are additional noteworthy examples.

AIM is the first mission dedicated to the study of NLCs and has discovered cloud structures that exhibit complex features similar to those present in normal tropospheric clouds; exploration of this mesospheric weather phenomenon is just beginning. The northern hemisphere NLC image below reveals a previously unobserved near circular void in the cloud field that is a common feature in AIM images. This similarity suggests that the mesosphere may harbor some of the same dynamical processes responsible for weather near the surface, and it opens up an entirely different view of potential mechanisms to explain why NLCs form and vary. AIM data also show that the NLC season turns on and off abruptly like a "geophysical light bulb" and they reinforce the remarkable notion that Earth's global atmosphere is a coupled system even on small scales. Results show that changes in polar stratospheric winds in the winter hemisphere are directly connected with NLC changes in the opposite summer hemisphere.

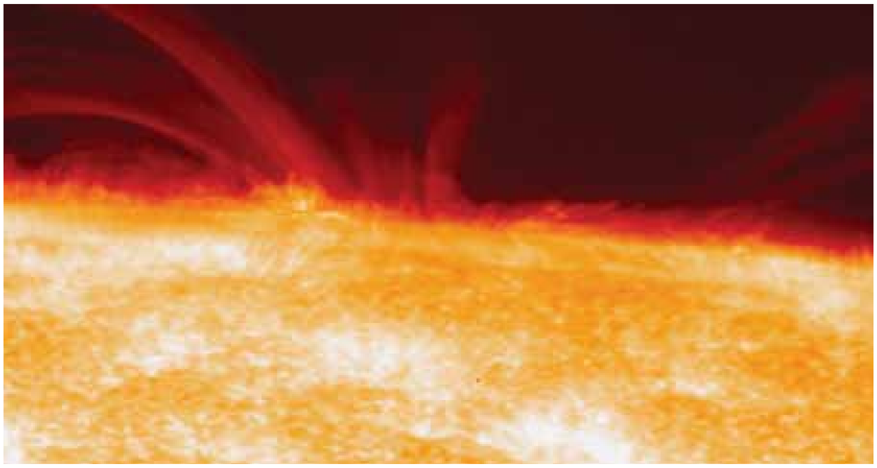


The measurements of the AIM mission are providing a greatly expanded understanding of NLCs and their relationship to global climate change.



This illustration shows the THEMIS spacecraft within a depiction of the Earth's magnetic field. The release of magnetic energy is shown downstream, in the tail of the Earth's magnetosphere where the field lines intertwine and reconnect. The aurorae created in the ionosphere by the reconnection current are indicated above the Earth's polar regions.

Using the five THEMIS satellites, researchers discovered that explosions of magnetic energy one-third of the way to the Moon power the substorms that cause sudden brightening and rapid movements of the auroras. Scientists found the cause to be magnetic reconnection and confirmed that magnetic reconnection triggers the onset of substorms. A long-standing challenge remains to understand the energy and mass transfer between the highly coupled magnetosphere and the ionosphere. Two of the THEMIS spacecraft will soon be redirected into lunar orbit to examine plasma processes occurring in the interaction of the solar wind with the Moon. This exploration of the lunar plasma environment will offer insight into the universal processes occurring in the interaction of plasma with rocky bodies and will be of significant benefit to the design and implementation of the human and robotic activities on the Moon.

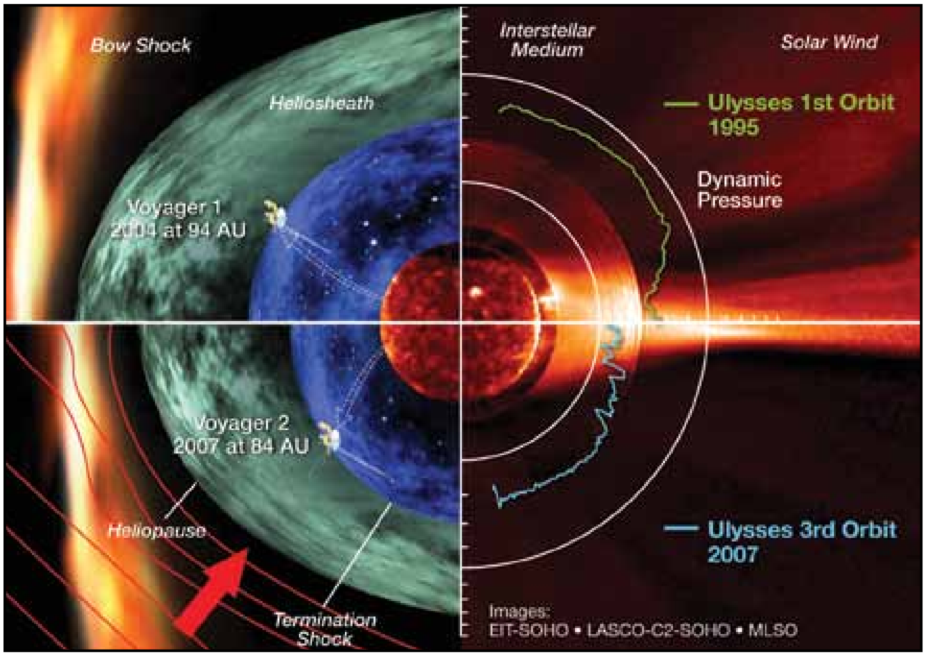


This picture was taken by Hinode's Solar Optical Telescope on November 11, 2006. In the foreground, this image reveals the fine-scale structure in the chromosphere that extends outward above the top of the convection cells, or granulation, of the visible solar surface layer, the photosphere. In the background, plasma above a sunspot traces out magnetic field lines into the corona.

The Hinode spacecraft's high-spatial resolution observations of the Sun have had an impact on solar physics comparable to the Hubble Space Telescope's impact on astronomy. Researchers are analyzing the plethora of new information on the magnetic carpet—the upward transfer of magnetic energy from the Sun's surface toward the corona above. These observations give insight into a variety of processes ranging from the quiet-time solar wind to the most intense solar eruptions that can endanger astronauts and robotic explorers in space. The STEREO spacecraft continue on their paths away from the Earth in leading and trailing orbits, tracking magnetic disturbances (coronal mass ejections (CMEs)) from Sun to Earth. On February 6, 2011, they will provide our first-ever observation of the full solar disk, which will enable scientists and forecasters to track large sunspot groups over their entire lifecycle.

Chapter 2

The Ulysses mission has found that the current solar wind magnetic field strength and dynamic pressure is about one-third lower than during any solar cycle since the space age began. Simultaneous measurements by the Solar Heliospheric Observatory (SOHO) spacecraft indicate that the Sun's polar fields are smaller by a factor of two. The change in strength suggests that the upcoming solar cycle may be significantly different from what we have observed in the past. The heliosphere as a whole, which is inflated by dynamic pressure, may temporarily shrink in size; therefore, the intensity of components of GCRs at Earth may rise to record levels. In this new environment, the recently launched IBEX mission will image, for the first time, the dynamic heliospheric interaction with the local interstellar medium via energetic neutral atoms. The twin Voyager spacecraft, the most distant man-made outposts, currently explore the heliosheath. Two crossings into the heliosheath at distances of 94 AU in 2004 and 84 AU in 2007 reveal a heliosphere that is likely time-dependent in size, in line with expectations. The energy from the sudden slowdown of the solar wind at the termination shock was widely expected to go into heating the solar wind, but that is not the case. The solar wind is far cooler in the heliosheath than expected and apparently the energy mostly goes into heating of particles that the solar wind has ionized and picked up on its outward journey from the Sun.



Left side: Outer heliosphere consequence? The schematic shows from inside out the heliosphere, heliosheath, and interstellar medium with a bow shock for two situations. The top segment is representative of a larger cross-section heliosphere from 2004, when Voyager 1 crossed into the sheath at a 94 AU distance from the Sun, and the lower is a smaller size when Voyager 2 crossed the termination shock at 84 AU. Interstellar magnetic field pressure (red arrow) and the difference in solar wind pressure may have contributed to the observed asymmetry.

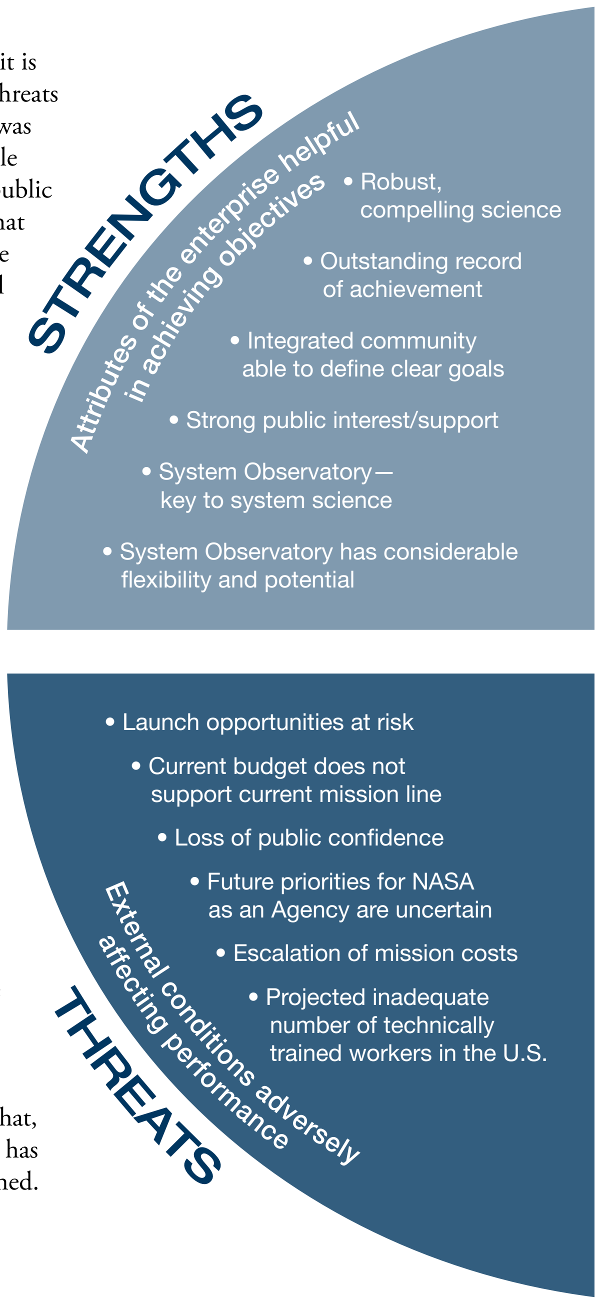
Right side: Loss of solar wind pressure is shown in the latitudinal cut of the inner heliosphere of solar wind dynamic pressure in consecutive solar minima as observed by Ulysses in 1995 (top) and 2007 (bottom).

The biggest surprise of all was that the expected enhancements of anomalous cosmic rays were not observed at the shock crossings. While this may be due to an inefficiency for the diffusive acceleration process at the location of where the Voyager spacecraft encountered the shock, it has called into question the efficiency of diffusive shock acceleration in general, which may have wide-ranging implications for particle acceleration throughout the heliosphere and in the interstellar medium.

Heliophysics Landscape—SWOT Analysis

In assessing the future direction of heliophysics research as a discipline, it is prudent to candidly consider the strengths, weaknesses, opportunities, and threats (SWOT) in the heliophysics landscape. The concept of a “SWOT” analysis was developed at Stanford University in the 1960s and has proven to be a valuable component of strategic planning across a wide range of organizations, both public and private. For this analysis, we considered internal attributes to be those that exist within the Heliophysics Division and/or heliophysics community, while external conditions are those that exist outside or beyond (but may be internal to NASA as an Agency). The intent was to provide a context for formulating the strategies, implementations, and decisions reached through this roadmapping effort.

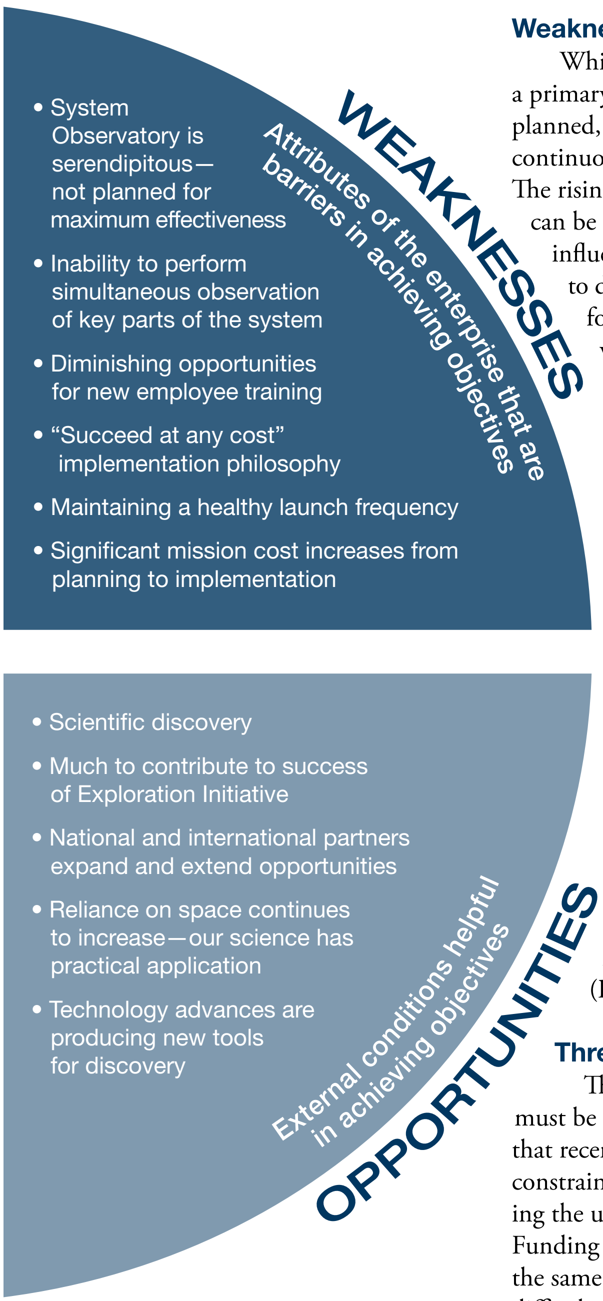
With this analysis, we found the Heliophysics Division to be healthy, vibrant, and becoming more integrated with the efforts of other agencies than ever before. Significant weaknesses and threats to the enterprise do exist and must not be ignored for successful execution of this science strategy, but if the enterprise (including NASA, the science community, and decision makers) is willing to take bold steps and determinedly exploit its strengths, then great opportunities for science and for society are within reach.



Strengths

A primary strength is that heliophysics has a portfolio of robust and compelling science with a potential for discovery. The science is broad and, at the same time, sufficiently deep to produce new discoveries and foster fundamental scientific understanding of our home in space and the interconnected physical processes that link the Sun to the Earth and planets out to the edges of the solar system. Along with a rich diversity of ideas, heliophysics benefits from a community that is more integrated than ever before and is therefore better able to define clear strategies and priorities across the discipline. This complements the fact that there is strong public interest in and support of the science of heliophysics. Both the community integration and public awareness are outcomes of concerted efforts over many years. A similar, but more tangible, strength is the concept of the Heliophysics System Observatory (HSO)—combinations of missions that, taken together, enable larger scale investigations. This distributed observatory has considerable flexibility and grows in capability with each new mission launched.

Objectives within the strategic plan were evaluated within the context of the SWOT to determine the achievability of each objective and how it might best be approached.



Weaknesses

While the existence and flexibility of the Heliophysics System Observatory is a primary strength, a weakness is that its collective capability is serendipitous, not planned, and somewhat fragile due to the aging of the satellite fleet. Long-term or continuous observations of key parts of the system are particularly hard to maintain. The rising cost of individual missions has reduced the number of investigations that can be accomplished within budget resources. Mission costs have been strongly influenced by external factors but also reflect some internal weaknesses related to disconnects between planning, procurement, and implementation methods, for example. Diminished launch frequency is an example of a weakness with long-term consequences through diminished opportunities to retain experienced personnel in flight hardware development and the inability to attract fresh talent to the field. The identified weaknesses represent opportunities for growth and improvement.

Opportunities

Heliophysics has much to contribute to other parts of the NASA enterprise. The science is basic to understanding many questions of the origin and evolution of the universe. Understanding and ultimate prediction of the space environment is important to reduce risk and improve productivity both within and outside of NASA. The expanding importance of the discipline provides opportunities to both educate the public and to meet the challenges of understanding the heliophysics system. Technological advances in information sharing, space instrumentation, propulsion, communications, and other areas are producing new tools that will enable discoveries at a rapid pace. At the same time, the increasing reliance of society on those technologies operating in space creates an urgency for the knowledge generated by the heliophysics program. Thus, there is a need for expanded and extended heliophysics partnerships with other agencies in the U.S. space enterprise (DoD, DOC, DOE, NSF, etc.).

Threats

Threats that lie outside of the direct influence of the heliophysics program must be considered in developing a rational strategy for the future. It is well known that recent elimination of the medium-class Delta II launcher has placed severe constraints on new missions, limiting them to smaller scientific payloads or requiring the use of much more expensive Evolved Expendable Launch Vehicles (EELVs). Funding projections are insufficient to meet the needs of the ongoing programs. At the same time, cost escalation pressures continue. The resultant shortfalls make it difficult to address the increasing complexity and data requirements, and the need for theory and visualization investment. Also impacted is the training of future engineers and scientists, which has the potential to lead to long-term disruptions to the vitality of science and the U.S. space capability. Within this environment, we have recommended scientific priorities to make fundamental contributions worthy of public investment.

Inferences Drawn From SWOT Analysis

The SWOT analysis provided valuable guidance for the development of this roadmap. The text on the next page summarizes the dominant issues raised by the analysis, identifies the NASA Heliophysics Division processes and structures affected, and then lists the solutions recommended in this roadmap. We intend to provide a future direction for heliophysics science at NASA that is based on an assessment of current challenges and constraints.

It is clear that in the coming years, heliophysics will be challenged to maintain and even expand the breadth of its system-level observatory to meet the needs of our space-faring Nation. Other key challenges to the research program include instability in the budget, the growth in cost of missions, and the uncertain availability of Delta-class launch vehicles that have been the workhorse launchers for the Heliophysics Division.

The premises of the roadmap have been conceived to address these challenges. Key among them is the development of a list of prioritized science targets that embody the science objectives of future missions. The science priorities were identified through a community-based process informed by recommendations of the National Academy, by Agency objectives, and other related needs of the Nation (see Appendix B for details). Important considerations were recent heliophysics accomplishments and expectations regarding the scientific contributions of missions under development. With a focus on science objectives rather than specific mission point designs, a flight mission implementation strategy was formulated with the flexibility needed to deal with new discoveries, budget changes, the availability or loss of launch options, and the potential for new partnership opportunities. It is anticipated that this approach will facilitate innovation and mitigate some areas of past cost growth.

It was determined that the Heliophysics System Observatory is a predominant asset and provides an outstanding capability for continued discovery. Significant synergy is manifested in adding missions to the existing portfolio of the system observatory. This is possible with frequent launches allowing investigation of heliophysics as a system of interconnected relationships within the Sun-heliosphere-planetary system and the potential for simultaneous observing from distributed, strategic viewpoints. We recommend (see Appendix B) a launch frequency model of two to three missions per decade for each of the strategic mission lines, Solar Terrestrial Probes (STP) and Living With a Star (LWS), excluding Explorer and Low-Cost Access to Space (LCAS) launches.

An absolutely critical requirement for achieving the recommended launch cadence is setting cost caps and controlling cost growth of the missions. We believe it is unrealistic to expect the division budget to expand to cover cost growth. Only strict control of mission costs will permit a healthy launch rate needed to meet the science requirements of heliophysics. Suggestions for limiting cost growth are discussed in Appendix C, and launch vehicle availability is discussed in Appendix D.

The supporting research program elements of the division should be strengthened to meet the future challenges to the scientific expectations of this roadmap. To be most effective, a careful review of resources across the set of programs is needed. The roadmap recommends that funding priorities recognize and consider this interdependence and complimentary aspect, even though, they are now largely run independently. The technology development program should be focused on enabling and enhancing the high-priority science target-derived missions. The data from the new target missions and the supporting observations of the Heliophysics System Observatory will need to be synthesized through analysis, modeling, and theory to develop the deep scientific understanding and practical knowledge urgently needed by our increasingly technical society.

Recommendation No.1
Implement a science target queue to address the most urgent heliophysics science problems facing the Nation.

Recommendation No.2
Strive to meet a launch frequency of two to three per decade for each of its STP and LWS strategic lines, allowing the entire range of most urgent scientific problems to be addressed and advancing a system-level understanding of heliophysics.

Recommendation No.3
Reduce cost growth to help meet launch frequency requirements of the science.

Recommendation No.7
Ensure that the existing supporting research programs be robustly supported, that the interdependence of each element be optimally defined and that funding of all efforts reflect the interdependence and the complementary aspects of each element.

Summary of SWOT Results:
- Progress across the system requires a broad-based approach best achieved with smaller missions deployed in a number of locations.
- Launcher availability crisis requires a flexible implementation approach.
- Budget uncertainties require a flexible implementation approach.
- Strategies are required for mission cost containment.

Derived Challenges:
- Identification of vital and urgent science problems.
- Launch cadence versus mission capabilities versus budget realities.
- Flexible flight mission strategy to yield:
  - New discoveries across the system.
  - Effective integration of technologies, theory, modeling, and data analysis.
  - Efficient budget management.
  - Compatibility with changing launch market.
  - Mission cost containment.
- Legacy planning-procurement-implementation processes.

Roadmap Solutions:
- Analysis of Decadal Survey Science Challenges as a function of progress and future capabilities.
- Prioritized science queue rather than a mission queue.
- Mission objectives that enable fundamental and system science.
- Compete mission architectures at formulation phase to:
  - Meet mission Life Cycle Cost (LCC) targets.
  - Provide greater launch frequency in both LWS and STP mission lines.
- Heliophysics System Observatory leverages science progress.
- Coordinated objectives for supporting research programs.
- Processes to “procure what you plan” and “implement what you procure.”

New Approach for Heliophysics Mission Planning and Implementation

Based on the lessons learned from the SWOT analyses, this roadmap presents a new approach for heliophysics strategic mission planning and implementation. With a focus on science rather than mission point designs, a strategy is presented with the flexibility needed to deal with new discoveries, budget fluctuations, the availability or loss of launch options, and the potential for new partnership opportunities. It is anticipated this approach will facilitate innovation and help mitigate cost growth through the introduction of competition in the mission design process when NASA is ready to proceed with the acquisition of a new mission.

The roadmap recommends a set of six new science targets along with a launch sequence, cadence, and mission size category. Science objectives, scope, and requirements are given. Specific mission architectures, point designs, or implementation approaches are not described. The roadmap recommends a competitive mission design process be initiated when NASA is ready to proceed with the next mission in the queue.

Recommendation No.3a
Peer review competition at the time of formulation be used to define the implementation of strategic missions to best address the recommended science goals within the resources available.

A competitive approach could make use of existing Science Mission Directorate (SMD) Announcement of Opportunity (AO) processes where each science target proposal would be led by a PI who is typically affiliated with a university, research institution, or government laboratory. The PI selects team members with the skills and experience to develop the science and define the mission. Specifics on project cost, management (Center-led or PI-mode), and acquisition of the spacecraft bus, launcher, and specific technologies are determined on a project-by-project basis and specified in the AO as constraints to mission design. Proposals will require careful tradeoffs between science and cost to design missions with the highest possible value for the cost cap specified. The proposal selections process could have several phases. The first phase would be designed to reduce the financial impact on proposing institutions and broaden participation. Other approaches using competed science and technology definition teams, for example, could also be effective.

While a science target approach may be new to the Heliophysics Division, the model has been used successfully by NASA within other programs. For example, in the New Frontiers program, the missions tackle specific solar system exploration goals identified as top priorities by consensus of the planetary science community. The program solicits proposals for an entire mission, led by a PI that develops the scientific objectives, instrument payload, and mission design. There is a cost cap specified. The first set of New Frontier priorities were determined by the Planetary Division's Decadal Survey, conducted by the Space Studies Board of the National Research Council (NRC) at NASA's request.

The approach set forth by this roadmap is similar in that target objectives and scope are determined by community-based strategic planning, the mission design is to be competed via an AO, and there is emphasis on cost containment.

The heliophysics community is committed to the principles of open competition and merit review as a key to excellence. The roadmap team believes this new approach has the potential to contribute to the containment of total mission cost and development time while improving performance through extensive competitive peer review, validated technologies, and control of design requirements while maintaining a strong commitment to scientific excellence.

SWOT analyses indicate that current planning/procurement processes can create unrealistic cost/schedule expectations.

Current Process

PLANNING

Current Process:
- Planning of specific mission designs
- Small teams study feasibilty and cost

Identified Risks:
- Overzealous advocacy
- Unrealistic program baselines
- Inadequate systems engineering

PROCUREMENT

Current Process:
- Objectives/requirements set by procurement of science investigation

Identified Risks:
- Technology development left to implementation phase
- Requirements instability compared to plan
- Unrealistic cost & schedule baseline
- Inadequate systems engineering

FORMULATION/ IMPLEMENTATION

Current Process:
- Specific mission design complete
- High-confidence cost & schedule baseline

Identified Risks:
- Late understanding of requirements leads to preception of cost growth
- Requirements instability compared to procurement

Decadal Surveys and their associated roadmaps are intended to be strategic planning documents. Mission point designs and acquisition specifics go well beyond strategy and into tactics. These tactics have proven to be unrealistic as the underlying resource, mission risk, and launcher assumptions changed over the course of the decade.

This Roadmap recommends a new approach to mission planning and implementation.

Recommended Process

PLANNING

Recommended Process:
- Prioritize target objectives and scope, no point designs
- Define target size in context of expected resources
- Develop potential technologies

PROCUREMENT

Recommended Process:
- Compete science and mission design within recommended mission size target
- Develop high-confidence requirements baseline
- Develop high-confidence cost and schedule baseline

FORMULATION/ IMPLEMENTATION

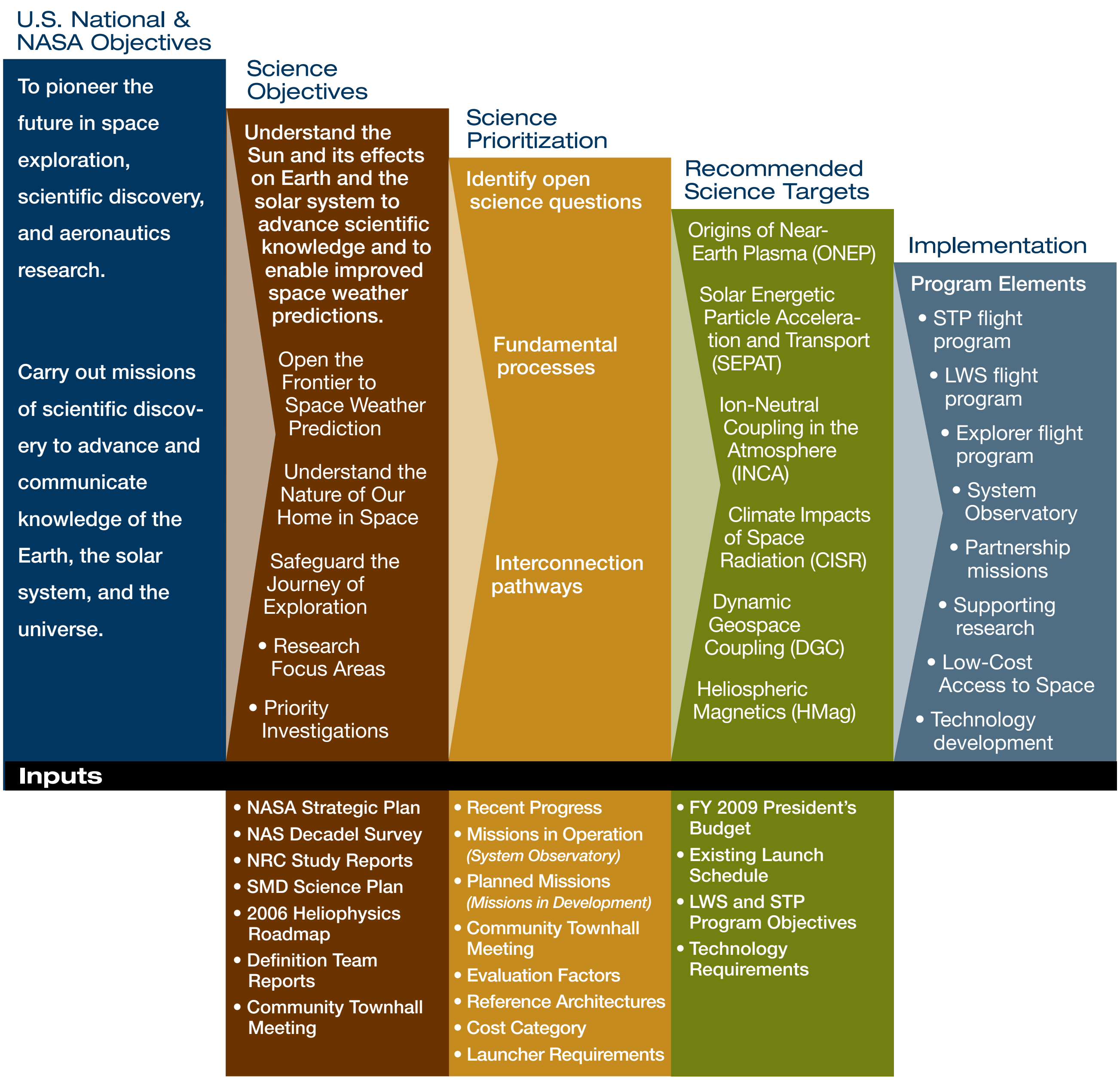
Recommended Process:
- Hold requirements to procured investigation
- Practice best project management and system engineering practices

The major strength of the new plan is in the separation of strategy and tactics. Planning processes focus on science prioritization, program structures, and implementation strategies. The definition of specific mission designs is left to thoughtful analysis from the community through peer review within the context of the resources and technologies available at the time of procurement. (see Appendix C).

Logical Framework for the Roadmap

The roadmap is built on a logical framework that begins with U.S. national and NASA objectives and follows a series of more and more detailed steps, resulting in a launch queue populated by priority science targets.

The science objectives described in Chapter 1, addressed in terms of RFAs and priority investigations, led us toward an implementation plan as illustrated in the graphic below. Analysis of past and recent progress resulted in a comprehensive list of open science questions associated with each of the priority investigations listed in the graphic to the right and described in detail in Appendix A. Gaps in our science plan exposed by the open science questions were then prioritized following the approach described in Appendix B. These open science questions became the basic science objectives for future missions and are called science targets to indicate that the science is focused, and they are not missions in the usual sense of the word. The six highest priority targets were assigned to either the STP or LWS mission lines, depending on the science content of the target. Successful implementation of missions based on the science targets will be through a process that involves all the research programs in the Heliophysics Division.



Science Flow From Objectives to Implementation

The Heliophysics Division science objectives are parsed into three general areas: Frontier (F), Home (H), and Journey (J). Four RFAs comprise each area as discussed in Chapter 1. From these, a set of priority investigations has been extracted. These investigations do not map one-to-one with the RFAs but are based on the RFAs and the 2003 Decadal Survey challenges. The investigations are further divided into two groups, those appropriate for funding through the STP mission line addressing fundamental processes and the LWS mission line addressing interconnections and societal relevance. The highest priority open science questions make up the recommended science targets, and the full suite of open science questions (Appendix A) also provides guidance to proposers in the Explorer Program and partnership missions.

Research Focus Areas

Open the Frontier to Space Environmental Prediction

F1: Magnetic reconnection

F2: Particle acceleration and transport

F3: Ion-neutral interactions

F4: Creation and variability of magnetic dynamos

Understand the Nature of Our Home in Space

H1: Causes and evolution of solar activity

H2: Earth's magnetosphere, ionosphere, and upper atmosphere

H3: Role of the Sun in driving change in the Earth's atmosphere

H4: Apply our knowledge to understand other regions

Safeguard the Journey of Exploration

J1: Variability, extremes, and boundary conditions

J2: Capability to predict the origin, onset, and level of solar activity

J3: Capability to predict the propagation and evolution of solar disturbances

J4: Effects on and within planetary environments

Investigations

Fundamental Processes

- What are the fundamental physical processes and topologies of magnetic reconnection?
- How are plasmas and charged particles heated and accelerated?
- How is solar wind plasma accelerated?
- How are planetary thermal plasmas accelerated and transported?
- What governs the coupling of neutral and ionized species?
- How do coupled middle and upper atmospheres respond to external drivers and to each other?
- How do planetary dynamos function and why do they vary so widely across the solar system?
- What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?
- What is the composition of matter fundamental to the formation of habitable planets and life?

Interconnection Pathways

- What are the precursors to solar disturbances?
- What is the magnetic structure of the Sun-heliosphere system?
- How do solar wind disturbances propagate and evolve through the solar system?
- How do the heliosphere and the interstellar medium interact?
- How are mass and energy transferred from the heliosphere to a planetary environment?
- What are the roles of mass and energy flows in the behavior of planetary environments?
- What is responsible for the dramatic variability in many of the state variables describing the ionosphere-thermosphere-mesosphere (ITM) region?
- How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?
- How do long-term variations in solar energy output affect Earth's climate?

Program Elements

STP — Solar Terrestrial Probes

LWS

Explorers

Theory and Technology Development Validation via Laboratory Experiments and Suborbital Program →

→ Research and Analysis
Modeling
New Theories
Space Weather
Applications

Chapter 3

HELIOPHYSICS: THE PROGRAM ELEMENTS

To achieve the science objectives of the Heliophysics Division, this roadmap recommends a strategy that leverages all program elements of the Heliophysics Division. The recommendations include new missions to be deployed by the Solar Terrestrial Probes (STP), Living With a Star (LWS), and Explorer mission lines and encourages extensive use of current assets in space—the Heliophysics System Observatory. This roadmap also recommends substantial investment in the supporting research programs including theory and modeling as well as technology development and suborbital campaigns. These programs provide the intellectual foundation for the flight missions. For each of these program elements, we discuss how they address the open science questions flowing from the science goals of the research focus areas (RFAs) and priority investigations described in Chapter 2. Each program element has a critical role in implementing the science-based launch queue strategy.

The Heliophysics Program Elements

The Heliophysics Program Elements are the Solar Terrestrial Probes, Living with a Star, and Explorer flight mission lines; the Heliophysics System Observatory; and a set of supporting research programs. All are critical to the development and unification of scientific understanding of the Heliophysics system. Partnerships with other national and international agencies and within NASA provide additional opportunities to meet shared science goals to the benefit of all.

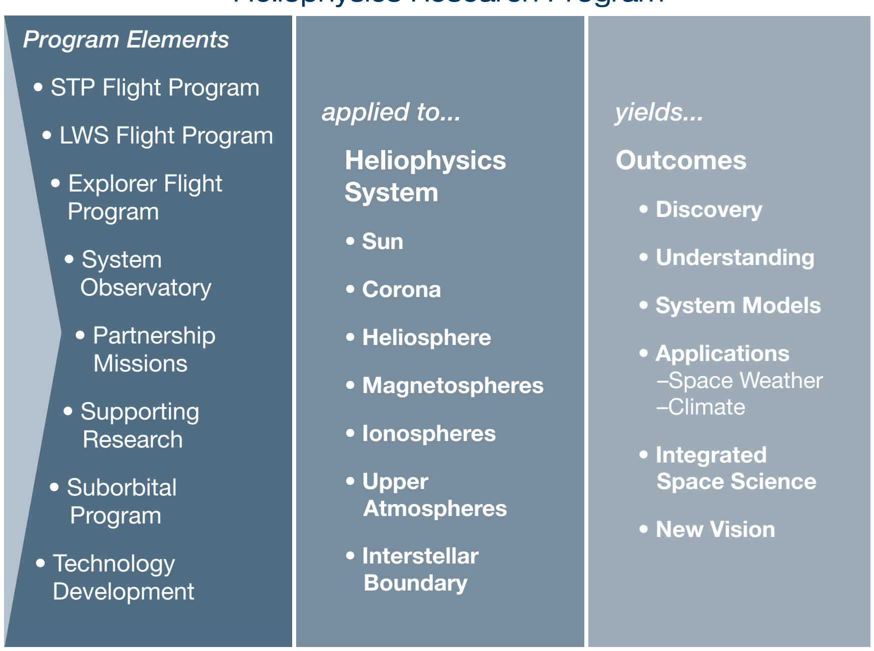
This chapter describes the program elements and their relationship to the science goals and objectives of the heliophysics science priorities as reviewed in Chapter 1. The state of the discipline and the process for developing the most important outstanding science questions was described in Chapter 2. This chapter defines each of the funded program elements and shows how the outstanding questions can be addressed through judicious use of those elements.

The description begins by reviewing the currently operating missions and the missions in development and the open questions currently being addressed. Next, the top priority unaddressed strategic science targets within the STP and LWS strategic program lines are identified. A set of six new science targets and a launch sequence and cadence are recommended. The assessment continues by reviewing the science that cannot be addressed within the strategic mission budget provided. It is clear that a robust Explorer mission line will be required to meet the full range of important science. The relationship of all these missions to the science Traceability Matrix (see Appendix A) is a key element in the logical framework of the roadmap. Descriptions of current missions, missions in development/formulation, and community-provided mission concepts are found in Appendix E.

The chapter concludes by describing the broad range of supporting research activities that will advance the state of our knowledge and provide the intellectual foundation for the flight missions. Flying space missions is what the Heliophysics Division does to advance science. The roadmap recommends appropriate resources in the supporting research programs to fully exploit the missions in which we have already made substantial investment.

Program resources should be devoted to the observation and study of the Heliophysics system to accomplish the desired science outcomes. Each of these programs requires robust funding and should be structured to achieve the integrated research approach to Heliophysics science as recommended by the Decadal Survey.

Heliophysics Research Program



The Flight Programs

This roadmap recommends science targets and associated missions that trace the flow of energy, mass, and momentum through regions and across boundaries. Predominantly, the flow and transfer originates in the Sun's interior, crosses interplanetary space, penetrates planetary magnetospheres, and finds a sink in planetary atmospheres and surfaces; or propagates out to the edges of our solar system where it interacts with interstellar space. This is the essence of the Integrated Research Strategy recommended by the 2003 Decadal Survey. This roadmap recommends a new method to achieve that integrated strategy consistent with the resources available.

The major portion of the heliophysics budget is assigned to the flight program elements — to the deployment of new STP, LWS, Explorer missions, and as deemed appropriate to extending those missions for the Heliophysics System Observatory. This roadmap endorses the continuation of these programs as currently structured.

The flight program serves the needs of a broad set of customers: the heliophysics science community, NASA mission operations, the national operational space weather community led by the National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DoD), other agencies of the U.S. Government affected by space weather; commercial, and other government agencies that operate spacecraft. The Heliophysics Division should continue its policy of engaging the stakeholder communities to ensure the identification of significant and compelling scientific goals through a variety of venues such as the Heliophysics Subcommittee of the NASA Advisory Council (NAC), the American Geophysical Union, the National Academies of Science and its Space Studies Board, and the Committee for Solar and Space Physics. The NASA Heliophysics Division provides the programs with their operating budgets, programmatic guidelines, and management of the scientific goals and objectives.

The flight programs follow NASA Policy Directive (NPD) 7120.4 (Program/Project Management) and NASA Procedural Requirement (NPR) 7120.5 (NASA Space Flight Program and Project Management Requirements) for both program and flight project management. Projects are formulated, approved, and terminated in accordance with these procedures. These procedures are implemented through the processes described in the NASA Headquarters Science Mission Directorate (SMD) Management Handbook. This roadmap is formulated in concurrence with these policies and procedures.

Solar Terrestrial Probes Flight Program

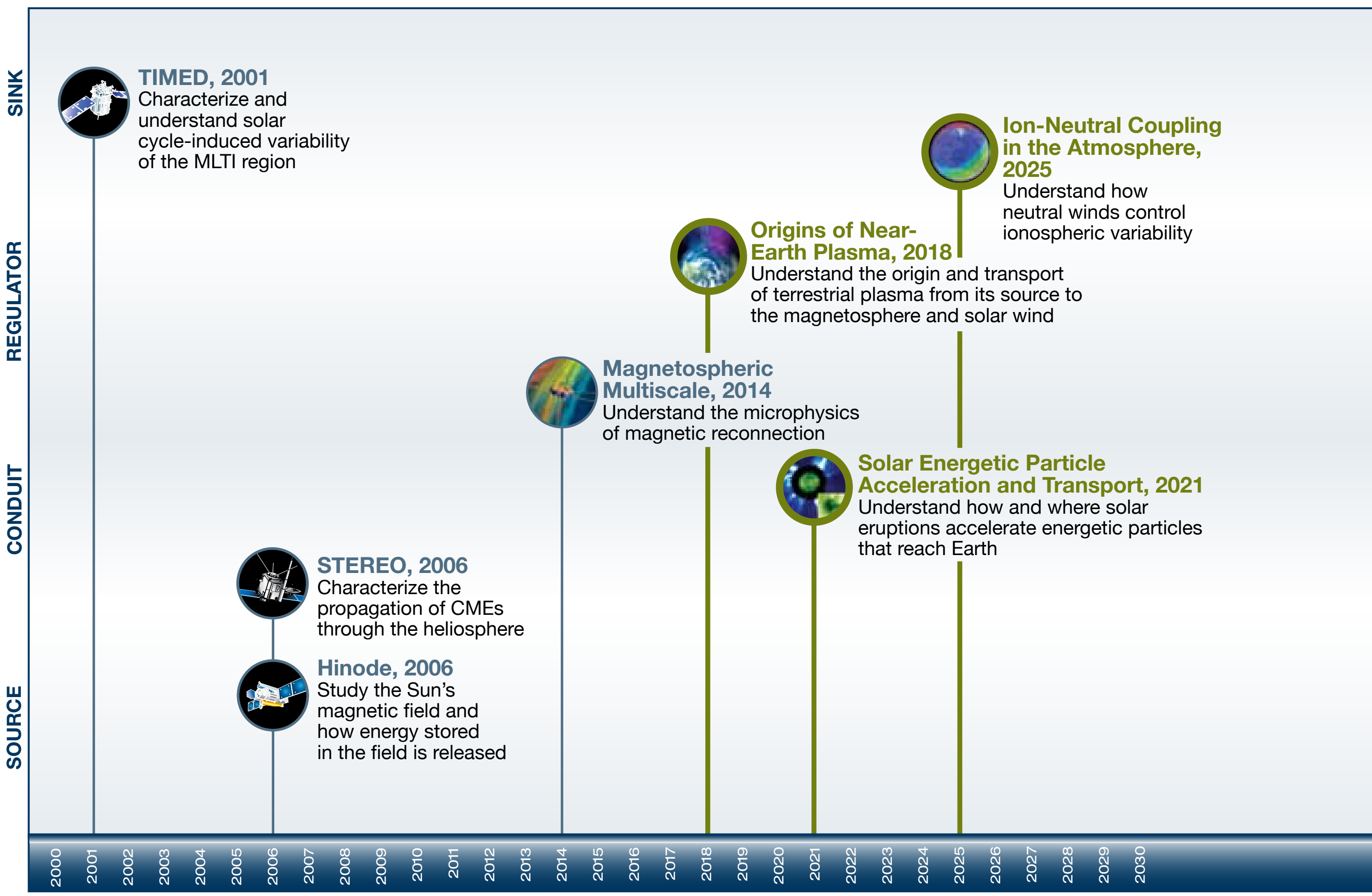
The STP program explores fundamental solar and space physics processes occurring within the solar system and how they affect the nature of our home in space.

The goal of the STP program is to understand the fundamental physical processes that determine the mass, momentum, and energy flow in the solar system from the Sun to planetary bodies including Earth and to the interstellar boundary. The Earth and Sun are linked together to form the system that has given origin and sustenance to our lives. STP missions study this system for insight concerning how it evolved, what will happen in the future, and how this will affect us. Successive missions target the "weakest links" in the chain of understanding. The missions use an innovative blend of in situ and remote sensing observations, often from multiple platforms.

The objectives of the STP program are to:

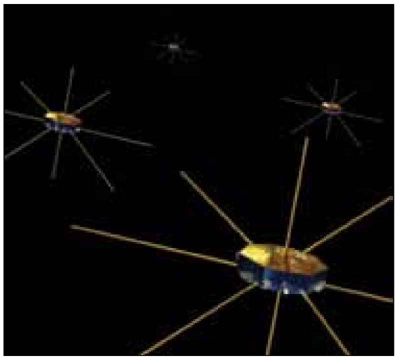
1. Understand magnetic dynamos, reconnection, heating, and particle acceleration.
2. Understand the coupling of charged and neutral particles.
3. Understand how the dynamic nature of the electromagnetic and plasma space environment determines the nature of our home in space and other planetary systems.

Solar Terrestrial Probes Flight Program



This is a conceptual framework to illustrate how the Decadal Survey Integrated Research Strategy may be achieved, where the Sun is shown as the source, interplanetary space as a conduit, the magnetosphere as a regulator, and the ionosphere-thermosphere as elements of the sink.

Missions Currently in Development



Magnetospheric Multiscale (MMS) Mission

Understand the microphysics of magnetic reconnection.

The MMS mission will use Earth's magnetosphere as a laboratory to study the microphysics of magnetic reconnection, a fundamental plasma-physical process that converts magnetic energy into heat and the kinetic energy of charged particles. In addition to seeking to solve the mystery of the small-scale physics of the reconnection process, MMS will also investigate how the energy conversion that occurs in magnetic reconnection accelerates particles to high energies and what role plasma turbulence plays in reconnection events. These processes—magnetic reconnection, particle acceleration, and turbulence—occur in all astrophysical plasma systems but can be studied in situ only in our solar system and most efficiently in Earth's magnetosphere, where they control the dynamics of the geospace environment and play an important role in the phenomena known as "space weather." The MMS mission comprises four identically instrumented spacecraft that measure particles, fields, and plasmas.

*Open Science Questions Currently Targeted by STP Missions**

What are the fundamental physical processes and topologies of magnetic reconnection?	*What are the fundamental physical processes of reconnection?*	
	Inventory the mechanisms leading to reconnection on the Sun. Where are they located? Where are the acceleration regions?	Hinode
	Understand the microphysics of magnetic reconnection by determining the kinetic processes responsible, especially how reconnection is initiated.	**MMS**
How are plasmas and charged particles heated and accelerated?	*How are charged particles accelerated and decelerated?*	
	Determine how particles are accelerated through magnetic reconfiguration	MMS
How is the solar wind accelerated?	*What are the sources of energy for solar wind acceleration?*	
	Investigate the interaction between the Sun's magnetic field and the corona	**Hinode**
	Where does solar wind acceleration occur?	
	Mechanisms of particle acceleration in the low corona and the interplanetary medium	**STEREO**
How do coupled middle and upper atmospheres respond to external drivers and to each other?	*Determine the internal coupling processes within the ITM system and the mediation and control of energy and momentum transfer*	
	Chemical pathways to radiation processes and global energy balance	**TIMED**
	Response to geomagnetic storms and solar variability	
	Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport	
	Solar spectral irradiance and variability	TIMED
What are the precursors to solar disturbances?	*Are there precursors in the surface magnetic and flow fields?*	
	Determine which surface field configurations are most likely to flare	Hinode
	Temporal changes preceding large flares and filament eruptions	Hinode
	Magnetic energy storage in the corona from photospheric field extrapolations	Hinode
How do solar wind disturbances propagate and evolve through the solar system?	*How do solar disturbances create particle radiation hazards?*	
	Global structure of CMEs and other transients, and how they evolve	STEREO

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
• Full traceability from Heliophysics Objectives and RFAs is provided in Appendix A.

Recommended New Science Targets for the STP Program

A detailed description of these targets is found in Chapter 4.

Origin of Near-Earth Plasma (ONEP)

Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.

Plasma of ionospheric origin is now widely recognized as a critical constituent of magnetospheric dynamics, providing the primary source of plasma for the ring current and plasma sheet during active conditions. The key unknown is how this plasma is heated and accelerated so that it may escape Earth's gravitational bounds.

Candidate heating processes include Joule dissipation through ion-neutral collisions, energetic particle precipitation, and wave heating. Information is needed on the sources of energy, the heating and dissipation processes, and characterization of the modes of energy transfer from above and below. *See page 66 for more details.*

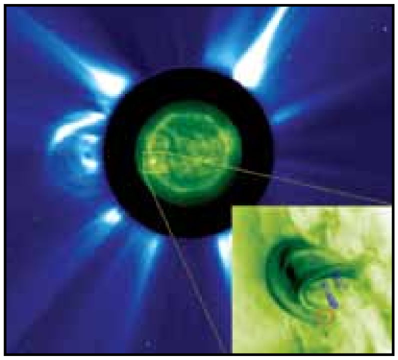
Recommended Mission Class: Small

Solar Energetic Particle Acceleration and Transport (SEPAT)

Understand how and where solar eruptions accelerate energetic particles that reach Earth.

Solar activity is often linked to the release of highly energetic particles, including heavy ions. The origin and the mechanisms that accelerate particles to high energies close to the Sun are not fully identified or understood. Heavy-ion charge states form an equilibrium shaped by the constant interaction with electrons in the strong solar magnetic fields. They are a key identifier for the site of acceleration and processes between the Sun and the spacecraft.

A strategy for a breakthrough in the area of solar particle acceleration is a mission that can separate the effects of particle transport from pure acceleration signatures. Thus, in situ measurements of energetic particles from multiple vantage points in the inner heliosphere, coupled with advanced particle transport modeling and theory, are needed to resolve this long-standing problem. *See page 68 for more details.*



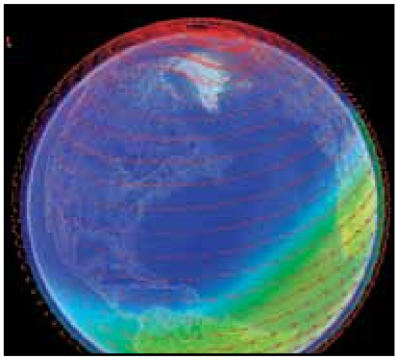
Recommended Mission Class: Small

Ion-Neutral Coupling in the Atmosphere (INCA)

Understand how neutral winds control ionospheric variability.

Measurements of neutral winds are crucial for understanding ionospheric variability; the paucity of such measurements represents the greatest experimental impediment to progress. Previous missions discovered that coupled parameters must be measured to understand the system and showed that the ion and neutral motions depend on prior history of the system, not just the present state.

There are almost no observations of the ionospheric density, composition, and the altitude variation of the neutral winds below 250 km. At low latitudes near 300 km, there are indications that the variability about the mean value is of the same order as the mean value itself. At high latitudes near 300 km, the neutral winds appear to be strongly driven by collisions with ions and electrodynamic coupling to the magnetosphere. *See page 70 for more details.*



Recommended Mission Class: Medium

*Highest Priority STP Open Science Questions Targeted by Recommended Programs**

How are plasmas and charged particles heated and accelerated?	*How are energetic particles transported?*	
	How and where solar eruptions accelerate the energetic particles that reach Earth	**STP #6 SEPAT**
How are planetary thermal plasmas accelerated and transported?	*What determines the composition of upwelling and escaping ionospheric plasma?*	
	Determine the dissipation processes that heat ionospheric plasmas and the coupling processes that affect planetary ionosphere scale heights	**STP #5 ONEP**
What governs the coupling of neutral and ionized species?	*How are dynamo potentials produced in interaction of atmospheres and magnetized thermal plasmas?*	
	Variability in the terrestrial wind dynamo and ionosphere	**STP #7 INCA**
How do coupled middle and upper atmospheres respond to external drivers and to each other?	*Determine the internal coupling processes within the ITM system and the mediation and control of energy and momentum transfer*	
	Neutral winds, disturbance dynamo, and equatorial electrojet	STP #7

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
• Full traceability from Heliophysics Objectives and RFAs is provided in Appendix A.

Living With a Star Flight Program

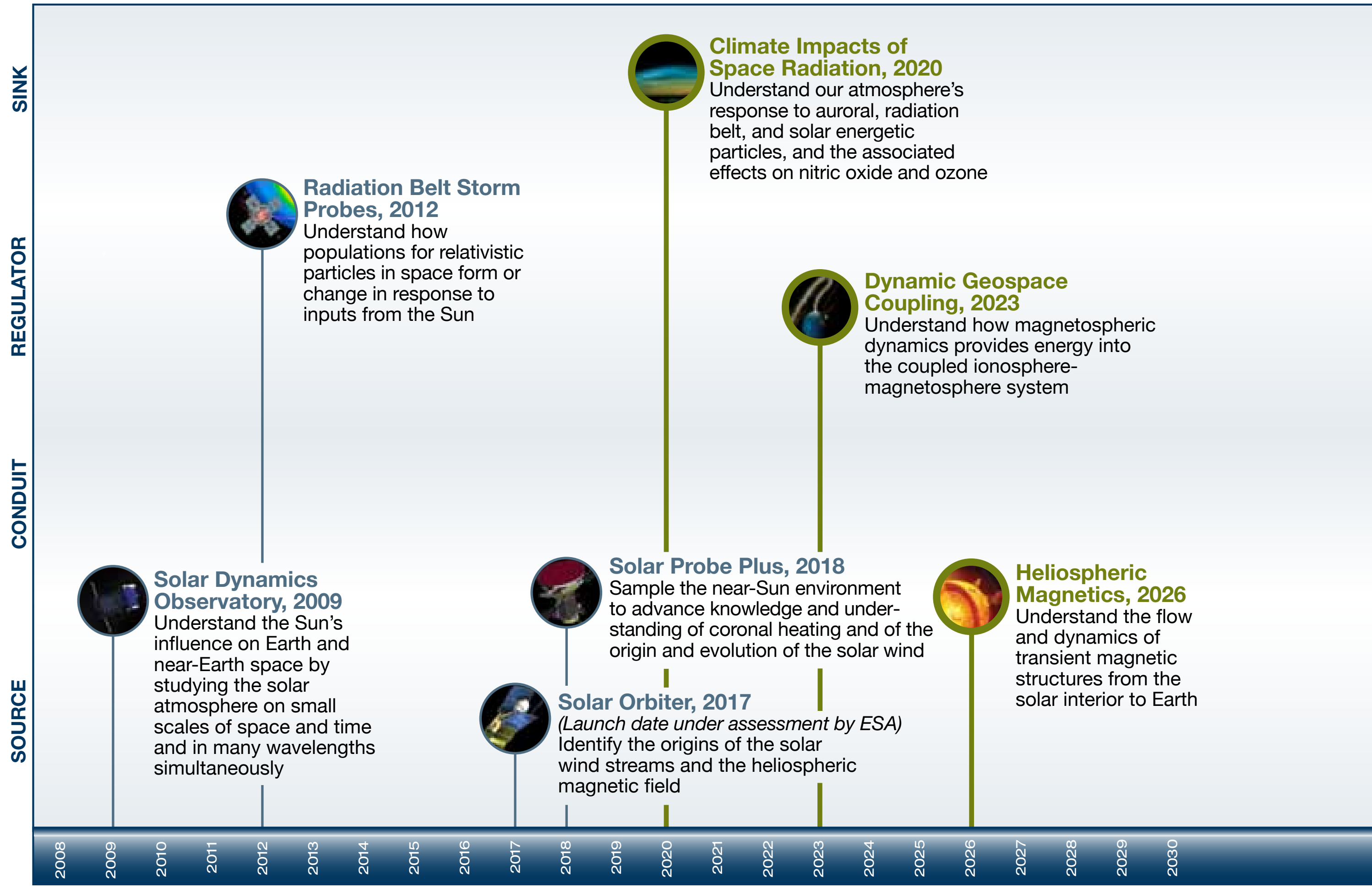
The LWS program targets specific aspects of the coupled Sun-Earth-planetary system that affect life and society and that enable robotic and human exploration of the solar system.

The LWS program emphasizes the science necessary to understand those aspects of the Sun and the Earth's space environment that affect life and society. The ultimate goal is to provide a predictive understanding of the system, and specifically of the space weather conditions at Earth and the interplanetary medium. LWS missions are formulated to answer the specific questions needed to understand the linkages among the interconnected systems that impact us. LWS products impact technology associated with space systems, communications and navigation, and ground systems such as power grids. Its products improve understanding of the ionizing radiation environment, which has applicability to human radiation exposure in the Space Station, to high-altitude aircraft flight, and to future space exploration with and without human presence. Its products impact life and society by improving the definition of solar radiation that is a forcing function for global climate change, surface warming, and ozone depletion and recovery.

The objectives of the LWS program are to:

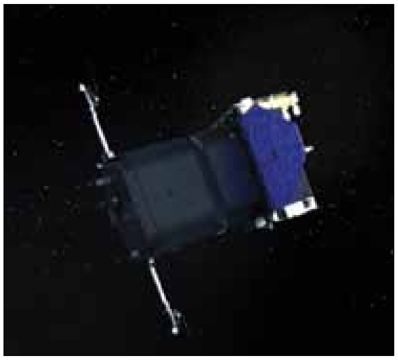
1. Understand how the Sun varies and what drives solar variability.
2. Understand how the Earth and planetary systems respond to dynamic external and internal drivers.
3. Understand how and in what ways dynamic space environments affect human and robotic exploration activities.

Living With a Star Flight Program



This is a conceptual framework to illustrate how the Decadal Survey Integrated Research Strategy may be achieved, where the Sun is shown as the source, interplanetary space as a conduit, the magnetosphere as a regulator, and the ionosphere-thermosphere as elements of the sink.

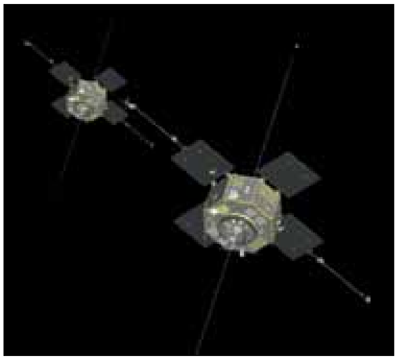
Missions Currently in Formulation/Development



Solar Dynamics Observatory (SDO)

Understand the Sun's influence on Earth and near-Earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously.

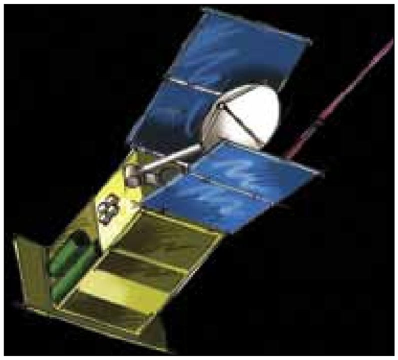
SDO's goal is to understand, driving toward a predictive capability, the solar variations that influence life on Earth and humanity's technological systems by determining how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in the solar irradiance. SDO will study how solar activity is created and how space weather emerges as a product of that activity. Measurements of the interior of the Sun, the Sun's magnetic field, the hot plasma of the solar corona, and the irradiance that creates the ionospheres of the planets are the primary data products.



Radiation Belt Storm Probes (RBSP)

Understand how populations of relativistic particles in space form or change in response to inputs from the Sun.

The RBSP mission will provide insight into the physical dynamics of particle acceleration within the radiation belts and give scientists the data they need to make predictions of changes in this critical region of space. Two spacecraft will orbit the Earth and sample the harsh radiation belt environment where major space weather activity occurs and many spacecraft operate. The two spacecraft will measure the particles, magnetic and electric fields, and waves that fill geospace. Only with two spacecraft taking identical measurements and following the same path can scientists begin to understand how the particle acceleration mechanisms operate in both space and time.

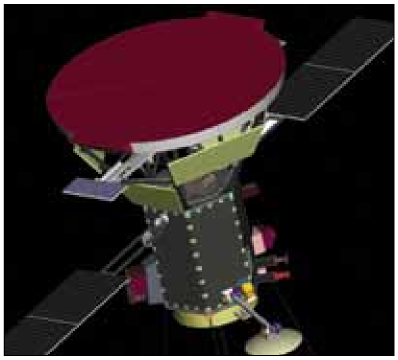


Solar Orbiter (SO)

Understand the inner heliosphere and the unexplored near-sun polar regions of the Sun.

ESA's SO mission will orbit within one-fifth of Earth's distance from the Sun to perform a close-up study of our Sun and inner heliosphere. At these distances, the spacecraft will be closer to the Sun than any previous mission and for short periods will almost corotate with the surface of the Sun. The goals of this mission are to determine in situ the properties and dynamics of plasma, fields, and particles in the near-Sun heliosphere; to survey the fine detail of the Sun's magnetized atmosphere; to identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere; and to characterize the Sun's polar regions and equatorial corona from high latitudes.

Missions Currently in Formulation/Development *(Continued)*



Solar Probe Plus (SP+)

Understand why the solar corona is so much hotter than the photosphere and how the solar wind is accelerated.

Solar Probe Plus will approach as close as nine solar radii from the surface of the Sun, repeatedly sampling the near-Sun environment. By directly probing the solar corona, this mission will revolutionize our knowledge and understanding of coronal heating and of the origin and acceleration of the solar wind, critical questions in heliophysics that have been ranked as top priorities for decades. Two of the transformative advances in our understanding of the Sun and its influence on the solar system were the discovery that the corona is hundreds to thousands of times hotter than the visible solar surface (the photosphere) and the development—and observational confirmation—of the theory of the corona's supersonic expansion into interplanetary space as the solar wind. By making the first direct, in situ measurements of the region where some of the most hazardous solar energetic particles are energized, Solar Probe Plus will make a fundamental contribution to our ability to characterize and forecast the radiation environment in which future space explorers will work and live.

Supporting Flight Elements

Space Environment Testbeds (SET)

The SET project will fly as a piggyback payload on the U.S. Air Force Deployable Structures Experiment (DSX) mission, which is scheduled for launch no earlier than 2010. This will perform flight and ground investigations to characterize the space environment and its impact on hardware performance in space.

The Balloon Array for RBSP Relativistic Electron Losses (BARREL)

BARREL is a balloon-based mission of opportunity to augment the measurements of the RBSP mission. There will be two campaigns of five to eight long-duration balloons aloft simultaneously over a 1-month period to provide measurements of the spatial extent of relativistic electron precipitation and to allow an estimate of the total electron loss from the radiation belts. Observations are planned for when the balloon array will be conjugate with the RBSP spacecraft, such that direct comparison is possible between them. The first campaign is scheduled for 2012, the second for 2013.

*Open Science Questions Currently Targeted by LWS Missions**

How are plasmas and charged particles heated and accelerated?	*How are charged particles accelerated and decelerated?*	
	Understand the mechanisms and importance of stochastic acceleration	RBSP
	Determine the importance of seed populations and how they are created	RBSP
How is the solar wind accelerated?	*Where does solar wind acceleration occur?*	
	Distinguish accelerating processes on the Sun	SO
	Distinguish accelerating processes near the Sun in situ	SP+
What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?	*What is the nature of subsurface flows and the subsurface magnetic field?*	
	Determine the relative importance of the two most important regions of dynamo action	SDO
	Determine the cause of the active longitudes and asymmetric hemispheres	SDO
What are the precursors to solar disturbances?	*Are there precursors observable beneath the solar surface?*	
	Observe how the Sun's magnetic field is generated and structured in its interior and how stored magnetic energy in the corona is released into the heliosphere	 **SDO**
What is the magnetic structure of the Sun-heliosphere system?	*What is the morphology of the heliospheric magnetic field?*	
	Determine the origins of solar wind streams and the heliospheric magnetic field	SO
How do solar wind disturbances propagate and evolve through the solar system?	*How do solar disturbances erupt and propagate?*	
	Understand the physical processes controlling the heating of the solar corona, the acceleration of the solar wind, and the magnetic release of eruptive activity	 **Solar Probe Plus**
	How do solar disturbances create particle radiation hazards?	
	Sources, acceleration mechanisms, and transport processes of solar energetic particles	 **SO**
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	*Determine the mass input and acceleration/loss processes that control the dynamics of the inner magnetosphere.*	
	Determine the major acceleration and loss process for the radiation belts	 **RBSP**
How do long-term variations in solar energy output affect Earth's climate?	*Measure the total solar irradiance and solar spectral irradiance as a function of wavelength and solar cycle*	
	Solar x-ray and EUV spectral variation	SDO

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
• Full traceability from Heliophysics Objectives and RFAs is provided in Appendix A.

Recommended New Science Targets for the LWS Program

A detailed description of these targets is found in Chapter 4.

Climate Impacts of Space Radiation (CISR)

Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on nitric oxide (NO) and ozone.

Generation of odd nitrogen in the thermosphere, especially at high latitude, is well known, but transport processes to the middle atmosphere are poorly understood due to a paucity of measurements.

Changes of odd nitrogen and ozone in response to solar energetic particle events have been observed but are not yet understood. Radiation belt particles penetrate into the mesosphere, but the causal linkage with middle-atmospheric chemistry is speculative. Changes in ozone alter the thermal budget of the middle atmosphere so that a climate linkage is possible, but without observations, this cannot be explored. *See page 72 for more details.*

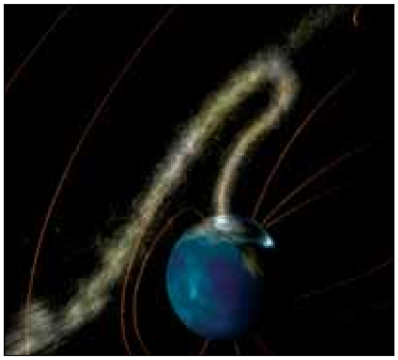
Recommended Mission Class: Small

Dynamic Geospace Coupling (DGC)

Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.

The coupled ionosphere-magnetosphere system is highly nonlinear and dynamic. Scientists have catalogued the responses of different parts of the system and the general nature of the connections between them. Yet the processes that control the coupling or how the dynamics of one region of this systems of systems drive the dynamics in other regions are not understood.

The next scientific step is to simultaneously probe the dynamics in the magnetosphere and ionosphere. Magnetospheric dynamics can be understood through in situ measurements across spatial scales characteristic of global circulation, while ionospheric dynamics can be remotely probed through auroral imaging. Auroral acceleration and heating change both ionospheric and magnetospheric currents and provide ionospheric plasma to the magnetosphere. The nature of these processes, their linked responses to solar wind driving, and the interrelationships between different regions are the key to understanding dynamic geospace coupling. *See page 74 for more details.*

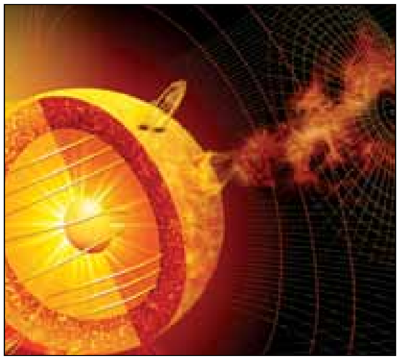


Recommended Mission Class: Medium

Heliospheric Magnetics (HMag)

Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

The causes and effects of transient solar activity are a main focus on the path to identifying the precursors and impacts of major solar eruptions. The solar tachocline and convection zone are the origins of strong dynamo magnetic fields. Detailed understanding of magnetic field formation and transport to the visible solar surface is crucial for the identification of triggers of sudden solar activity. Trigger mechanisms may then be linked with the propagation and evolution of existing plasma and fields in the solar corona and inner heliosphere. The synthesis of these elements leads to better physics-based predictive capabilities of space weather. A systematic approach is needed, one that combines the physics of the solar interior with the evolution of the inner heliosphere, ideally from a location that permits observations of the Sun-Earth line. *See page 76 for more details.*



Recommended Mission Class: Medium

*Highest Priority LWS Open Science Questions Targeted by Recommended Programs**

What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?	*What is the nature of subsurface flows and the subsurface magnetic field?*	
	Properties of subsurface magnetic fields and characteristics of meridional flows	LWS #9
What is the magnetic structure of the Sun-heliosphere system?	*How does magnetic variation propagate through the heliosphere?*	
	Understand how background magnetic fields influence the flow and dynamics of transient activity	**LWS #9 HMag**
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	*What are the processes that control the dynamics of the aurora?*	
	Relationship of Alfvén and electrostatic acceleration mechanisms and how they evolve	LWS #8
How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?	*How does energy and momentum from the solar wind propagate downward through geospace to Earth?*	
	Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system	**LWS #8 DGC**
How do long-term variations in solar energy output affect Earth's climate?	*Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport*	
	Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on ozone	**LWS #7 CISR**

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
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Explorer Flight Program

The Explorer Program provides frequent flight opportunities for world-class scientific investigations from space to address heliophysics and astrophysics space science goals.

Explorer missions play a major role in the ability of the Heliophysics Division to fulfill its science objectives. These investigations target very focused science topics that augment, replace, or redirect strategic line missions. The mission results fill important science gaps in the prescribed program. As such, it is an indispensable element of this roadmap plan. Highly competitive selection ensures that the most current and best strategic science will be accomplished. The missions are led by a single Principal Investigator (PI). The PI defines modest and focused scientific investigations that can be developed relatively quickly, generally in 36 months or less, and executed on-orbit in less than 2–3 years.

There are two serious issues with this tremendously productive mission line:

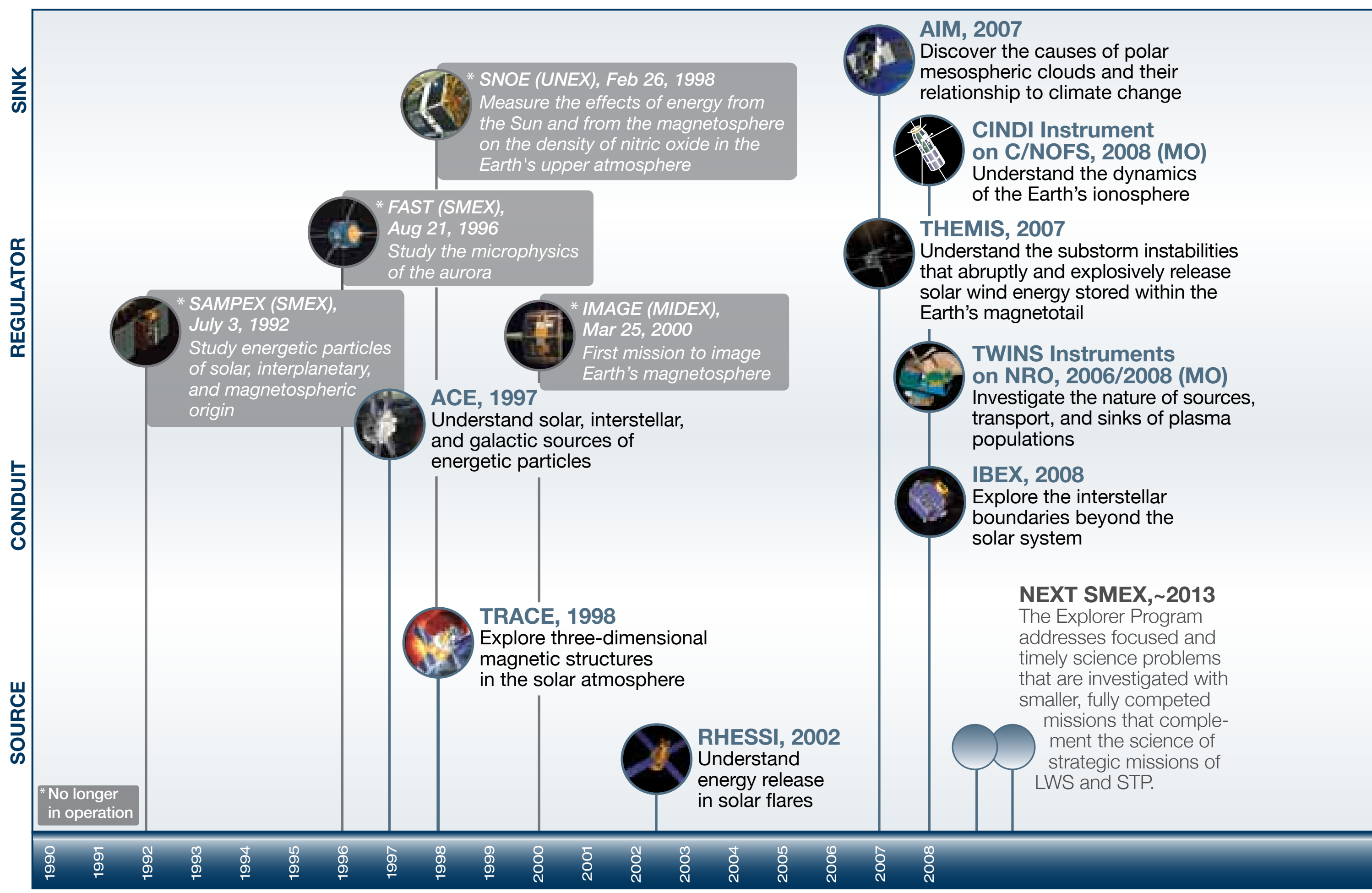
1. The recent decline in the Explorer Program budget is reflected in its lower launch cadence. These missions, in combination with the Heliophysics System Observatory,

Recommendation No.4
Pursue a restoration of the Explorer program to reestablish a desired mission cadence of 18 months with an equal number of SMEX and Mid-Size Explorer (MIDEX) opportunities.

The objectives of the Explorer program:

1. Be responsive to new knowledge, technology, and science priorities.
2. Be competed within the science community.
3. Occur with regularity and high frequency.
4. Be low cost and have a short development cycle.

Explorer Flight Program



This is a conceptual framework to illustrate how the Decadal Survey Integrated Research Strategy may be achieved, where the Sun is shown as the source, interplanetary space as a conduit, the magnetosphere as a regulator, and the ionosphere-thermosphere as elements of the sink.

are capable of addressing many open science questions. NASA should pursue a restoration of funds to the Explorer program in recognition of the value of the Explorer program to meeting NASA's science objectives.

2. In addition, the need for a mix of smaller (SMEX) and medium (MIDEX) missions requires a solution to the launcher availability issues attendant to the loss of medium class Delta II launch vehicles.

*Open Science Questions Currently Targeted by Explorer Missions**

What are the fundamental physical processes and topologies of magnetic reconnection?	*What are the magnetic field topologies for reconnection?*	
	Discover the dynamics, scale size, and energy balance of distant magnetotail reconnection and turbulence processes	ARTEMIS
How is the solar wind accelerated?	*What are the sources of energy for solar wind acceleration?*	
	Reveal the dynamics of the solar chromosphere and transition region	**IRIS**
How do coupled middle and upper atmospheres respond to external drivers and to each other?	*Understand the global and local electrodynamics of the ITM system in response to geomagnetic dynamics*	
	Global characteristics and small-scale physics of plasma irregularities	**CINDI**
What is the composition of matter fundamental to the formation of habitable planets and life?	*What is the composition of material entering, and interacting with, our solar system? (e.g., interstellar medium, galactic and anomalous cosmic rays)*	
	Measure and compare the composition of several samples of matter, including the solar corona, the solar wind, and other interplanetary particle populations, the local interstellar medium, and galactic matter	**ACE**
What is the magnetic structure of the Sun-heliosphere system?	*What is the role of the interstellar magnetic field?*	
	Determine the direction of the ISM field and its influence on particle acceleration in the heliosheath	IBEX
How do solar wind disturbances propagate and evolve through the solar system?	*How do solar disturbances erupt and propagate?*	
	Propagation path and evolution of CMEs to 1 AU, including how these conditions evolve through the solar cycle	ACE
	How do solar disturbances create particle radiation hazards?	
	Investigate particle acceleration and energy release in solar flares	**RHESSI**
How do the heliosphere and the interstellar medium interact?	*What are the properties of the termination shock, heliopause, heliospheric shock, bow shock, and the conditions of the local interstellar medium?*	
	Map the global properties of the termination shock and heliosheath	**IBEX**
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	*Establish the global connectivities and causal relationships between processes in different regions of the Earth's magnetosphere*	**TWINS**
	Determine the processes that control mass and energy storage, conversion, and release in the magnetotail	
	Substorm initiation location	**THEMIS**
	Relate the aurora to magnetospheric drivers	**THEMIS**
How do long-term variations in solar energy output affect Earth's climate?	*Quantify solar cycle and secular change in the middle atmosphere, thermosphere, and ionosphere*	
	Determine why polar mesospheric clouds form and vary	**AIM**

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
• Full traceability from Heliophysics Objectives and RFAs is provided in Appendix A.

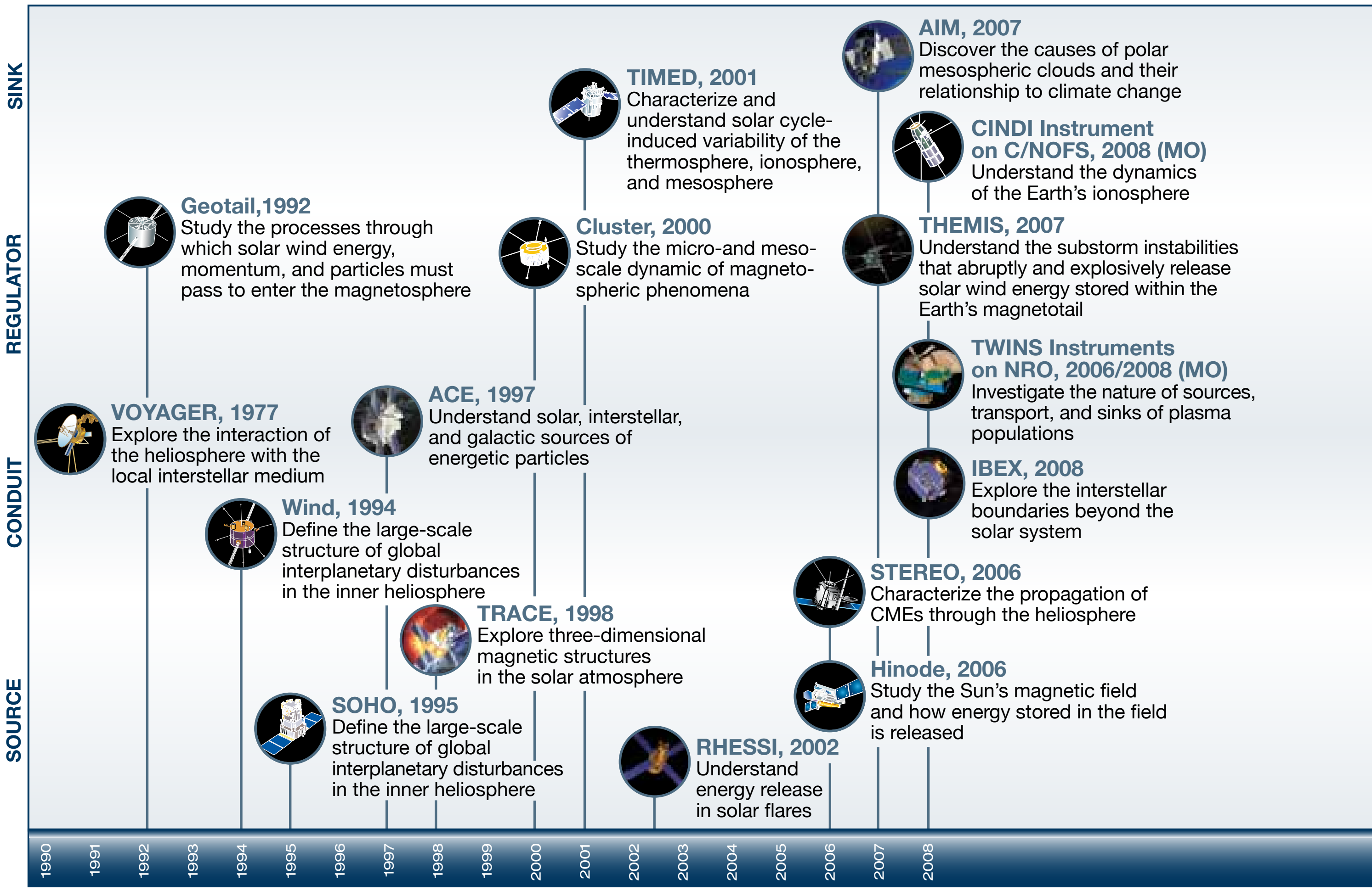
The Heliophysics System Observatory (HSO)

By combining the measurements from all deployed space assets, an HSO is created that enables interdisciplinary heliophysical science across the vast spatial scales of our solar system.

The HSO is a construct that utilizes the entire fleet of solar, heliospheric, geospace, and planetary spacecraft as a distributed observatory to discover the larger scale and/or coupled processes at work throughout the complex system that makes up our space environment. Supported and maintained by the Mission Operations and Data Analysis (MO&DA) budget, the HSO is a central element in the Integrated Research Strategy of the 2003 Decadal Survey and a key element toward closing many of the identified open science questions.

The combination of two or more missions gives capabilities beyond the sum of the individual missions. Ultimately, the combination of new heliophysics knowledge and a well-supported HSO can facilitate the path towards an operational capability to predict space weather. The HSO arose from a series of individual missions, without intentional planning. The opportunity exists now to deliberately evolve this distributed observatory to better meet the needs of heliophysics and the vision for space exploration.

Heliophysics System Observatory



This is a conceptual framework to illustrate how the Decadal Survey Integrated Research Strategy may be achieved, where the Sun is shown as the source, interplanetary space as a conduit, the magnetosphere as a regulator, and the ionosphere-thermosphere as elements of the sink.

*Additional Open Science Questions That can be Addressed by Extending Current Assets**

What are the fundamental physical processes and topologies of magnetic reconnection?	*What are the magnetic field topologies for reconnection?*	
	Quantify the characteristics of reconnection (i.e., scale sizes, geometries, candidate processes, locations, consequences, and frequencies of occurrence)	Several Missions
How are plasmas and charged particles heated and accelerated?	*How are charged particles accelerated and decelerated?*	
	Understand the mechanisms and importance of diffusive shock acceleration and auroral acceleration	Several Missions
	How are energetic particles transported?	
	Connect the particles producing solar radio bursts back to the corona	RHESSI
	Determine acceleration mechanisms for anomalous and GCRs	Voyager, IBEX
How are planetary thermal plasmas accelerated and transported?	*How are thermal plasmas accelerated and transported by electromagnetic fields?*	
	Determine role of induction fields and wave heating processes	THEMIS
	What determines the composition of upwelling and escaping ionospheric plasma?	
	Determine the drivers of energy deposition	Cluster
What is the composition of matter fundamental to the formation of habitable planets and life?	*What is the composition of particles emanating from the Sun?*	
	Solar energetic particle abundances and solar wind CNO charge-state separation	Several Missions
What are the precursors to solar disturbances?	*Are there precursors observable beneath the solar surface?*	
	Understand the causes and mechanisms of CME initiation and propagation	**SOHO**
What is the magnetic structure of the Sun-heliosphere system?	*What is the relationship between closed and open flux?*	
	Discover whether open flux can disconnect from the Sun in interplanetary space	Wind STEREO
	What is the role of the interstellar magnetic field?	
	Determine the direction of the ISM field and its influence on particle acceleration in the heliosheath	Voyager
How do solar wind disturbances propagate and evolve through the solar system?	*How do solar disturbances erupt and propagate?*	
	Propagation path and evolution of CMEs to 1 AU, including how these conditions evolve through the solar cycle	**Wind**
How do the heliosphere and the interstellar medium interact?	*What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?*	
	Discover the properties of the termination shock	**Voyager**
How are mass and energy transferred from the heliosphere to a planetary magnetosphere?	*What are the relative contributions of processes which transfer particles and energy across magnetospheric boundaries?*	
	Mechanisms controlling the entry and transport of plasma into the magnetosphere	**Geotail**
	Three-dimensional studies of plasma structures at the bow shock, magnetopause, dayside cusp, magnetotail, and solar wind	**Cluster**

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
• Full traceability from Heliophysics Objectives and RFAs is provided in Appendix A.

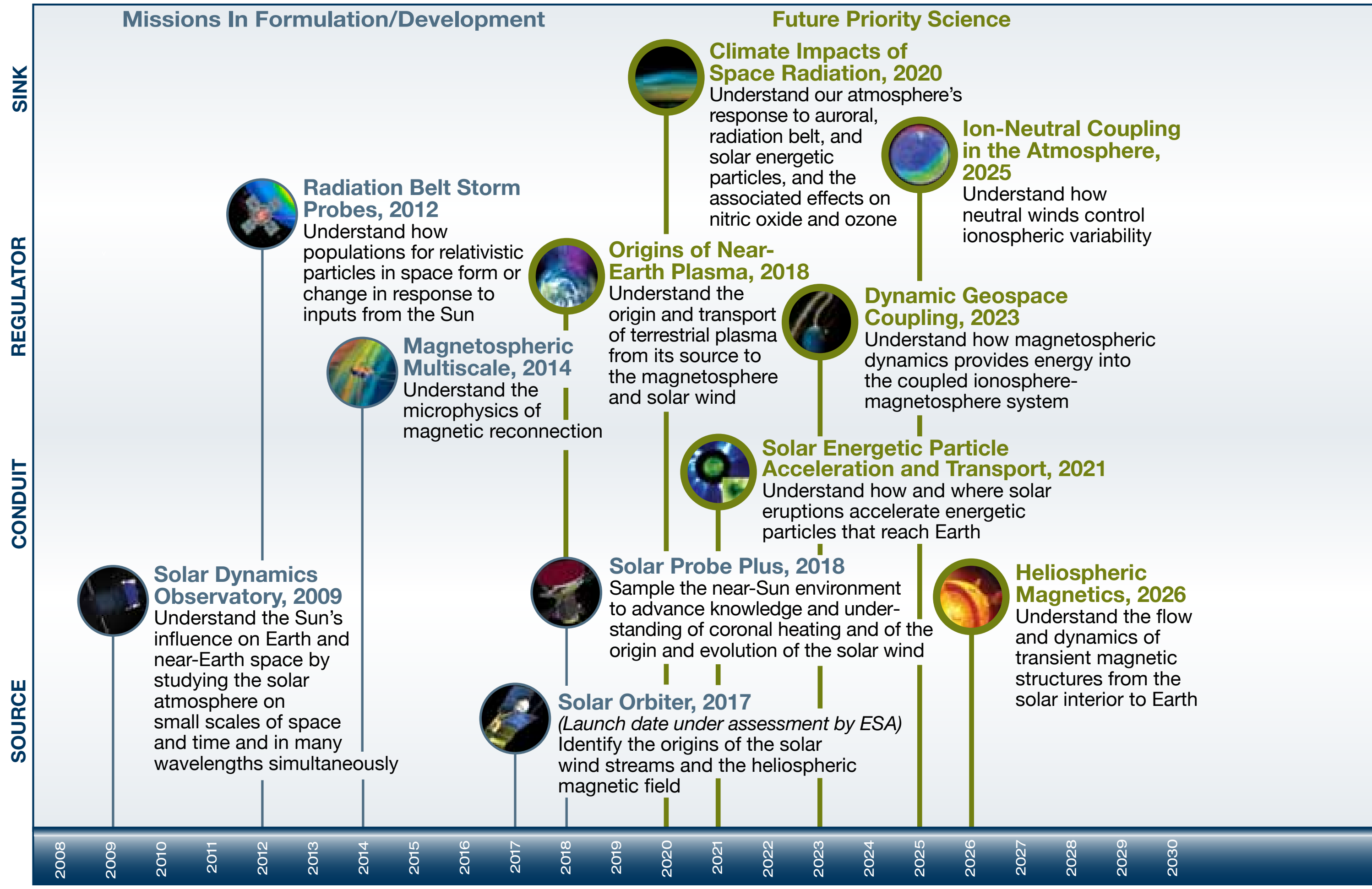
The Evolving Heliophysics System Observatory

The HSO 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 provide the variety of observation posts needed to study the range of Sun-solar system connections. A great strength of this fleet is that it is regularly evaluated and reviewed to maximize the return on Agency investments. This senior review process determines which spacecraft are most necessary to meet the needs of the heliophysics program as defined by the community-developed strategic roadmap. The criteria for continuation include relevance to the goals of the Heliophysics Division; impact of scientific results as evidenced by publications, awards, and press releases; spacecraft and instrument health; productivity and vitality of the science team (i.e., quality and impact of published research, training of younger scientists and education and public outreach); promise of future impact and productivity (e.g., due to uniqueness of orbit, instrumentation, and location or solar cycle phase); and broad accessibility and usability of the data.

The HSO of the future will continue to evolve. We have inherited a very capable suite of satellites. It is important to keep in mind that regardless of the great assets presently in space for the study of our discipline, they are all temporary. The outstanding science questions are many, and a continued distributed observing

Recommendation No.5
Continue preparation and launch of the current missions in development.

Heliophysics System Observatory of the Future



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capability will be required into the foreseeable future. New missions are needed, and they are needed in a timely manner. Launches must occur with a reasonable frequency, and new approaches must be used to lengthen the lifetime of newly launched missions. In this way, we can meet the goals, aspirations, and potential of heliophysics.

*Open Science Questions Potentially Addressed by Partnerships or Future Explorer Missions**

What are the fundamental physical processes and topologies of magnetic reconnection?	*What are the fundamental physical processes of reconnection?*	
	Microphysics of reconnection at the Sun: Do the processes differ from those at Earth? What triggers fast reconnection in large flares?	Remaining to be addressed
	How do the large-scale topologies of magnetic reconnection affect microphysical processes, and vice-versa?	Cross-Scale/ SCOPE
How is the solar wind accelerated?	*What is the role of waves and dissipation in solar wind acceleration?*	
	Understand the energy dissipation modes that dominate heating	Remaining to be addressed
	Determine the importance of small-scale magnetic reconnection	Remaining to be addressed
What is the composition of matter fundamental to the formation of habitable planets and life?	*What is the composition of material entering, and interacting with, our solar system? (e.g., interstellar medium, galactic and anomalous cosmic rays)*	
	Determine the composition of low-energy GCRs, the local interstellar plasmas, and interstellar dust populations	Interstellar Mission
What are the precursors to solar disturbances?	*Are there precursors in the chromosphere and corona?*	
	Magnetic energy storage in the corona from chromospheric, transition region, or coronal field measurements	Solar C
How do solar wind disturbances propagate and evolve through the solar system?	*How do solar disturbances erupt and propagate?*	
	Evolution of source conditions for eruptions over the three-dimensional Sun and inner heliosphere	Remaining to be addressed
	Impact of CMEs and other solar wind disturbances on the global heliosphere	Remaining to be addressed
	How do solar disturbances create particle radiation hazards?	
	Discover which magnetic and shock structures in the corona accelerate energetic electrons	Remaining to be addressed
How do the heliosphere and the interstellar medium interact?	*What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?*	
	Discover the properties of the local interstellar medium, how it changes with time, and determine the implications for our solar system	Interstellar Mission
	Determine whether the termination shock or heliosheath accelerates anomalous cosmic rays	Remaining to be addressed
How are mass and energy transferred from the heliosphere to a planetary magnetosphere?	*What is the global response of the magnetosphere and aurora to the solar wind?*	
	What controls mass and energy transfer at other magnetospheres?	
	Impact of magnetosphere size, rotation rate, orientation, and solar wind IMF on the transfer of mass and energy	Remaining to be addressed
What is responsible for the dramatic variability of the ionosphere-thermosphere-mesosphere region?	*Discover the connections between spatial and temporal scales in the ionosphere-thermosphere system*	
	Understand the electrodynamics that couple the magnetosphere and ionosphere-thermosphere	Remaining to be addressed
How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?	*How does energy, mass, and momentum propagate upward through geospace?*	
	Poleward transport of ionospheric plasma energizing magnetic storms	Remaining to be addressed
	Temporal/spatial distribution of ion outflow	
	Dependence of heating rates/outflow on scale size of magnetospheric input, solar flux	

* Notes: • Missions in bold are "primary contributors" and those in gray "partially contribute."
• Full traceability from Heliophysics Objectives and RFAs is provided in Appendix A.

Role of Partnerships

The urgent need for progress across a range of topic areas coupled with limitations of resources underscores the value of partnerships to increase scientific return.

Partnerships with other divisions within NASA, with other government agencies, and with international partners have already demonstrated their value in missions such as Messenger, Coupled Ion Neutral Dynamic Investigation/Communications/Navigation Outage Forecasting System (CINDI-C/NOFS), and Cassini. Some opportunities for future collaboration are highlighted here.

Intra-NASA Partnerships

Heliophysics benefits from missions in the Planetary Science Division and the Exploration Systems Mission Directorate (ESMD). New opportunities are clearly evident in the ESMD Lunar Reconnaissance Orbiter (LRO). It is the first mission in NASA's plan to return to the Moon. LRO launched on June 18, 2009 with the objectives of finding safe landing sites, locate potential resources, characterize the radiation environment, and demonstrate new technology.

Also important to heliophysics is the Lunar Atmosphere and Dust Environment Explorer (LADEE), which will orbit the Moon. Its main objective is to characterize the atmosphere and lunar dust environment and "...determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity."

The Mars Program has planned launches throughout the coming decade to study the geology and atmosphere of Mars. The Mars Science Laboratory (MSL) and Mars Atmosphere and Volatile Evoltion (MAVEN) missions are of particular relevance. Other important measurements from the Planetary Division are the solar wind measurements at Pluto from the New Horizons mission and the comprehensive particles, waves, magnetometry and auroral imaging at Jupiter from the Juno spacecraft.

Lunar Reconnaissance Orbiter (LRO)

Mars Missions Beyond 2009

National Agency Partnerships

Recently, heliophysics instruments addressing some of the scientific goals enunciated in this roadmap have found ride opportunities on non-NASA payloads. Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) will enable the three-dimensional visualization and the resolution of large-scale structures and dynamics within the magnetosphere for the first time. In collaboration with the U.S. Air Force, CINDI was supplied by NASA as part of the payload for the Air Force C/NOFS satellite. CINDI is investigating the study of unique plasma bubbles that have the potential to disrupt critical radio signals.

This roadmap supports efforts of NASA and other agencies to develop an operational capability to deal with the eventual loss of the Advanced Composition Explorer (ACE), Wind, and Solar Heliospheric Observatory (SOHO) spacecraft that provide critical space weather information for science, commercial, and military applications.

Air Force Communication/Navigation Outage Forecast System (C/NOFS) Satellite

Commercial Ride Opportunities

The commercial space market provides about half of the global demand for launch vehicles. The 2004 Federal Aviation Administration/Commercial Space Transportation Advisory Committee (FAA/COMSTAC) forecast of commercial demand indicates that the launch rate will remain static at ≈22 per year from 2000 until 2013. Some of the launch organizations have indicated a willingness to accommodate piggyback science payloads on their spacecraft. This could be an important route to orbit for some heliophysics payloads.

Potential International Partnerships

The International Living With a Star (ILWS) program was established in January 2002 by the Interagency Consultative Group (IACG). The charter for ILWS is to "stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity." More than 25 contributing organizations are listed at <http://ilws.gsfc.nasa.gov>. ILWS offers opportunities for cooperation between national space agencies for space flight opportunities.

Jointly developed missions such as Cassini/Huygens, SOHO, and Hinode missions have significantly 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. Examples of potential international partnerships with high value to the heliophysics program are listed below.

SOLAR-C

Japan Aerospace Exploration Agency (JAXA) is considering a follow-on to the highly successful Hinode mission. Two potential science issues are under consideration to investigate the magnetism of the Sun and its role in heating the solar corona. Option A consists of out-of-ecliptic observations of the Sun's polar and equatorial regions to investigate properties of the polar dynamo, and option B consists of high spatial resolution, high throughput, and high cadence spectroscopic observations.

CROSS-SCALE/SCOPE

The Cross-Scale and Scale Coupling in the Plasma Universe (SCOPE) missions will investigate the dynamics of space plasma interactions by simultaneously measuring those plasma characteristics at three length scales—electron kinetic (10 km), ion kinetic (100s km), and magnetohydrodynamic fluid scales (1,000s km)—at the Earth's bow shock and magnetosheath, and within the Earth's magnetotail. Cross-Scale is led by ESA, and SCOPE by JAXA. Together these missions seek to understand the interactions between nonlinear phenomena operating between these scale lengths.

ORBITALS

The Outer Radiation Belt Injection, Transport, Acceleration, and Loss Satellite (ORBITALS) is a Canadian Space Agency- (CSA-) sponsored mission to understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere. Together with other ILWS missions, such as NASA's RBSP, ORBITALS will provide a unique and global view of the inner magnetosphere.

INTERSTELLAR MISSION

The nature of composition and dynamics of the interstellar medium are among the highest ranked science questions in heliophysics. No international partnership opportunity to explore the interstellar boundary is known at this time. Were it to materialize, these questions could be addressed by a spacecraft directly sampling the environment outside the heliosphere.

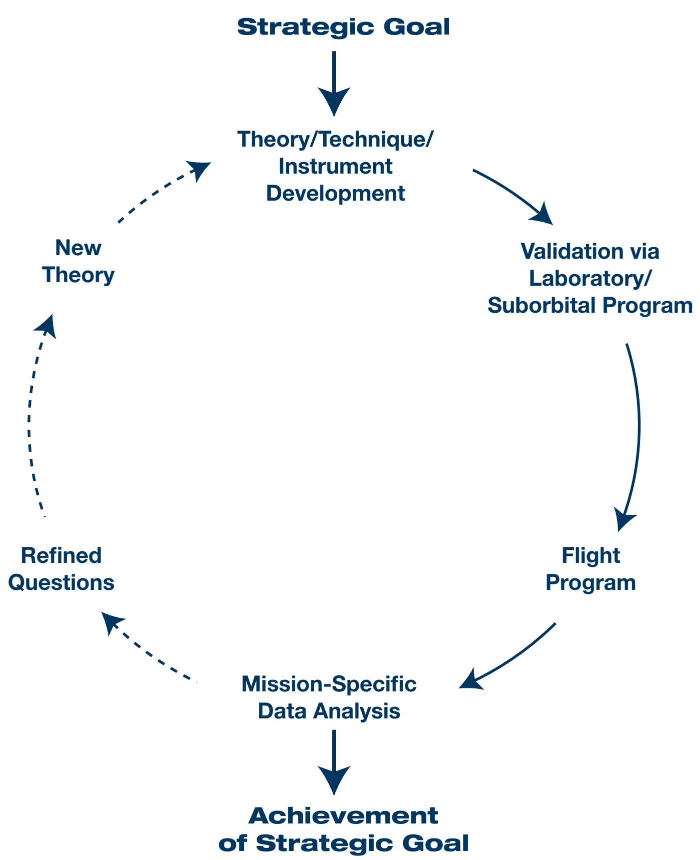
The next logical step in exploration would be to directly sample the medium that lies beyond the extended solar atmosphere. The solar wind and magnetic field keep the unique plasma of the interstellar medium outside the heliosphere. A partnership mission to interstellar space would allow us to sample its unique dynamics and composition and to access the regime of low-energy cosmic rays that helps us understand cosmic particle acceleration processes for the first time.

Recommendations for Supporting Research Programs

The supporting research programs are absolutely vital to the Heliophysics Division. They provide the scientific foundation for the missions that are flown and are the method by which the science of heliophysics is ultimately realized. A descriptive objective for each of the elements is provided that elucidates the specific role each plays. One of the strengths of the program elements is their integrated nature. To be most effective, a careful review of resources across the set of programs is needed, and the roadmap recommends that funding priorities recognize and consider this interdependence and complementary aspect; currently, they are largely run independently. Other aspects to be taken into account are the special needs driven by the increasing complexity of missions, the associated increasing complexity and volume of data, and the need for innovative and enabling technologies. Finally, the programs need to address the pressure on theory and modeling resources, the need to train new scientists and engineers, and the increasing importance of a well supported Heliophysics System Observatory. This roadmap recommends that the existing supporting research programs be robustly supported, that the inter-dependence of each element be better defined, and that funding of various efforts reflect the interdependence and complementary aspects of each element.

The role of the supporting research programs in the scientific method is illustrated in the following figure.

Recommendation No.7
Ensure that the existing supporting research programs be robustly supported, that the interdependence of each element be optimally defined and that funding of all efforts reflect the interdependence and the complementary aspects of each element.



Supporting Research Contributions to the Scientific Process

- A strategic goal requires the development of:
  - Theory
  - Data Analysis Techniques
  - Models
  - Instruments
- The above are tested via the:
  - Laboratory
  - Suborbital Program
- Testing leads to flight programs and analysis of mission data
- Flight programs and mission data analysis result in:
  - Achievement of the goal
  - Greater understanding that leads to a New Cycle
- A new cycle will lead to understanding and achievement of the goal

Basic Research, Theory, and Modeling

Basic research based on data analysis, theory, and modeling form a major part of our strategy for understanding the heliophysics system. The advancement of knowledge and progress of transitioning science products to applied and operational environments are significantly driven by new theories and enabled by improved data analysis and newly created models.

Heliophysics by its very nature must contend with a huge range of energy, spatial, and temporal scales in an interconnected large and very complex system. As new observations potentially lead to discoveries, a more detailed picture of the heliophysics system is painted with ever increasing amounts of data. The role of data analysis, theory, and modeling is becoming more important because (1) the complex coupled heliophysics system can best, and perhaps only, be understood via theories and models and subsequently validated or constrained by observations and data analysis, (2) future mission objectives are driven by the questions theories pose and predictions that models make, and (3) the advanced mathematics used to understand the heliophysics system, such as coupled nonlinear equations, can be applied to other areas of science.

A strong and robust research program will enhance the value and planning for the priority science targets recommended in this roadmap. The program should support theory and modeling teams of sufficient size and capability to enable significant progress in target science areas. The process of determining what aspect of heliophysics is to be investigated next requires a strong scientific rationale that comes from theories and models.

Heliophysics provides a unique opportunity to advance incredibly difficult predictive and modeling capabilities that can have far reaching applications. This is because of the complex and coupled nature of heliophysics science, and the amazing detail of the observations made with a myriad of technologies and across a huge range of scales. This creates the unique opportunity to model heliophysics plasmas using very advanced mathematics that require cutting-edge processing techniques.

There are several research programs that support this work. Generic program descriptions follow immediately, while specific information can be found in the annual Research Opportunities in Space and Earth Sciences (ROSES) announcements. It is the overall guiding objective of each of these programs to contribute as effectively and directly as possible to the achievement of NASA strategic goals, and the priority for selections should be given to those proposals that most clearly demonstrate the potential for such contributions.

Theory Program

The Theory Program is the intellectual compass of the program. It leads the way to new understanding of previous investigations and drives the science concepts for future strategic missions. The Theory Program supports large PI-proposed team efforts that require a critical mass of expertise to make significant progress in understanding complex physical processes with broad importance. It is expected that this program will support the six high-priority science targets in the recommended science queue.

Supporting Research and Technology

The Supporting Research and Technology (SR&T) program is the advanced planning arm of the heliophysics research program. Results of investigations in the program help guide the direction and content of future science missions. This program supports individual research tasks that employ a variety of research techniques (e.g., theory, numerical simulation, and modeling), analysis and interpretation of space data, development of new instrument concepts, and laboratory measurements of relevant atomic and plasma parameters, all to the extent they have a clear application to heliophysics program goals.

Guest Investigator

The Guest Investigator (GI) program is a critical component supporting the Heliophysics System Observatory. The GI addresses science questions using data from the HSO. The GI program enables a broad community of heliophysics researchers in universities and other institutions to use the HSO data in innovative scientific investigations pursuing the goals of this roadmap. The focus of competitively selected research continuously evolves to ensure that the most important questions are addressed.

Targeted Research and Technology

The LWS Targeted Research and Technology (TR&T) component uniquely satisfies two critical LWS needs. It addresses unresolved questions that cross the usual boundaries between scientific disciplines and research techniques, and it develops specific, comprehensive models focused to understand heliophysics as a system, particularly those that have an applied aspect such as space weather operational forecasting and nowcasting. The targeted questions are recommended on an annual basis by a TR&T Steering Committee. Awardees are chosen with cross-disciplinary skills to provide an integrated approach to address larger science problems than is possible for individual researchers. The models that are supported are made available via strategic tools (e.g., at the Community Coordinated Modeling Center (CCMC)) for use by the scientific community and for evaluation for potential transition to operations.

Mission Operations and Data Analysis

Progress in space science is sparked by space observations, which also provide the “ground truth” to test simulations and models. It is essential that observations be properly recorded, analyzed, released, documented, and rapidly turned into scientific results. Stringent budget environments and the associated decline in funding have been somewhat compensated by improvements in information technology making data analysis more efficient; however, the full spectrum of operations and data analysis for missions extends well beyond data analysis.

For heliophysics missions, the mission science teams are assigned the task of ensuring the availability of well-calibrated data throughout the operational phase of the mission. Although the instrumental characterization task is ideally turned into a semi-autonomous process, degradation and other changes of the instrument operations require continuous monitoring and alteration of algorithms and data processing software by cognizant scientists. Access to these data and continuously updating quality factors can be difficult for those not directly connected to the mission teams. The Heliophysics Division has recognized these patterns and funds additional activities within the MO&DA program to facilitate a smooth data flow. All these activities undergo a regular competitive process, a senior review, where the level of support is adjusted according to the anticipated scientific productivity and mission maintenance requirements.

The roadmap team strongly endorses the MO&DA program that supports turning raw measurements into robust data products for use in the scientific community. It also endorses the continuation of effective utilization of the calibrated data through competitive grants in the GI program, the SR&T program, and the TR&T program that generate tangible scientific results from the rich data sets of the heliophysics system.

Data Centers and Virtual Observatories

System-level observations and interpretation require new concepts for data manipulation and exploitation. These changes are being driven by several factors. Information from a single spacecraft vantage point is being replaced by multispacecraft distributed observatory methods and adaptive mission architectures termed “sensor webs” that require computationally intensive analysis methods. Future explorers far from Earth will need real-time data assimilation technologies to predict space weather. Modeling will be an integral element of future mission data products. Other modeling efforts will assimilate data collected by multiple missions into coherent visualizations of broader physical systems. Well-managed archives, virtual observatory systems, and the vigorous application of knowledge support tools are central to achieving the major heliophysics science goals in the coming decades.

Some groundwork for these activities has begun. A confluence of new technologies (Internet, XML, and Web services; broadband networking; high-speed computation; distributed grid computing; ontologies; and semantic representation) is dramatically changing the data landscape. Distributed data and computing resources are being linked together for a more rigorous approach in the verification and validation of predictive models.

Examples include the Columbia supercomputer that uses 10,240 processors and provides an order of magnitude increase in NASA's computing capability, and the Virtual Observatory (VO) programs that will provide pattern and feature recognition to allow large datasets to be mined for events, particularly those detected by multiple platforms.

The VO program is designed to develop an integrated approach to scientific research and analysis (R&A) by enabling the use of diverse datasets via the Web in an easily accessible way. This approach will reduce the exclusivity of NASA mission data and associated data products including models and theoretical predictions. The VO data and products are colocated with the relevant expertise, but accessible to the entire community. The VOs are a whole new approach in the curation of these data assets, which is essential in advancing our understanding of the heliophysics system. The VO program now includes several prototype heliophysics VOs listed at the side. As these and other VOs come on-line, they will provide seamless access to all of the heliophysics mission data essential for new cross-cutting discoveries that will open up the heliophysics frontier.

Future progress will require a carefully designed science-driven systems architecture to provide the necessary synergism among robust data sets, state-of-the-art models and simulations, high data rate sensors, and high-performance computing. The emerging linkage of rich data sets, high-performance computing, models, and sensors will lead to even greater scientific understanding of how our realm of heliophysics operates as a system and how we can enable a research-supported space weather capability.

Heliophysics Virtual Observatories currently supported:

Virtual Cosmic Ray Observatory (ViCRO)

Virtual Heliospheric Observatory (VHO)

Virtual Ionosphere, Thermosphere, Mesosphere Observatory (VITMO)

Virtual Magnetospheric Observatory (VMO)

Virtual Radiation Belt Observatory (ViRBO)

Virtual Solar Observatory (VSO)

Suborbital Programs

The suborbital programs, whose key elements are the Low-Cost Access to Space (sounding rocket) and Balloon program, are an essential component of our research strategy. These investigations make cutting-edge science discoveries using state-of-the-art instruments developed in a rapid turnaround environment. Like Explorer missions, suborbital investigations address important open science questions, thereby augmenting the science accomplished in the strategic line missions. These investigations, selected for the best science, serve three additional purposes that cannot be adequately addressed in other flight programs: the training of experimental space physicists and engineers, the development and flight verification of new instrumentation and methods, and the investigation of coupling between the ionosphere/thermosphere in the 80- to 200-km altitude region and the magnetosphere above and the atmosphere down to the troposphere.

A Terrier-Black Brant XI Rocket lifts off from Poker Flat Research Range near Fairbanks, AK on its way into an aurora to study high-altitude plasma waves.

Photo courtesy of Chuck Johnson, UAF Geophysical Institute.

The scientific relevance of the rocket program is illustrated in the following examples:

NASA's first "tailored" rocket trajectory revealed downward winds over an auroral arc, defying the usual presumption that Joule heating would drive neutral upwelling in the regions of arcs. Observed as the payload traversed a stable auroral arc, the results came as a complete surprise, suggesting upper atmosphere gravity waves dominate the physics of the interaction of aurora with the thermosphere.

In a remote launch campaign at Kwajalein Atoll near the equator, sounding rockets provided the first vertical profiles of the electrodynamics at the onset of equatorial "spread-F," an ionospheric instability that generates a broad spectrum of irregularities that have profound space weather implications. The rockets also revealed the presence of bottom-side waves that could be the sought-after "trigger" of the instability.

In the area of solar physics, the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS) sounding rocket provided unprecedented high temporal resolution results that challenge existing models of the solar corona. Probing the inner solar corona with a cadence ≈2 sec allowed unprecedented studies of evolving and transient structures, including measurements in a coronal bright point at temperatures in excess of $2{\times}10^6$ K, the highest temperatures recorded in such regions.

A high-altitude auroral zone experiment will soon attempt a quantitative investigation of the role of Alfvénic processes in particle acceleration. Alfvén waves have been implicated as a critical component of particle acceleration in space plasmas and as a mass source for the magnetosphere.

Balloon program missions have also had an outstanding record of scientific discovery. For example, the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) Explorer mission depended on the balloon flights of a high Resolution X-ray (HIREX) spectrometer (1980–1989) that discovered superhot (>30 MK) flare plasmas and hard X-ray microflares, on the 1991–1993 flights of the HIgh REsolution Gamma-ray and hard X-ray Spectrometer (HIREGS) flown in Antarctica, and the High Energy Imaging Device (HEIDI) (flown on a high-altitude balloon in 1993), which demonstrated the rotating modulation collimator technique for hard X-ray/gamma-ray imaging (HEIDI) and the sub-arcsec solar aspect system.

The suborbital programs provide important hands-on training for engineers and scientists needed by NASA and the Nation in the future. The program involves numerous undergraduate and graduate students from diverse institutions. Graduate students can participate in the entire life cycle of a scientific space mission, from design and construction to flight and data analysis—something no other flight program can do. The rocket program alone has resulted in more than 375 Ph.D.s. In addition, a rocket or balloon experiment offers the chance for younger scientists to gain the project management skills necessary for more complex missions. The combination of unique science, advanced instrument development, and training makes suborbital research a critical path item for achieving NASA's national space science goals.

Black Brant XI launch.

Balloon launch with heliophysics payload.

Technology Development

Innovation is the engine that drives scientific progress. The invention, development, and application of new technologies lead to new windows into nature's works. Heliophysics is a lively field that applies new technology and thus achieves the return of never-before-seen information. Heliophysics fosters a feedback loop between scientists specializing in data analysis, modeling, and instrument development to uncover the missing links of the larger heliophysics system picture. This systematic quest for discoveries leads to new interpretations and theories that make predictions. Predictions spark the need for testing, fueling the need for new, focused measurements and technologies. Predictions and forecasts can have immediate applications, adding to the scientific arsenal that deals with the variability in the solar terrestrial environment. Deeper understanding of the heliophysical system emerges and so do applications that mitigate the effects of adverse space weather on society.

To pursue a rigorous study of the heliophysical system, we recommend rapid development and infusion of new, mission-enabling technologies. Many new technologies we require have a specific heliophysics focus, but there are also mission-enabling technologies with cross-disciplinary character for which we recommend heliophysics participation.

The ability to achieve the recommended science targets and those of future missions beyond this roadmap timetable would be greatly enhanced with technology developments in two key technology areas—instrument development and software development. Existing programs support instrument development as a subset of SR&T. Other parts of this program, along with the heliophysics theory, LWS TR&T, and the heliophysics GI program support software development for modeling the heliophysics system. The Low-Cost Access to Space (LCAS) program, which includes balloon and sounding rocket investigations, also furthers instrument development but serves only a part of the heliophysics community. The technologies identified below are deemed to provide the best return on investment with regard to addressing the prioritized science for strategic missions. The mapping indicates possible applications for new technologies in the priority science targets. However, technology development should remain open to new technology ideas that we can apply outside the strategic mission lines, such as the Explorer Program and Missions of Opportunity.

Heliophysics Technology: Instrument Development

It is recommended that increased investment in instrument development and related technologies be made through the SR&T and LCAS program elements. Key areas that would potentially benefit missions in development and the science targets prioritized in this roadmap would include improving detectors in functionality, components, and design. Desirable improvements would include, but are not limited to, the following:

	MMS	ONEP	SEPAT	INCA	RBSP	BARREL	SO	SP+	CISR	DGC	HMag
New technologies with reduced noise and insensitivity to heat and radiation for missions approaching the Sun			●				●	●			
Improved sensitivity to UV and EUV for solar and auroral remote sensing (LWS #7, #9), but also solar blind/UV blind ENA sensors for magnetosphere and heliosphere imaging									●	●	●
Adaptability of geometric factor, fast pulse-height analysis, and radiation hardness to increase operability during radiation events or in radiation belts			●		●	●	●	●	●		●
Improved in situ particle optics with larger apertures and/or improved identification for in situ composition analysis	●	●	●	●	●		●	●	●		
Larger array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing		●	●	●			●			●	●
Increased spectral resolution systems and lifetimes for IR, FUV, and EUV for solar and planetary upper atmosphere spectroscopy		●	●	●					●	●	
Improved polarization measurements, more effective IR detector cooling devices, higher reflectivity mirrors, and diffraction-limited optics for EUV for space climate and solar remote sensing			●	●					●	●	

Cross-Discipline Technology That Enables Future Mission Concepts

Several unresolved but high-priority science questions cannot be reasonably addressed with currently existing technology or resources. This drives the associated science missions beyond the recommended science queue. Before progress can be made, investments in critical technologies must be made that enable those missions to become feasible. This investment should be made in the near term in order that the technology can mature to the point that the associated science missions are enabled in a timely fashion. Example technologies are listed below:

- In-space propulsion — solar sails, stable solar electric propulsion for reaching and maintaining vantage points in space.
- Improved power sources for near-Sun and deep-space missions.
- Radioisotope supply for near-Sun or deep-space power generation.
- High-rate, long-distance optical communications for increased data rate of deep space or fleet missions.

New technologies that should be rapidly employed by heliophysics, but also would equally benefit the other SMD science divisions include onboard data compression, fault-tolerant computing, miniaturized electronics and power supplies, low-power sensors, and application-specific integrated circuits. The common thread of these technologies is that they help the Agency accommodate the best possible scientific sensor solutions on upcoming missions. Therefore, it is imperative that heliophysics does not fall behind in applying them.

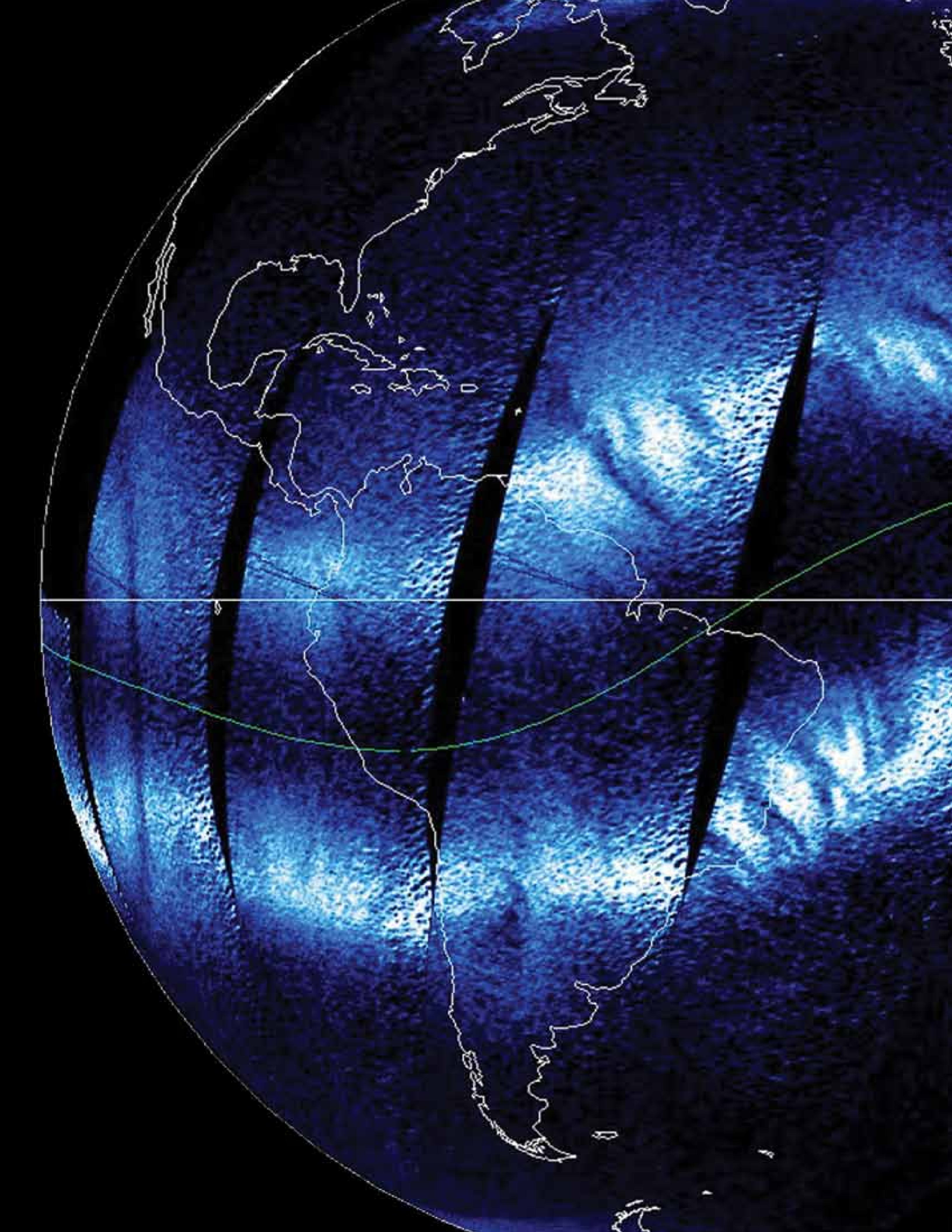
The Heliophysics Division alone is not able to shoulder a number of major developments that have immediate applications across NASA's Science Divisions, other NASA Directorates, or other national agencies. Examples of new technologies are listed below:

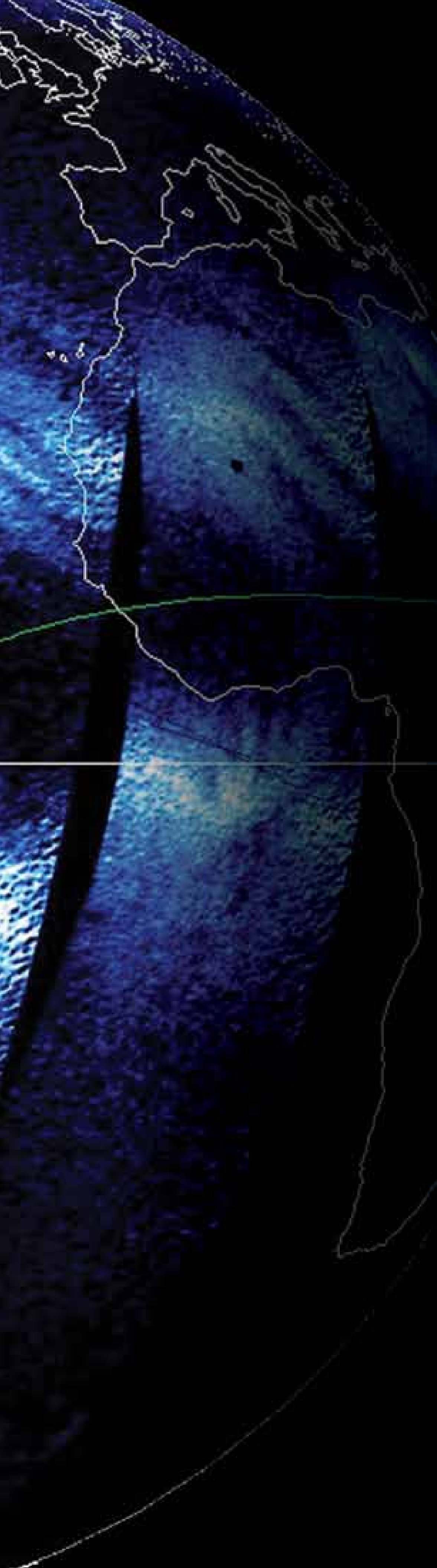
- Low-cost launch platforms and spacecraft buses.
- Lightweight structures and nanotube technology.
- Replacement for a Delta II launch capability.

Cross-Discipline Technology: Advanced Information Technology

We look forward to a continuing exponential growth in science data resources returned from our space missions. This explosion, in terms of volume, complexity, and multiplicity of sources will call for new and innovative analysis paradigms to transform that data into knowledge and understanding. Advances in computer science and technology afford vital opportunities to deal with this challenging new environment and enhance science productivity. It is recommended that increased investments be made in the area of heliophysics informatics to include the following:

- Computational methods and algorithms for multidimensional data analysis and visualization.
- Numerical laboratories for modeling and simulating physical processes and effects.
- "Science Discovery Infrastructure" consisting of robust tool sets for mining huge volumes of multidimensional data from all observatories and models and extracting and cataloging features and events.
- Onboard science autonomy for sensor webs drawing from heliophysics observatories.





Chapter 4

HELIOPHYSICS: PRIORITY SCIENCE TARGETS

In recent years, the nature of scientific research in general has been evolving toward a greater emphasis on multidisciplinary research. For heliophysics, we are on the cusp of a significant shift toward an integrated framework of understanding of the heliophysics system. System science invites and encourages exploratory data analysis, looking for unexpected linkages that are beyond what one might hypothesize in advance. At the same time, continued detailed scientific research in the cartesian sense is absolutely required to deepen our understanding of the fundamental physical processes.

Both detailed in-depth and inductive approaches to science are foundational to the heliophysics strategy. The first is evident in the structure of the science flow down leading to science targets designed to reveal the fundamental workings of the system. The incorporation of new target missions into the Heliophysics System Observatory (HSO) and the synthesis and modeling provided by the supporting research program elements enable comprehension of the whole.

This chapter provides science background for the highest priority science targets introduced in Chapter 3 and the vision of the heliophysics discipline for the future. A science queue is presented that illustrates the anticipated launch dates of the Solar Terrestrial Probe (STP), Living With a Star (LWS), and Explorer missions, including the missions addressing the highest priority science targets. Chosen to break through present blockages in our knowledge, their eventual impact will be a significant advance of understanding. They are an element of the full program of exploration, observation, theory, modeling, and simulation that are critical for the development of our knowledge of the past and for extending what is learned to deal with the present and predict the future.

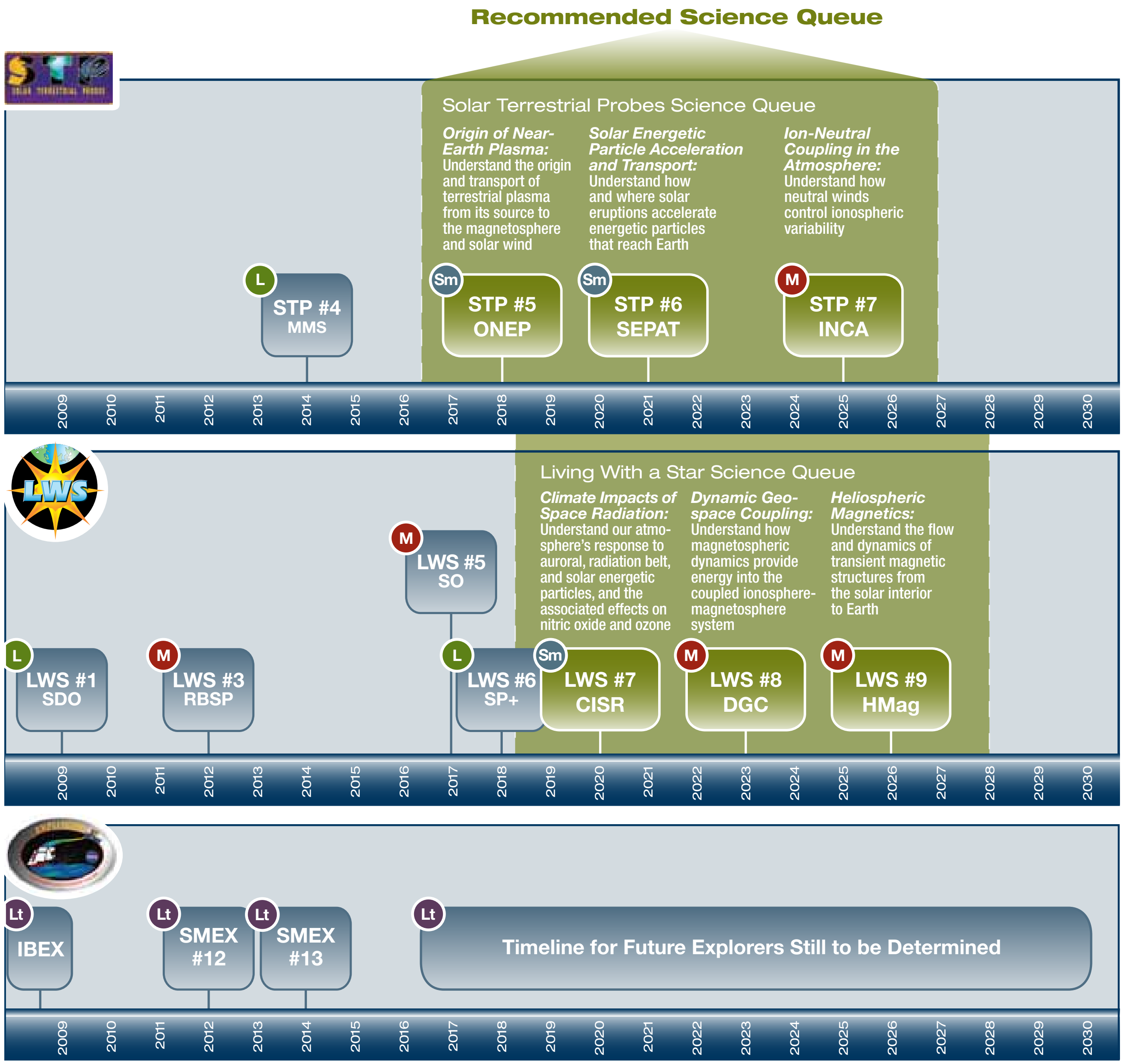
Science Prioritization and the Science Queue

For the first time, we recommend a new, flexible heliophysics research strategy based on prioritized science objectives. The science queue consists of science targets that at this point in their development do not have fixed point designs as their implementation strategies. These priority science targets should, at a later date, be implemented through resources of the strategic mission lines in heliophysics.

Recommendation No.1
Implement a science target queue to address the most urgent heliophysics science problems facing the Nation.

By evaluating both the science and implementation factors, the roadmap team has associated the highest priority science targets with cost categories (i.e., light, small, medium, and large) and placed them into a science queue in either the STPs or the LWS mission lines consistent with the goals of each mission line and the science objective. The timing of the projects was based on the required launch frequency and the FY 2009 President's budget with a 1% inflation beyond the 5-year horizon of the budget. Besides the science queue, the team identified one high-priority science target for a potential international partnership, interstellar mission and identified other existing international partnership opportunities. All science targets are described in this chapter to the extent that the science queue warrants (i.e., without prescribing implementation or procurement requirements).

The graphic indicates launch dates for strategic and Explorer missions as presently understood. The missions in development (grey boxes) and the new science targets (purple boxes) are marked with a colored dot, indicating the mission cost class. The boxes are centered on the launch date. The bottom panel lists potential international and intra-NASA partnership opportunities.



Cost Definitions for Missions

- N Nominal
- Lt Light: <$250M
- Sm Small: $250M–$500M
- M Medium: $500M–$750M
- L Large: $750M–$1B

Per NPR 7120.5 D

Potential International Partnerships

- Lt SOLAR-C (JAXA)
- N ORBITALS (CSA)
- Lt Cross-Scale/Scope (ESA/JAXA)
- Sm Interstellar Mission

Color of button indicates size of NASA contribution. Funding is not reflected in roadmap budgeting and would require additional resources.

Intra-NASA Partnerships

- JUNO
- Mars Atmosphere and Volatile EvolutioN (MAVEN)
- Mars Science Laboratory (MSL)
- Lunar Reconnaissance Orbiter (LRO)
- Lunar Atmosphere and Dust Environment Explorer (LADEE)

No contribution of funds is anticipated.

Note: LWS #2 and LWS #4 are the Space Environment Testbeds (SET) and the Balloon Array for RBSP Relativistic Electron Losses (BARREL) suborbital project, respectively.

STP #5

Origins of Near-Earth Plasma (ONEP)

Science Target

To understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.

Science Rationale Summary

The STP #5 science target ONEP follows from the fundamental processes investigation: How are planetary thermal plasmas accelerated and transported? It is also related to the societal relevance investigation: How do the magnetosphere and the ionosphere-thermosphere systems interact with each other? Understanding planetary plasma acceleration and transport processes is fundamental in determining how planetary ionospheres can contribute to magnetospheric-plasma populations. Additionally, some of the ionospheric plasma can ultimately escape into the solar wind. Loss of ionospheric plasma also results in atmospheric loss, since the ionosphere is created through ionization of the neutral atmosphere. In addition, plasma of ionospheric origin often consists of heavier ions, such as atomic oxygen ions. The increased mass density can change the characteristics of the magnetospheric plasma, affecting processes such as reconnection.

To assess how ionospheric plasma is distributed throughout the magnetosphere requires knowledge of how the ions are energized as they escape from the Earth's gravitational potential well. For example, oxygen ions must be accelerated and heated to energies much higher than typical ionospheric temperatures to escape; however, protons can escape relatively easily. At the same time, since the heavier ions tend to have lower velocities, they are more likely to be affected by other processes such as convection, and the final disposition of these ions requires detailed knowledge of their energy distribution as they leave the ionosphere.

The fundamental process of planetary ion outflow has particularly important implications for life on Earth, not only in the study of atmospheric loss but also in the understanding of geomagnetic storms, their magnitude, and duration. We must better understand the nonlinear processes and feedback that enhance or moderate electrical currents in the magnetosphere to predict storm strength and subsequent societal effects. Ionospheric plasma is a major contributor to the plasma pressure and currents throughout the magnetosphere during these storms. Because the magnitude of ion outflow is related to the storm strength but also contributes to the storm strength, the interchange of mass and energy between the ionosphere and magnetosphere constitutes the largest nonlinear system in geospace.

Example questions for this science target are:

- What are the sources of energy that drive ionospheric outflows?
- How are these energy sources partitioned as a function of altitude and location (e.g., the auroral oval versus the dayside cusp)?
- Where do the different energy sources deposit their energy?
- How does the neutral atmosphere respond to the energy deposition?
- Does variability in winds, etc., within the neutral atmosphere affect the ionospheric response to the energy sources?
- To what degree do feedback and saturation processes control the outflow of plasma?
- What feedback is there on the magnetospheric drivers of the outflows?

This science target is primarily relevant to Decadal Survey Challenges numbers 3–5:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a 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 Earth's magnetosphere and ionosphere.

This science will address components of Decadal Survey moderate missions #9: Stereo Magnetospheric Imager and #5: Geospace Electrodynamic Connections.

Mapping to RFAs, Decadal Challenges, and Decadal Missions

This investigation primarily addresses research focus areas F2 (to understand the plasma processes that accelerate and transport particles) and F3 (to understand the ion-neutral interactions that couple planetary ionospheres to their upper atmospheres and solar and stellar winds to the ambient neutrals).

Measurements

Measurements over a range of spatial and temporal scales could include:

- Ion and neutral composition: thermal energies.
- Ion and neutral flow velocities.
- Ion energy and pitch angle distribution: up to 20 keV.
- Electron energy and pitch angle distribution: up to 20 keV.
- Magnetic fields DC: 1 kHz.
- Electric fields DC: 1 kHz.
- Plasma density, electron temperature.

Note that this is not a prioritized or complete list.

Enhancing Technologies

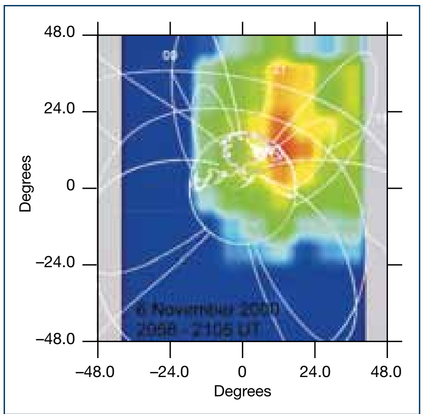
Technology investments to enhance the return of this science target include:

- Low mass/power neutral mass spectrometers.
- Spacecraft potential control for measurement of low-energy ions.
- Enhanced ion measurement capabilities for energies <10 eV.
- Spectrographic imaging telescopes for imaging upwelling ion distributions.

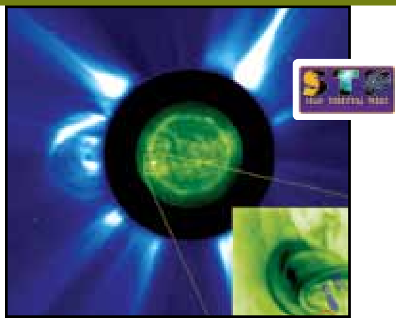
Note that this is not a prioritized or complete list.

Enhancing Premission R&A Focus Areas

- Multifluid MHD, incorporating mass outflows.
- Dynamic magnetosphere-ionosphere-thermosphere coupling models, including wave, collisional, and particle heating.



Ionospheric plasma outflows as imaged by the IMAGE spacecraft (Fuselier et al., *JGR*, 2007)



STP #6

Solar Energetic Particle Acceleration and Transport (SEPAT)

Science Target

To understand how and where solar eruptions accelerate energetic particles that reach Earth.

Science Rationale Summary

The STP #6 science target derives from priority investigations #2 (How are charged particles accelerated and transported?) and #12 (How do solar wind disturbances propagate and evolve through the solar system?). These general questions can be investigated in many places within the solar system and many were considered. Several important science questions derive from these general questions, and some are being investigated by STEREO, ACE, Wind, SOHO, Hinode, and RHESSI, while others will be addressed by SDO. MSL, LRO, MMS, Solar Probe Plus, and RBSP will also provide insight to the general question of particle acceleration and/or transport, but the highest priority science question remaining open was the acceleration due to solar eruptions. Relevance is found in all three of the objectives for the division and acute interest and urgency to the Agency's goal of protecting human and robotic explorers. Solar activity is often linked to the release of highly energetic particles, including heavy ions. The origin and the mechanisms that accelerate particles to high energies close to the Sun are not fully identified or understood. We need to understand how the variability in solar energetic particle (SEP) charge states, composition, and spectra relate to the initiation and evolution of solar and interplanetary disturbances to unravel the physics behind SEP creation. Heavy-ion charge states, which form an equilibrium shaped by the constant interaction with electrons in the strong solar magnetic fields, provide a record of the coronal conditions to which the SEP source population was subjected. SEP timing studies in the inner heliosphere combining in situ and remote observations of evolving coronal and interplanetary disturbances enable accurate determination of the temporal sequences associated with the formation and injection of flares, coronal mass ejections (CMEs), and interplanetary shocks. Such sequences are critical for sorting out the complementary roles that these processes play in SEP formation. Further, coordinated in situ and remote studies of SEPs and plasma conditions in the inner heliosphere test the connections between SEP acceleration, wave growth, and the suprathermal seed populations in the interplanetary medium. A strategy for a breakthrough in the area of solar particle acceleration is a mission that can separate the effects of particle transport from pure acceleration signatures while resolving compositional signatures of SEP, suprathermal ion, and solar wind sources. Thus, in situ measurements of energetic particles and solar wind plasma from multiple vantage points in the inner heliosphere, coupled with advanced particle transport modeling and theory, are needed to resolve this long-standing problem.

Example questions for this science target are:

- How is variability in the intensity, spectrum, and composition of the suprathermal seed population reflected in high-energy SEPs?
- How do solar energetic particles reach a wide range of heliospheric longitudes and latitudes and what are the time scales involved?
- How does the three-dimensional distribution of energetic electrons, various elements, and their ionic charge states evolve in the heliosphere?
- Do multiple acceleration mechanisms, including shock acceleration associated with fast CMEs and stochastic acceleration in flares, contribute to large SEP events seen at 1 AU?
- What is the importance of diffusive shock acceleration?
- Where are particles accelerated and released from solar flares?
- What are the roles of waves, turbulence, and electric fields for particle acceleration?

This science target is primarily relevant to Decadal Survey Challenges numbers 1, 2, and 4, and would build a foundation for 5:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.

Challenge 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.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a 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 Earth's magnetosphere and ionosphere.

This science target will address components of Decadal Survey moderate mission #4 (Multispacecraft Heliospheric Mission) and #8 (Solar Wind Sentinels).

Mapping to RFAs, Decadal Challenges, and Decadal Missions

Although relevant across the objectives, this science target primarily addresses the RFA F2 and, in turn, prepares for solving challenges in J2 and J3. F2 targets our understanding of the plasma processes that accelerate and transport particles; J2 urges the development of the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and safe intervals. J3 demands the development of the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

Measurements

Measurements over a range of spatial and temporal scales could include:

- Energetic particle intensity, anisotropy, composition, and charge state.
- Solar radio observations.
- Solar wind and interplanetary magnetic field.
- Coronal x-ray imaging/timing.

Note that this is not a prioritized or complete list.

Enhancing Technologies

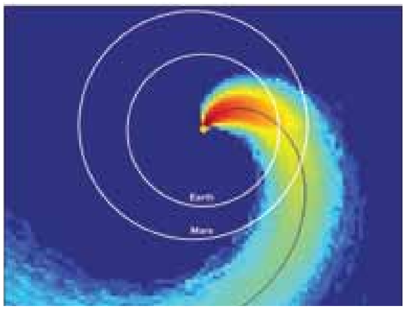
Technology investments to enhance the return of this science target include:

- Rapid application of new technologies with reduced noise and insensitivity to heat and radiation for missions approaching the Sun.
- Adaptability of geometric factor, fast pulse-height analysis, and radiation hardness to increase operability during radiation events or in radiation belts.
- Improved in situ particle optics with larger apertures and/or improved identification for in situ composition analysis.
- Larger array complementary metal oxide semiconductor (CMOS) detectors for increased sensitivity to short-wavelength remote sensing.
- More effective IR detector cooling devices for solar remote sensing.

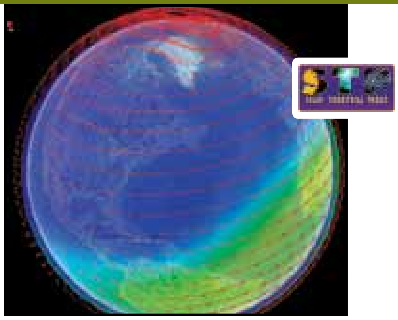
Note that this is not a prioritized or complete list.

Enhancing Premission R&A Focus Areas

Particle transport modeling in the active region/corona/heliosphere system; readdressing particle event analysis measured simultaneously at widely separated spacecraft in the inner heliosphere (e.g., Helios).



Slice through a three-dimensional simulation with simplifying assumptions of particle transport from a point-source at the Sun into the inner heliosphere. The model visualizes the distribution of 4 MeV protons 24 hours after injection, to be verified with SEPAT inner-heliosphere multipoint observations. Image courtesy of W. Droege, J. Kartavykh, G.A. Kovaltsov, and B. Klecker.



STP #7

Ion-Neutral Coupling in the Atmosphere (INCA)

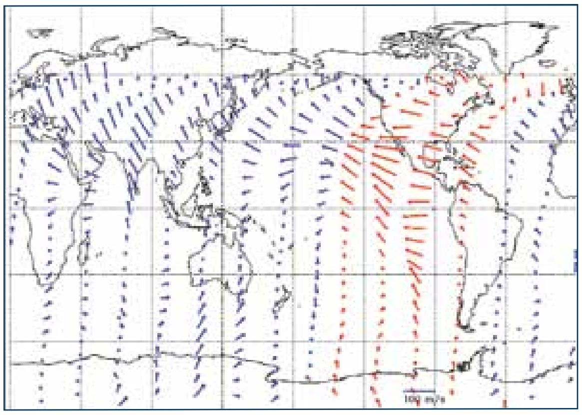
Science Target

To understand how neutral winds control ionospheric variability.

Science Rationale Summary

The STP #7 science target INCA derives from the priority investigation under fundamental processes: What governs the coupling of neutral and ionized species? This general question can be investigated in many places within the solar system and many were considered to address this fundamental process. Several important science questions derive from this general question, some of which are being investigated by planetary missions and the solar mission Hinode and others, will be addressed by SDO. The highest priority science question remaining open was the study of the interaction in the weakly ionized plasma of the Earth's atmosphere/ionosphere system. Better understanding of neutral and ionized species under the conditions we find in the ionosphere is applicable to planetary atmospheres, the solar photosphere, and even in the theory of accretion discs in astrophysical systems. But what is it about the atmosphere/ionosphere system that we do not understand that prevents us from a clear understanding of its variability?

We know that important sources of energy that drive the upper atmosphere and ionosphere are externally imposed, such as solar extreme ultraviolet (EUV) radiation and solar energy imparted to the atmosphere through the solar wind and the magnetosphere during magnetic storms. Until now we have not had a good understanding of the dynamics of the system. This lack of knowledge has been recently underscored by observations that clearly show that dynamical disturbances generated in the troposphere modify the wind structure in the upper atmosphere and significantly affect the properties of both the atmosphere and the ionosphere.



Model result showing winds and real-time GPS measurements of total electron content. Assimilation of GPS transects to form global knowledge of the ionosphere is now regularly performed, while no such assimilation is currently possible due to the total lack of measurements. Thus, the science of ion-neutral coupling in geospace is lacking a key component of the system.

Example questions for this science target are:

- What are the basic wind fields in the upper atmosphere, especially in the transition region from a mixed to a diffusive regime in the lower thermosphere?
- How do large-scale processes in the lower and middle atmosphere control and influence the upper atmosphere and ionosphere?
- What is the relative importance of coupling due to large-scale waves, wind-driven electrodynamics, composition, and temperature changes in the neutral atmosphere?
- What causes the spatial and temporal variability of the ionosphere and what is the role of the electric field?
- What is the relationship between winds, electric fields, composition, and temperature in understanding the flow of plasma in the ionosphere, especially during magnetic storms?

Mapping to RFAs, Decadal Challenges, and Decadal Missions

This investigation primarily addresses research focus areas F3 (to understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system) and H2 (to understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects).

This science target is primarily relevant to Decadal Survey Challenges numbers 2–4:

Challenge 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.

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

This science investigation will address components of Decadal Survey moderate mission #5 (GEC) and part of moderate mission #2 (ITSP of the Geospace Network).

Measurements

Measurements over a range of spatial and temporal scales could include:

- Ionospheric-thermospheric (IT) winds and temperatures.
- Altitude profiles of neutral and ion properties.
- Lower atmospheric waves.
- DC E fields and ion drifts.
- Knowledge of E field with neutral wind.
- Knowledge of neutral winds with ion density.
- Gravity waves in the middle atmosphere.
- Range of spatial and temporal scales.

Note that this is not a prioritized or complete list.

Enhancing Technologies

Technology investments to enhance the return of this science target include:

- Improved sensitivity to UV and EUV for solar and auroral remote sensing.
- Improved in situ particle optics with larger apertures and/or improved identification for in situ composition analysis.
- Larger array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing.
- Increased spectral resolution systems and lifetimes for IR, far ultraviolet (FUV), and EUV for solar and planetary upper atmosphere spectroscopy.
- Improved polarization measurements, more effective IR detector cooling devices, higher reflectivity mirrors, and diffraction-limited optics for EUV for space climate and solar remote sensing.

Note that this is not a prioritized or complete list.

Enhancing Premission R&A Focus Areas

Additional knowledge concerning the properties of upper atmospheric winds would enhance the design and implementation of INCA. Research should include additional measurements of the winds using rocket-based investigations in LCAS. Modeling and theory are also needed to help us understand the large-scale structure of the wind system.

LWS #7

Climate Impacts of Space Radiation (CISR)

Science Target

To understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on nitric oxide (NO) and ozone.

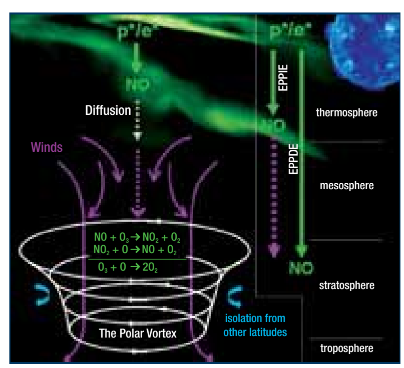
Science Rationale Summary

The LWS #7 science target CISR derives from priority investigation #18 under societal relevance: How do long-term variations in solar energy output affect Earth's climate? The solar UV radiation and total solar irradiance side of the question is being addressed by the Solar Radiation and Climate Experiment (SORCE)/ Earth Observing System (EOS), TIMED, and SDO missions. The solar cycle and secular changes in the middle atmosphere, thermosphere, and ionosphere are being addressed by the TIMED and AIM missions. The remaining highest priority science question is the atmospheric response to energetic particles.

The upper and middle atmosphere are important for climate change studies both as an active participant in modulating climate and as a sensitive (and thus early) indicator of possible changes already underway. Most of these effects are due to anthropogenic changes in atmospheric composition, but solar influences become progressively more important with increasing altitude. Understanding the influence of energetic particle fluxes into the upper atmosphere is especially motivated by their influence on ozone chemistry. There is a dramatic natural variability in the production and transport of NO above 100 km in response to particle precipitation during magnetic storms. This contributes to the odd-nitrogen balance of the mesosphere as the NO is transported downward during the winter polar night, which contributes to the catalytic destruction of mesospheric ozone. Higher energy particles such as from the radiation belts can penetrate directly into the mesosphere, and ionization and creation of odd nitrogen can occur even in the stratosphere during intense solar energetic particle events. These processes have been observed for some events, but there is no systematic understanding of whether the indirect transport mechanism is as important as direct in situ ionization. The global scale climate impacts of the production and transport of these reactive species also remains unknown.

Example questions for this science target are:

- What is the relative importance of auroral, radiation belt, and solar energetic particle processes for the generation of reactive chemicals and ozone destruction in the middle atmosphere?
- How large are ozone depletions during solar energetic particle events?
- What are the global transport processes for reactive species?
- What is the response of mesospheric and thermospheric state variables to reactive species concentration and distribution?



Direct and indirect impact of energetic particles on odd-nitrogen and ozone destruction in the middle atmosphere.

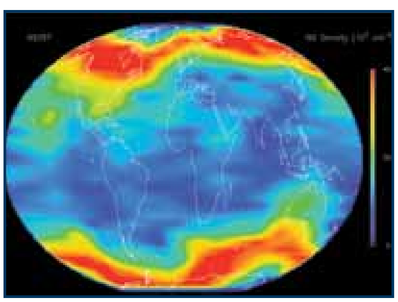
Mapping to RFAs, Decadal Challenges, and Decadal Missions

This science target primarily addresses research focus area H3 to understand the role of the Sun and its variability in driving change in the Earth's atmosphere and is closely linked to priority investigations #6 (How do coupled middle and upper atmospheres respond to external drivers and to each other?) and #15 (What are the roles of mass and energy flows in the behavior of planetary environments?).

This science target is primarily relevant to Decadal Survey Challenge number 3:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

This science investigation will address some components of Decadal Survey moderate mission #5 (GEC) and part of moderate mission #2 (ITSP of the Geospace Network).



Global measurement of NO density at 105-km altitude following a geomagnetic storm.

Measurements

Measurements over a range of spatial and temporal scales could include:
- High-energy particle inputs to the upper atmosphere.
- Auroral particle inputs to the upper atmosphere.
- Reactive chemical distribution, including ozone and various odd-nitrogen compounds.
- Upper- and middle-atmosphere temperature profiles.
- Upper- and middle-atmosphere neutral winds.

Note that this is not a prioritized or complete list.

Enhancing Technologies

Technology investments to enhance the return of this science target include:
- Improved sensitivity of UV detectors for auroral remote sensing.
- Large-array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing.
- Improved in situ particle detectors with larger apertures and/or improved identification for in situ composition analysis.
- Increased spectral resolution systems and lifetimes for IR instruments for solar and planetary upper atmosphere spectroscopy.
- Efficient IR detector cooling devices.
- Reliable and stable doppler interferometry for wind measurements.

Note that this is not a prioritized or complete list.

Enhancing Premission R&A Focus Areas

Improvement of coupled models of mesosphere and lower thermosphere chemistry and dynamics prior to this investigation will greatly enhance the focus of the investigation and enable greater advancement of knowledge of the climate implications of solar variability.

LWS #8
Dynamic Geospace Coupling (DGC)

Science Target

To understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.

Science Rationale Summary

The LWS #8 science target DGC derives from the priority investigation: How do the magnetosphere and the ionosphere systems interact with each other? This science target addresses fundamental questions related to plasma processes that determine how energy and momentum from the solar wind propagate downward through geospace to Earth. Understanding the dominant plasma acceleration and transport processes operative in the Earth's geospace region has general applicability across the Sun-Earth-Heliosphere coupled system. Particle acceleration and particle transport are two of the most fundamental processes in the plasma universe occurring in essentially every region of the heliosphere from the Sun to the heliopause, in the solar wind, in planetary magnetospheres and ionospheres, in cometary tails, and many others. The same processes that have been discovered by heliophysics missions form a foundation for understanding astrophysical systems.

The question that specifically motivates science target LWS #8 is how mass and energy flows in magnetospheric-ionospheric systems determine and control their coupled behavior. It is in the magnetosphere-ionosphere system where the basic physical processes of particle acceleration and transport have the most direct impact on human activity. These impacts include space weather effects on satellite operations, disruption of electromagnetic signals passing through the ionosphere, and dramatic reconfigurations of the electrodynamic currents that connect the Earth to the heliosphere through the ionosphere and magnetosphere. The DGC science target was specifically formulated to understand how particle acceleration and transport couple the ring current and inner plasma sheet (the primary repositories of energetic particles in the magnetosphere) to the ionosphere through current fields and the flow of mass and energy.

The next step in answering these questions will be achieved through simultaneous measurement of the dynamics of the ionospheric and magnetospheric auroral regions over global scales with high time and spatial resolution. Magnetospheric dynamics can be understood through global energetic neutral atom (ENA) imaging of the ring current complimented by in situ measurements across spatial scales characteristic of global circulation while ionospheric dynamics can be remotely probed through auroral imaging. The aurora are much more than a passive manifestation of the deposition of energy into the ionosphere by magnetospheric particles and currents. Auroral acceleration and heating change both ionospheric and magnetospheric currents and provide a mass flow of ionospheric plasma to the magnetosphere. Achieving insight into the nature of these processes, their linked responses to solar wind driving and the interrelationships between different regions, is the key to understanding dynamic geospace coupling.

Example questions for this science target are:

- How do magnetospheric particle and field signatures relate to visible/UV auroral forms?
- To what extent are auroral forms conjugate?
- What magnetospheric parameters control the degree of conjugacy?
- What do nonconjugate auroral forms tell us about the ionospheric control of magnetosphere-ionosphere coupling?
- How does magnetosphere-ionosphere coupling control particle outflow from the auroral regions?
- What are the sources of currents that couple the magnetosphere and ionosphere?
- What is the energy input from the magnetosphere to the ionosphere through precipitating particles?
- To what extent do the ionosphere and magnetosphere "drive" the dynamics of the other region?

Mapping to RFAs, Decadal Challenges, and Decadal Missions

This science target primarily falls under research focus areas H2 to understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects and F2 to understand the plasma processes that accelerate and transport particles.

This science target is primarily relevant to Decadal Survey Challenges numbers 3, 4, and 5:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a 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 Earth's magnetosphere and ionosphere.

Measurements

Measurements over a range of spatial and temporal scales could include:

- Composition and morphology of the inner magnetosphere and plasma sheet.
- Composition, conductivity, and morphology of the ionosphere in the polar regions.
- Conjugate observations of the aurora.
- Knowledge of the E and B fields in the inner magnetosphere extending into the ionosphere.

Note that this is not a prioritized or complete list.

Enhancing Technologies

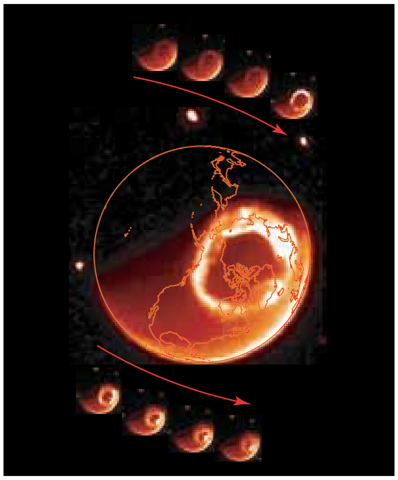
Technology investments to enhance the return of this science target include:

- High spatial and temporal auroral imaging in the EUV/FUV wavelengths.
- Electric field instruments with lower spacecraft impact than current systems.
- Low-resource plasma and energetic particle measurements with ion composition.
- Innovative systems to neutralize spacecraft potential and technologies.
- Processes to reduce cost and risk in multispacecraft missions.

Note that this is not a prioritized or complete list.

Enhancing Premission R&A Focus Areas

The science return from missions fulfilling science target LWS #8 could be significantly enhanced through advanced R&A of data collected from simultaneous measurements of magnetospheric dynamics and auroral processes. Theory and modeling of global electrodynamics, the effects of particle precipitation, and expectations for auroral conjugacy would also provide high value.



Evolution of the aurora during the July 15, 2000, Bastille Day magnetic storm. 1423UT–1512UT

LWS #9

Heliospheric Magnetics (HMag)

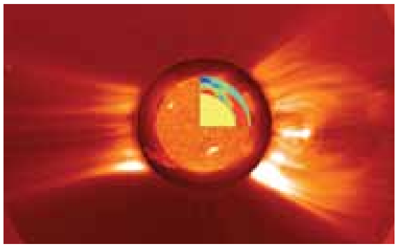
Science Target

To understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

Science Rationale Summary

The LWS #9 science target derives from two societal relevance investigations: What are the precursors to solar disturbances and what is the magnetic structure of the Sun-heliosphere system? The ultimate goal is to obtain a physical understanding of the evolution of heliospheric magnetic fields from their origin deep within the Sun near the tachocline through subsurface motions of magnetic fields before they appear in the photosphere as sunspots and into the corona and interplanetary space. After an eruption has occurred, the path of ejecta through the heliosphere is then controlled by the interaction of the large-scale magnetic fields that shape interplanetary space. Several important science questions derive from this general question and some are being investigated by the solar missions SOHO and STEREO, while others will be addressed by SDO. Solar Orbiter and Solar Probe Plus will also provide insight to the general question, but the highest priority science question remaining open was connecting the magnetic field from the solar interior to Earth. Relevance is found in all three of the Objectives for the Division, and acute interest is also found in the Agency's goal of protecting human and robotic explorers.

The causes and effects of transient solar activity are a main focus on the path to identifying the precursors and impacts of major solar eruptions. The solar tachocline and convection zone are the origins of strong dynamo magnetic fields. Detailed understanding of magnetic field formation and transport to the visible solar surface is crucial for the identification of triggers of sudden solar activity. Trigger mechanisms may then be linked with the propagation and evolution of existing plasma and fields in the solar corona and inner heliosphere. The synthesis of these elements leads to better physics-based models of space weather. A systematic approach is needed, one that combines the physics of the solar interior with the evolution of the inner heliosphere, ideally from a location that permits observations of the Sun-Earth line.



A composite image of the Sun that depicts the range of a system-level approach to understanding the connection between plasma in the solar interior and the corona, in this case highlighting SOHO's scientific research. The interior image from the Michelson Doppler Imager (MDI) indicates the differential rotation of the solar interior as a function of depth. The yellow zone indicates the region of the Sun currently inaccessible using measurements from a single point in space. The surface image was taken with the EUV Imaging Telescope (EIT) at 304 Å. Both were superimposed on a Large Angle Spectroscopic Coronograph (LASCO) C2 image, which blocks the Sun so that it can view the corona in visible. The image suggests the range of SOHO's research from the solar interior, to the surface and corona, and out to the solar wind.

Example questions for this science target are:

- Are there precursors to new active regions and CMEs observable beneath the solar surface?
- Are there precursors of solar activity in the surface magnetic and flow fields?
- What is the magnetic field structure of the heliosphere?
- Are there precursors in the chromosphere and corona?

Mapping to RFAs, Decadal Challenges, and Decadal Missions

Although it is relevant across the objectives, this science target primarily addresses research focus areas F4 (understand the creation and variability of magnetic dynamos) and H3 (develop the capability to predict the propagation and evolution of solar disturbances).

This science target is primarily relevant to Decadal Survey Challenges numbers 1, 4, and 5:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: "Developing a 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 Earth's magnetosphere and ionosphere."

This science investigation will address components of Decadal Survey large mission #1 (Solar Probe), moderate mission #8 (Solar Wind Sentinels), and small mission #4 (Solar Orbiter). It will also complement and extend Solar Dynamics Observatory.

Measurements

Measurements over a range of spatial and temporal scales should include:

- Helioseismology and vector magnetic field.
- Heliospheric imager.
- Coronal UV/IR x-ray imaging and spectroscopy.
- In situ solar wind plasma and magnetic field measurements.
- Energetic particle instruments.

Note that this is not a prioritized or complete list.

Enhancing Technologies

Technology investments to enhance the return of this science target include:

- In-space propulsion to maintain the spacecraft at the L-5 Lagrangian point trailing the Earth by 60 degrees.
- Enhanced telemetry compression and a high-bandwidth telemetry solution for large data volumes required by helioseismology.

Note that this is not a prioritized or complete list.

Enhancing Premission R&A Focus Areas

- Obtain improved inversions of solar vector magnetic field measurements in the chromosphere, transition region, and corona.
- Development of improved energetic particle propagation models that take into account the detailed structure of the heliospheric magnetic field.
- Development of dynamic solar-chromosphere-corona models giving the detailed interconnection between heliospheric magnetic fields and solar-magnetic reconfiguration.
- Development of dynamo models with surface field boundary conditions with solar wind and open magnetic field.

Image of a CME from STEREO-A'/SECCHI's Heliospheric Imager taken on November 5, 2007

The Vision for the Future...

Heliophysics began with a revolution: At the dawn of the space age, rockets became available that allowed us to journey directly into the new and uncharted realms of Earth's upper atmosphere, the magnetosphere, and the solar wind, and to place observatories into space to discover how the Sun controls these space environments. We discovered the regions and boundaries that separate and protect Earth from the harsh conditions in the solar wind unleashed by the Sun's violent outbursts of magnetic and particle energy. We discovered new forms of radiation that were trapped in the magnetic fields surrounding our home in space. Heliophysics was thus born in a pioneering era of explosive discovery at the dawn of the space age.

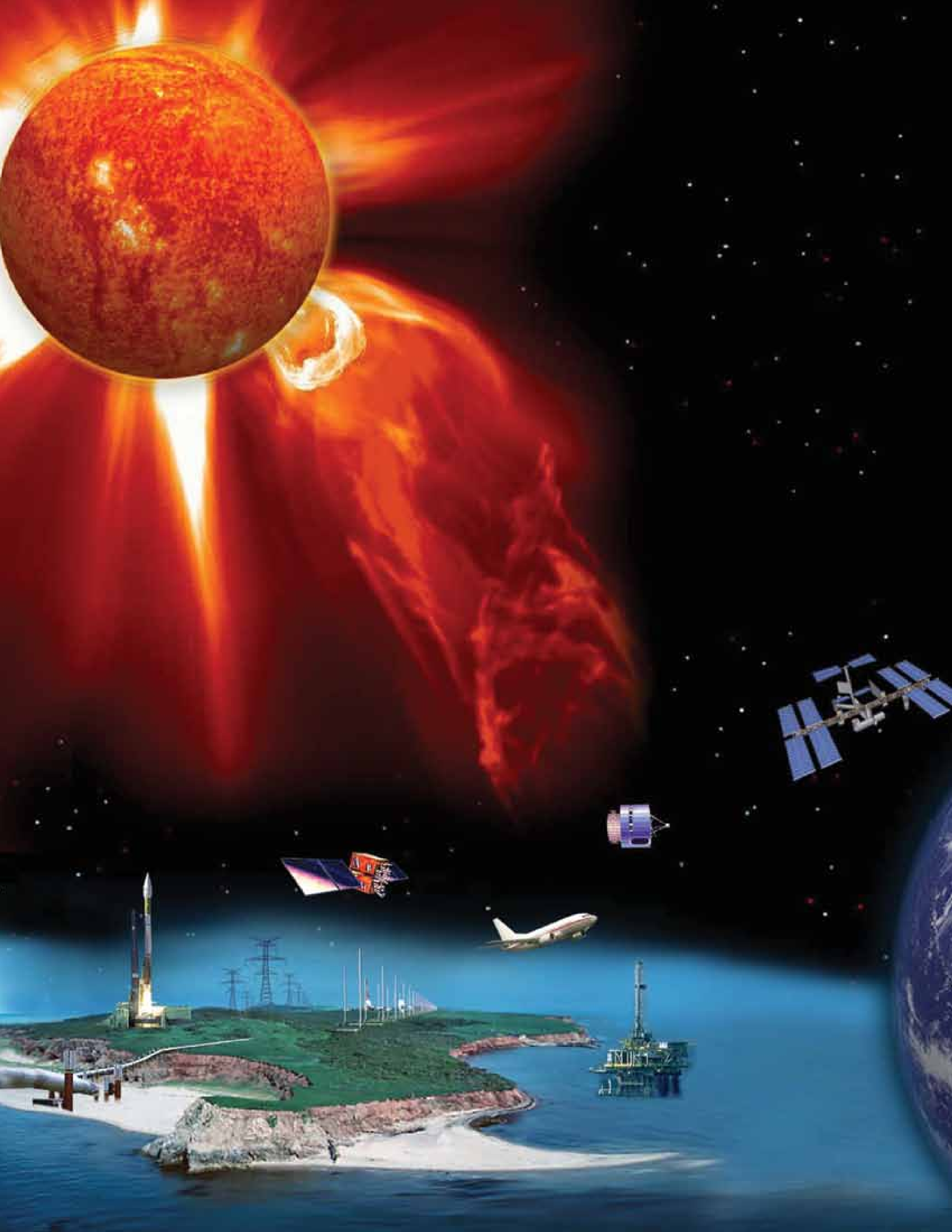
As our field advanced, we realized that we were uncovering a new realm of physics in which matter is organized more by magnetic than gravitational fields. We were able to study this regime in our cosmic backyard (within the solar system) and apply the newly discovered physics of magnetically organized matter throughout the cosmos. We discovered energetic particles and cosmic rays and investigated their source regions and theorized on the cause of galactic and extragalactic cosmic rays. We discovered the sources of magnetic fields within our Sun and are applying our models of the solar dynamo to understand the formation and evolution of other stars. We discovered that the Sun's million-degree corona is the source of the supersonic solar wind that carves out the boundaries that surround our entire solar system and protects it from the harsh radiation of the local interstellar medium. We discovered plasma processes in the outermost reaches of our atmosphere that inform studies of planetary and strongly magnetized plasmas throughout the universe.

We also came to realize that the system was highly complex over large and small scales, from lengths of astronomical units down to the gyration of a single electron. The long-range connections between the Sun and the Earth still contain unsolved mysteries due to unidentified processes or complex interdependencies that have yet to be discovered. This complexity means that different components of the system are intertwined, complicating the study of isolated parts. The observational datasets we use are no longer artificially segregated into scientific subdisciplines. Processes observed in one part of the system are used to correlate to and understand observations made elsewhere.

The need for a broader and more inclusive approach leaves very little wiggle room for loosely conceived ideas. The physics of the system can be triangulated. Holes in understanding can be identified and often tracked back to missing information on small spatial or temporal scales or a lack of understanding in the governing physical organization. Models of the system are increasingly forced to be global and, if they exclude a physical process, often miss the mark on key observed quantities. The challenge we face is to continue to build upon our understanding of the system as an integrated whole.

In the continued advancement of heliophysics, we aspire to develop models that can be used to predict the space environment. Having entered the digital age, we find that our technological society is increasingly susceptible to the disturbances from the Sun and the particle radiation that impacts Earth's magnetic boundaries.

A host of interconnected physical processes, strongly influenced by solar variability, affect the geospace environment, the health and safety of travelers in space, and the habitability of environments on other worlds. Our expanding access to and reliance on space drives us to transform our exploration and discovery of the phenomena of heliophysics into a predictive understanding of our home in space and the hazardous space weather to which it responds. Discovery of the fundamental processes that control our space environment relies on direct exploration and observation of these processes in action. Therefore, we push the frontiers of heliophysics into new domains in our quest to explore, discover, and understand the interconnections through the hazardous space environment from the Sun to Earth, to the planets, and out to the boundaries of our solar system. As we chart the course of humanity and face mounting challenges to the technological development of society, we are forced with ever-greater urgency to learn to navigate the space environment, to discover the full extent of its influences over our planet and society, and understand its connections throughout the cosmos.



Chapter 5
HELIOPHYSICS: APPLICATIONS

Focused research programs addressing specific space environmental hazards will help guide the design and operation of safe and productive missions. At the same time, we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space. The payoff in achieving this understanding will be predictions of how human society, technological systems, and the habitability of planets are affected by solar variability. Because it is a complex system, we tend to study individual "disciplines" or "components;" therefore, the Nation's efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, geospace, and other planetary environments as a single connected system. We make advances by extending the necessarily sparsely-sampled measurements through modeling and theory to achieve system-wide understanding. In time, as the physics-based models mature from the domain of the researcher, they will be transitioned into operational settings where heliophysics becomes the applied science called "space weather," which has real societal impacts.

Space Weather Impacts on Society and Exploration

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious and more worrisome. A report issued in December 2008 by the Space Studies Board of the U.S. National Academies addressed the impacts of space weather events on human technologies. The report, "Severe space weather events—Understanding societal and economic impacts: A workshop report," estimates that the economic cost of a severe geomagnetic storm could reach U.S. $1– $2 trillion during the first year alone, with recovery times of 4–10 years. These long recovery times could result from severe damage to large power transformers and other hard-to-replace facilities. Such a scenario would result from a storm of the magnitude of one that occurred in September 1859 (Baker, "What Does Space Weather Cost Modern Societies?," *Space Weather*, 7, S02003, doi:10.1029/2009SW000465, 2009).

Modern society depends heavily on a variety of technologies that are susceptible to the extremes of space weather—severe disturbances of the upper atmosphere and of the near-Earth space environment that are driven by the magnetic activity of the Sun. Strong electrical currents driven in the Earth's surface during auroral events can disrupt and damage modern electric power grids and may contribute to the corrosion of oil and gas pipelines. Changes in the ionosphere during geomagnetic storms driven by magnetic activity of the Sun interfere with high-frequency radio communications and Global Positioning System (GPS) navigation. During polar cap absorption events caused by solar protons, radio communications can be severely compromised for commercial airliners on transpolar crossing routes. Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers used on commercial and government satellites.

Cooperating Agencies and Organizations

The goals and objectives of heliophysics can directly trace ties to all three science disciplines within NASA's Science Mission Directorate (SMD). There is, for example, an explicit strategic link to Earth Science through our recommended LWS #7 science target of solar energetic particle (SEP)-induced changes in atmospheric chemistry. Ties to astrophysics lie in fundamental plasma physics and the study of the Sun as a star through helioseismology. The same processes and phenomena that drive space weather in our solar system also shape environments throughout the universe.

Heliophysics also has close ties to NASA's Exploration Initiative, and other NASA Mission Directorates. Examples include: Aeronautics, where heliophysics characterization of the Earth's ionosphere and radiation belt environment is needed to design reliable electronic subsystems for use in air and space transportation systems; Exploration Systems relies on heliophysics to define the radiation and plasma environment to enable exploration of interplanetary space by humans; and Space Flight needs to understand surface-charging environments that affect launch vehicles, spacecraft, and space weather events that affect the safety of humans.

Currently, protection of humans in space is an operational activity within the Space Operations Mission Directorate, which supports the International Space Station and Space Shuttle flights. The Heliophysics Division cooperates with the Space Radiation Analysis Group at Johnson Space Center, which is responsible for ensuring that the radiation exposure of astronauts remains below established safety limits.

Beyond NASA, interagency coordination in space weather activities has been formalized through the Committee on Space Weather, which is hosted by the Office of the Federal Coordinator for Meteorology. This multiagency organization is co-chaired by representatives from NASA, NOAA, DoD, and NSF and functions as a steering group responsible for tracking the progress of the National Space Weather program. External constituencies requesting and making use of new knowledge and data from NASA's efforts in heliophysics include the FAA, DoD, and NOAA.

Recommendation No.8
Plan with other agencies for the eventual loss of capability in space to measure conditions in the solar wind critical to both operational and scientific research.

Partnerships with one or more other agencies may be the preferred method for satisfying the national need for observations from L1, measuring solar wind input into geospace. Presently, this is accomplished with aging scientific satellites making available highly-compressed, relevant measurements in near real-time. This is one of the examples of interagency cooperation where "beacons" on NASA spacecraft have provided timely science data to space weather forecasters. Successful examples include ACE measurements of interplanetary conditions from L1, CME alerts arising from SOHO observations, and STEREO beacon images of the far side of the Sun. This roadmap recommends continued cooperation between NASA and other agencies to plan for the eventual loss of capability in space to measure conditions in the solar wind critical to both operational and scientific research.

Some of the commercial ventures impacted by space weather are shown below. The power industry has been aware of the vulnerability of the grid for many decades, and satellite manufacturers and operators take environmental risks into account during the design phase and during flight operations. More recently, space weather awareness has expanded into industries that include operators of transpolar aviation routes and precision positioning and navigation companies.

	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 Navigating and Forecasting
NASA CONSTITUENCIES						
Space Operations Mission Directorate	●		●			
Satellite Operations Directorate	●	●				●
Exploration Systems Directorate		●				●
DSN/TDRSS/Other Communications	●		●	●		●
EXTERNAL CONSTITUENCIES						
NOAA/National Weather Service (NWS)	●	●				●
FAA	●			●		
DoD	●	●	●	●		
Commercial Satellite Operators	●	●	●			
Power Industry	●					●
Communication Industry	●			●	●	●
Airline Industry	●			●		●
Precision Navigation Industry	●			●		●

Transition to Operations

The transition of scientific knowledge, usually incorporated in models and simulations, to organizations that could use that knowledge is often a serious challenge in space weather as in most fields. The interface between the scientific community and the community responsible for the operation of space systems, air transportation systems, and other operators is at the end of the line for the scientific investigator and upstream for the operators dealing with day-to-day issues; hence, neither is well equipped to ease the transition. But it is clearly important to reap the investment in space missions and meet the goals in objectives H and J. This roadmap encourages continuation of the existing NASA efforts to transition new scientific knowledge in heliophysics to operational use within the Agency and by other agencies and institutions.

Recommendation No.6
Continue the existing NASA efforts that transition new scientific knowledge in heliophysics to operational use.

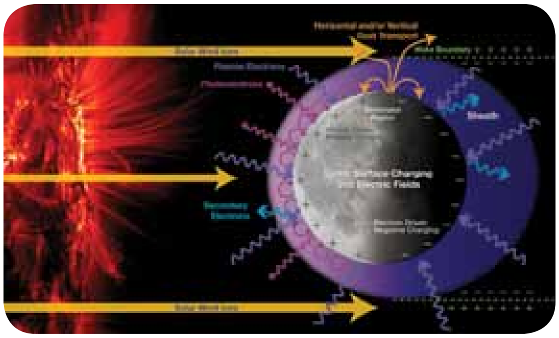
Cross-Disciplinary Science

In addition to the contribution of heliophysics to the solution of practical problems described in previous paragraphs, the contribution to the intellectual pursuit of space science and other cross-disciplinary science is also important. The heliophysics studies of plasmas apply to solar flares, storms in the Earth's magnetosphere, and disruptions in laboratory fusion experiments. These are examples of large-scale explosive events driven by the free energy of the magnetic field. The process plays a key role in numerous astrophysical phenomena: star formation, solar flares, and intense aurora. Magnetic reconnection also prevents the efficient production of electricity in controlled fusion reactors, potential sources of electricity for the future.

Heliophysics must deal with a large, complex system that requires the collection and analysis of large, multidimensional data sets extending over years of space exploration. The investigators are located across the globe and all need access to the results of space experiments, theory, and modeling. Moreover, the very nature of understanding the large, complex coupled system that is heliophysics, requires advances in techniques to solve coupled, nonlinear mathematical equations. This problem is common to many research areas and is at the forefront of mathematics. Thus, the tools and techniques developed and being developed by this community provide a framework and an example for other disciplines faced with understanding complex phenomena.

Heliophysics Science and the Moon

The Moon is immersed in a plasma environment—the local cosmos—that is "magnetized." It is threaded with magnetic fields that are often "frozen" into the plasma, a state of high electrical conductivity that effectively couples the motions of the plasma and the magnetic field. This inherently strong coupling means that the structure and evolution of magnetic fields (of the Sun, of the Earth, and even of the Moon) play an essential role in organizing and regulating the local environment of the Moon—the environment to be experienced by our explorers. By working to understand and predict the variations that occur from day to day, and from region to region, the productivity and overall success of future lunar robotic and manned missions can be significantly enhanced.



The most interesting challenge of the lunar plasma field environment is that it is alternately dominated by the extended, but variable, outer atmosphere (the "magnetosphere") of the Earth and by the extended, but highly variable, atmosphere of the Sun (the "heliosphere"). The Moon spends nearly 20% of its orbital period immersed within the Earth's magnetosphere, which offers some degree of shielding from heliospheric effects; the remaining time is spent exposed to the full effects of the Sun's radiation and interplanetary fields. Thus, the lunar plasma environment offers unique opportunities to study a variety of fundamental plasma physics processes—processes that have application to many other objects throughout the rest of the universe.

The heliophysics science associated with the return to the Moon is relevant to RFA J4 (understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities) and the Decadal Survey Challenge 4 (to understand the basic physical principles manifest in processes observed in solar and space plasmas).

In February 2007, a group of approximately 20 experts on solar and space physics met as part of the Lunar Science Workshop in Tempe, Arizona. At this workshop, sponsored by the NASA Advisory Council (NAC) and its Science Subcommittees, input from the scientific community regarding recommendations for science associated with the return to the Moon was presented, discussed, and distilled into a series of recommended scientific objectives, each with specific science goals and benefits and implementation considerations. Those objectives are articulated in a report called "Heliophysics Science and the Moon" (NP-2007-07-80-MSFC, Pub 8-40716). In 2008, the NAC commissioned the Lunar Exploration Analysis Group (LEAG) to develop a priority list of science associated with the return to the Moon. The Moon Report team and the heliophysics subcommittee assessed the science objectives of the Moon report by sorting them into one of four categories: Compelling science and should be done at the Moon, compelling science but better done elsewhere, interesting science and should be done at the Moon, and interesting science better done elsewhere. The science objectives that are evaluated to be compelling science and should be done at the Moon fell into three distinct areas of research: (1) investigate plasmas near or on the lunar surface including interaction of plasma and dust grains, (2) observe radio emissions of solar flares and CMEs, and (3) characterize the radiation bombardment on the lunar surface.These three compelling science objectives are consistent with the priority investigations articulated in the roadmap. Achieving them will provide the foundational understanding of the "perilous ocean" that space-faring spacecraft and crews must traverse in order to reach their destinations within the solar system.

Note that objectives associated with investigating historical record of the Sun, solar wind, and the local interstellar medium using the lunar regolith were not considered in this evaluation. The planetary science community is assessing this area of research with a similar effort.

Chapter 6

HELIOPHYSICS: EDUCATION AND PUBLIC OUTREACH

For nearly 50 years, NASA's journeys into air and space have developed humankind's understanding of the universe around us and the planet on which we live. These accomplishments share a common genesis, education. Previous experience has shown us that implementing exciting and compelling NASA science missions are critical to inspiring the next generation of explorers and leaders. Through partnerships with the Agency's mission directorates, other Federal agencies, private industry, scientific research, and education organizations, we leverage NASA's unique resources to engage the public, inform teachers, and excite students.

The Science Mission Directorate (SMD) implements NASA's three major education goals in coordination with the NASA Education Office:

- Strengthen NASA and the Nation's future workforce.
- Attract and retain students in science, technology, engineering, and mathematics (STEM) disciplines.
- Engage Americans in NASA's programs.

SMD plays an essential role in NASA's Strategic Education Framework to "inspire, engage, educate and employ." Using programmatic tools and resources, SMD continues to build strategic Education and Public Outreach (E/PO) partnerships to enhance the Nation's formal education system and contribute to the broad public understanding of STEM. SMD's E/PO programs share the results of our mission and research with wide audiences. In addition, E/PO programs promote inclusiveness and provide opportunities for minorities, students with disabilities, minority universities, and other target groups to compete for and participate in science missions, research, and education programs. The combined emphasis on precollege and preworkforce education, diversity, and increasing the general public's understanding and appreciation of STEM areas encompass all three major education goals.

NASA's Strategic Education Framework emphasizes three main areas of E/PO: Formal Education, Informal Education, and Public Outreach.

- **Formal Education** takes place primarily in the classroom setting involving smaller audiences with more contact time resulting in a deeper understanding of the material. This typically involves a formal curriculum with textbooks, teacher workshops, and course work at the K–12, undergraduate, and graduate levels.
- **Informal Education** involves settings outside the classroom such as programs held at museums, libraries, or parks. There is usually a much larger audience, less contact time with participants, and information is broader in scope and is aimed at a more general audience.
- **Public Outreach** events are unique opportunities for providing larger audiences with relatively new information that excites interest and stimulates curiosity. Efforts tend to make the information accessible and relevant, and to reach out to people and relate it to their everyday lives.

FORMAL EDUCATION:

Heliophysics Summer School

Heliophysics, as a coherent intellectual discipline, is being taught for the first time through a 3-year summer school series that started in 2007. The school focuses on select fundamental plasma-physical processes that are behind many aspects of space weather, including energetic particle generation and its effects, and addresses the climate systems formed by the solar dynamo and the Earth's atmosphere.

The summer school has two principal aims: (1) to educate close to 100 students (selected through a competitive process) and two dozen teachers in heliophysics as a coherent science through highly interactive seminars and hands-on working groups, and (2) to produce a series of textbooks from which heliophysics may be taught in the future at universities around the world.

The summer school is sponsored by NASA and the University Corporation for Atmospheric Research Visiting Scientist programs. The third heliophysics summer school will be held in Boulder, CO, July 22–29, 2009.

For more information, see: ***http://www.vsp.ucar.edu/HeliophysicsSummerSchool/***

INFORMAL EDUCATION:
NASA Family Science Night:
Changing Perceptions One Family at a Time

Family Science Night is a monthly program for middle school students and their families. The program provides a venue for families to explore the importance of science and technology in their daily lives by engaging in learning activities that change their perception and understanding of science. Family Science Night strives to change the way that students and their families participate in science within the program and beyond.

The program consists of nine 2-hour sessions held at the Goddard Space Flight Center (GSFC) Visitor's Center during the school year from September through May. It covers a wide range of heliophysics-related topics: How Big?, How Far?, and How Old? (size and scale of the universe); Have You Ever Seen the Invisible? (light and spectrum); Tis the Seasons (seasons); and Batteries Not Included (solar power and engineering).

The NASA Robert H. Goddard Award for Exceptional Achievement in Outreach was awarded to the NASA GSFC Family Science Night team for their contribution to education and public outreach in the local community on September 10, 2008. This program is a partnership between the Solar Dynamics Observatory, the Astrophysics Science Division, and the Rochester Institute of Technology Center for Imaging Science Insight Lab.

For more information, see: ***http://sdo.gsfc.nasa.gov/epo/families/fsn.php***

While there are key differences between formal education, informal education, and public outreach, substantial connections and overlaps exist. The ability to recognize these intersections and take advantage of the opportunities they provide is essential to maximizing the value of E/PO programs and activities.

The Heliophysics Division has made a remarkable impact through the commitment of substantial funds for E/PO programs and activities over the last decade or more. E/PO is an important element of heliophysics flight and research programs, and, moving forward, we envision a more coherent and more integrated set of activities. This reflects the evolution of heliophysical science to a system-wide approach of studying the Sun and its effects throughout the solar system. As a result, the heliophysics community will continue to contribute to a broad public understanding of the science and its relevance to society. Community participation is vital to the success of the Heliophysics E/PO program.

The Heliophysics Division goal is to ensure a coordinated, balanced, and broad portfolio of activities in formal education, informal education, and public outreach through full and open competition. To achieve this goal, the Heliophysics E/PO program is currently being realigned to maximize limited E/PO funding and resources and to correspond with a new SMD E/PO approach.

Significant opportunities exist to extend the impact of heliophysics 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 and the world via the press and other communication outlets. Therefore, it is necessary to target the following four strategic communication objectives:

- Seek opportunities to increase and maintain public awareness of heliophysics science through activities, materials, and events.
- Engage students and sustain their interest in heliophysics-related STEM subjects.
- Collaborate with and engage educators to enhance their knowledge of heliophysics-related subjects and activities.
- Build awareness among students, educators, and the public on the diverse range of career opportunities related to heliophysics science and missions.

Establishing partnerships between heliophysics missions and other successful E/PO programs that utilize established infrastructures and leverage existing resources are essential to the development of a dynamic and effective E/PO program with national and international impact. Through these partnerships, Heliophysics E/PO can avoid duplicating efforts and ensure E/PO funds are invested for highest impact.

In the modern age, space exploration continues to thrill the public with new discoveries that help them build a better understanding of the Sun, near-Earth space, the solar system, and the universe. Heliophysics E/PO will continue to play a leading role as an innovator in the formal education arena (K–12 and postsecondary), in museums and science centers, through high-production-value films, and rich Web site environments, ensuring that a significant fraction of the U.S. population retains its abiding fascination with space exploration and discovery.

PUBLIC OUTREACH:

SunWorks Exhibit Blends Science and Art

SunWorks is an imaginative, diverse exhibit of art from artists of all ages and from all around the world whose themes feature the science of heliophysics. The 24 pieces in the exhibit were selected from over 500 submissions to the SOHO SunWorks art contest that ran for 10 months and ended in March 2006.

The SunWorks exhibit has been displayed at over 14 venues in the U.S. since its opening at the United Nations in Vienna, Austria, in early 2007. The pieces include a 30-inch aluminum Sun, an exotic solar facemask, a Lego block sun, a stained glass piece, and a blown glass plate that looks amazingly Sun-like. The exhibit's schedule has taken it to museums, universities, and libraries through Colorado and California to Florida, including the Kennedy Space Visitor's Center, and it is still going strong. The show is sponsored by the International Heliophysical Year Education and Public Outreach Program and SOHO, an international mission of cooperation between NASA and the ESA.

For more information, see: ***http://sohowww.nascom.nasa.gov/sunworks/***

Appendices

Appendix A—Science Traceability Matrix

The scientific goals taken from the basic documents and the RFAs articulated in the 2006 Heliophysics Roadmap were the scientific foundations for the development of this roadmap. Discussions at the Community Workshop, review of recent progress in heliophysics science, and other documents and inputs led to a restatement of the RFAs into 18 priority investigations as discussed in Chapter 2 and listed in column #1 in the spreadsheet in this appendix.

For each of the priority investigations, an analysis of the science needs led to a set of questions shown as headings in column #2. At the next level, a set of science questions referred to as the critical open science questions were identified and listed as science objectives in column #2. For each of the open science questions, an assessment was made of the degree to which they were being addressed by either operating missions in the HSO (column #3 labeled In Flight) or expected to be addressed by missions in development (column #4).

Many open science questions remained unaddressed. These were prioritized following Appendix A. The highest priority science targets are shown in column labeled Next Priority (#5). Six of these targets are recommended for implementation in this roadmap. Other science questions still remain unaddressed (#6) and are candidates for future strategic missions or could be addressed with Explorer, LCAS, or partnership missions.

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
What are the fundamental physical processes and topologies of magnetic reconnection? *Associated RFAs: (F1, H1, H4, J2)*	*What are the magnetic field topologies for reconnection?*				
	Quantify the characteristics of reconnection (i.e., scale sizes, geometries, candidate processes, locations, consequences, and frequencies of occurrence).	HSO			
	Discover the dynamics, scale size, and energy balance of distant magnetotail reconnection and turbulence processes	ARTEMIS			
	What are the fundamental physical processes of reconnection?				
	Inventory the mechanisms leading to reconnection on the Sun. Where are they located? Where are the acceleration regions?	Hinode			
	Understand the microphysics of magnetic reconnection by determining the kinetic processes responsible, especially how reconnection is initiated		**MMS**		
	Microphysics of reconnection at the Sun: Do the processes differ from those at Earth? What triggers fast reconnection in large flares?				Remaining to be addressed
	How do the large-scale topologies of magnetic reconnection affect microphysical processes, and vice-versa?				Cross Scale (Partnership Opportunity)
How are plasmas and charged particles heated and accelerated? *Associated RFAs: (F1, F2, H4)*	*How are charged particles accelerated and decelerated?*				
	Understand the mechanisms and importance of diffusive shock acceleration and auroral acceleration	HSO			
	Determine how particles are accelerated through magnetic reconfiguration		MMS		
	Catalogue the interaction of energetic particles with the moon and Mars		MSL, LRO		
	Understand the mechanisms and importance of stochastic acceleration		RBSP		
	Determine the importance of seed populations and how they are created		RBSP		
	How are energetic particles transported?				
	Connect the particles producing solar radio bursts back to the corona	RHESSI			
	How and where solar eruptions accelerate the energetic particles that reach Earth			**STP #6**	
	What is the relative importance of different mechanisms in different environments?				
	Determine acceleration mechanisms for anomalous and galactic cosmic rays	Voyager IBEX			
	Determine acceleration mechanisms for energetic storm particles in geospace				Remaining to be addressed
	Determine the acceleration mechanisms for energetic particles in solar flares				Remaining to be addressed

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
How is the solar wind accelerated? *Associated RFAs: (F2, J1, J3)*	*What are the sources of energy for solar wind acceleration?*				
	Investigate the interaction between the Sun's magnetic field and the corona	**Hinode**			
	Relative heating of electrons and ions and nonthermal signatures within the corona	ACE			
	Study processes that accelerate the solar wind and generate coronal mass ejections				Remaining to be addressed
	Reveal the dynamics of the solar chromosphere and transition region			IRIS	
	Measure gradients in energy density in the corona				Remaining to be addressed
	Where does solar wind acceleration occur?				
	Mechanisms of particle acceleration in the low corona and the interplanetary medium	**STEREO**			
	Distinguish accelerating processes on the Sun			SO	
	Distinguish accelerating processes near the Sun in situ			SP+	
	What is the role of waves and dissipation in solar wind acceleration?				
	Understand the energy dissipation modes that dominate heating				Remaining to be addressed
	Determine the importance of small-scale magnetic reconnection				Remaining to be addressed
How are planetary thermal plasmas accelerated and transported? *Associated RFAs: (F2, H2)*	*How are thermal plasmas accelerated and transported by electromagnetic fields?*				
	Determine role of induction fields and wave heating processes	THEMIS	RBSP		
	What determines the composition of upwelling and escaping ionospheric plasma?				
	Determine the drivers of energy deposition	Cluster			
	Determine thermal plasma composition		ePOP		
	Determine the dissipation processes that heat ionospheric plasmas and the coupling processes that affect planetary ionosphere scale-heights			**STP #5**	
	Does the solar wind affect ionospheric plasma transport at planets such as Mercury, Venus, and Mars?				
	Determine how in situ ionization affects pick up of planetary exospheres, how the interplanetary magnetic field transports ionospheric plasmas, and what mechanisms transfer momentum and energy between the solar wind and planetary ionospheres		Mars Scout		Future Planetary Missions
What governs the coupling of neutral and ionized species? *Associated RFAs: (F3, H3)*	*How are dynamo potentials produced in interaction of atmospheres and magnetized thermal plasmas?*				
	Determine what ionospheric current systems are driven by I-T coupling in gas giants		JUNO		
	Variability in the terrestrial wind dynamo and ionosphere			**STP #7**	
	Energization of terrestrial wind dynamo and the dissipation of that energy				Remaining to be addressed
	What are the consequences of the direct interaction of plasma with planetary, cometary, satellite, and solar atmospheres?				
	Varying Martian atmospheric erosion rates in magnetized regions	Mars Express			
	Solar wind IMF penetration into the Venus ionosphere and affects on mass loss	Venus Express			
	Pickup ionization rate at the Saturniun moons	Cassini			
	Signatures of pickup ions in the solar corona			SP+	
	How do neutral-ion coupling effects govern fundamental processes at the Sun?				
	Reconnection in the partially ionized chromosphere	Hinode			
	First ionization potential fractionation in the low solar atmosphere				Remaining to be addressed

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
How do coupled middle and upper atmospheres respond to external drivers and to each other? *Associated RFAs: (F3, H3, J4)*	*Determine the internal coupling processes within the ITM system and the mediation and control of energy and momentum transfer*				
	Chemical pathways to radiation processes and global energy balance	**TIMED**			
	Response to geomagnetic storms and solar variability	TIMED			
	Neutral winds, disturbance dynamo and equatorial electrojet			STP #7	
	Understand the processes that couple the ITM system to the atmosphere and drive variability				
	Understand the temperature and composition in the ionosphere including those induced by wave and tidal processes				Remaining to be addressed
	Understand the global and local electrodynamics of the ITM system in response to geomagnetic dynamics				
	Global characteristics and small-scale physics of plasma irregularities	**C/NOFS**			
	Global energy characteristics of auroral precipitation				Remaining to be addressed
	Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport				
	Solar spectral irradiance and variability	TIMED SOURCE	SDO		
	Atmospheric response to auroral, radiation belt, and SEPs and transport of reactive chemicals and the effect on ozone				Remaining to be addressed
How do planetary dynamos function and why do they vary so widely across the solar system *Associated RFAs: (F4, H4, J2)*	Earth	CHAMP	SWARM		Future Earth Science and Planetary Missions
	Mars, Venus, Mercury	Messenger	Mars Scout		
	Gas giants, astroids, plutoids	Cassini	Pluto, JUNO		
What is the fundamental nature of the solar dynamo and how does it produce the solar cycle? *Associated RFAs: (F4, H4, J1)*	*What is the nature of subsurface flows and the subsurface magnetic field?*				
	Relative importance of the two most important regions of dynamo action. Determine the cause of the active longitudes and asymmetric hemispheres	SOHO	SDO		
	Properties of subsurface magnetic fields and characteristics of meridional flows			LWS #9	
	Determine the existence and nature of convective cells				Remaining to be addressed
	Measure the effects of differential rotation				Remaining to be addressed
	Can measurements of subsurface flows and magnetic fields result in understanding the solar activity cycle?				Remaining to be addressed

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
What is the composition of matter fundamental to the formation of habitable planets and life? *Associated RFAs: (H4, J2)*	*What is the composition of particles emanating from the Sun?*				
	Solar energetic particle abundances and solar wind CNO charge-state separation	HSO			
	Inventory fractionation processes (e.g., FIP effect)		SDO		
	Determine rare isotopic origins and abundances (3He)				Remaining to be addressed
	What is the composition of planetary magnetospheres and ionospheres?				
	Mercury, Venus, Mars, Uranus, Neptune, Ceres, Vesta encounter	HSO	MSL		
	Pluto, Mercury	Messenger, New Horizons	Bepi Colombo		
	What is the composition of material entering, and interacting with, our solar system? (e.g., interstellar medium, galactic and anomalous cosmic rays)				
	Measure and compare the composition of several samples of matter, including the solar corona, the solar wind, and other interplanetary particle populations, the local interstellar medium, and galactic matter	**ACE**			
	Determine the relationship of anomalous cosmic rays with the Kuiper belt	Voyager			
	Characterize interstellar dust that penetrate close to the Sun	Cassini, Stardust		SP+	
	Determine the composition of low-energy galactic cosmic rays, the local interstellar plasmas, and interstellar dust populations				Remaining to be addressed
What are the precursors to solar disturbances? *Associated RFAs: (F4, H1)*	*Are there precursors in the surface magnetic & flow fields?*				
	Determine which surface field configurations are most likely to flare Temporal changes preceding large flares & filament eruptions	Hinode			
	Magnetic energy storage in the corona from photospheric field extrapolations	Hinode			
	Are there precursors observable beneath the solar surface?				
	Understand the causes and mechanisms of CME initiation and propagation	**SOHO**			
	Observe how the Sun's magnetic field is generated and structured in its interior and how stored magnetic energy in the corona is released into the heliosphere		**SDO**		
	Are there precursors in the chromosphere and corona?				
	Magnetic energy storage in the corona from chromospheric, transition region or coronal field measurements			**HMag**	

Appendix A

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
What is the magnetic structure of the Sun-heliosphere system? *Associated RFAs: (F4, J3)*	*What is the morphology of the heliospheric magnetic field?*				
	Determine the origins of solar wind streams and the heliospheric magnetic field	HSO	SDO	SO	
	What is the relationship between closed and open flux?				
	Discover whether open flux can disconnect from the Sun in interplanetary space	Wind STEREO			
	Determine whether open/closed regions map to distinctive structures on the Sun and how steady is the boundary between those regions			SP+ SO	
	How does magnetic variation propagate through the heliosphere?				
	Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth			**LWS #9**	
	Discover how the global magnetic field reverses and why there is a delay between photospheric, coronal, and interplanetary field reversals				Remaining to be addressed
	What is the role of the interstellar magnetic field?				
	Determine the direction of the ISM field and its influence on particle acceleration in the heliosheath	IBEX Voyager			
	Determine the strength and influence of the interstellar magnetic field on the shape of the termination shock and heliopause				Remaining to be addressed
How do solar wind disturbances propagate and evolve through the solar system? *Associated RFAs: (F2, H1, J3)*	*How do solar disturbances erupt and propagate*				
	Propagation path and evolution of CMEs to 1 AU, including how these conditions evolve through the solar cycle	Ace **Wind**			
	Understand the physical processes controlling the heating of the solar corona, the acceleration of the solar wind, and the magnetic release of eruptive activity			**Solar Probe+**	
	Determine how coronal mass ejections evolve in the inner heliosphere			SO	
	Evolution of source conditions for eruptions over the three-dimensional Sun and inner heliosphere				Remaining to be addressed
	Impact of CMEs and other solar wind disturbances on the global heliosphere				Remaining to be addressed
	How do solar disturbances create particle radiation hazards				
	Investigate particle acceleration and energy release in solar flares	**RHESSI**			
	Global structure of CMEs and other transients, and how they evolve	STEREO			
	Sources, acceleration mechanisms, and transport processes of solar energetic particles			**SO**	
	Discover which magnetic and shock structures in the corona accelerate energetic electrons				Remaining to be addressed
How do the heliosphere and the interstellar medium interact? *Associated RFAs: (F3, H1, J3)*	*What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?*				
	Discover the properties of the termination shock	**Voyager**			
	Map the global properties of the termination shock and heliosheath	**IBEX**			
	Discover the properties of the local interstellar medium, how it changes with time, and determine the implications for our solar system				Interstellar Mission
	Determine whether the termination shock or heliosheath accelerates anomalous cosmic rays				Remaining to be addressed

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
How are mass and energy transferred from the heliosphere to a planetary magnetosphere? *Associated RFAs: (F1, F2, F4, H2)*	*What are the relative contributions of processes which transfer particles and energy across magnetospheric boundaries*				
	Mechanisms controlling the entry and transport of plasma into the magnetosphere	**Geotail**			
	Three-dimensional studies of plasma structures at the bow shock, magnetopause, dayside cusp, magnetotail and solar wind	**Cluster**	MMS		
	What is the global response of the magnetosphere and aurora to the solar wind				
	What controls mass and energy transfer at other magnetospheres				
	Perform initial survey of processes especially mass loading by planetary sputtering, Moons and Rings	Cassini Messenger	JUNO Bepi-Columbo		
	Impact of magnetosphere size, rotation rate, orientation and solar wind IMF on the transfer of mass and energy				Remaining to be addressed
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres? *Associated RFAs: (H2, J1)*	*Establish the global connectivities and causal relationships between processes in different regions of the Earth's magnetosphere*	**TWINS**			
	Determine the mass input and acceleration/loss processes that control the dynamics of the inner magnetosphere				
	Determine the major acceleration and loss process for the radiation belts		**RBSP** CSA-Orbitals JAXA-REG		
	Determine local time and radial dependences of inner magnetosphere processes, including ring current formation/decay and plasmasphere dynamics				Remaining to be addressed
	Determine the processes that control mass and energy storage, conversion, and release in the magnetotail				
	Small-scale evolution and dynamics of plasmasheet structures at ~19 RE	Cluster			
	Substorm initiation location	**THEMIS**			
	Radial and longitudinal plasma sheet dynamics, small and large-scale				Remaining to be addressed
	Role of ionospheric plasma in magnetotail dynamics/ spatial and temporal dependence				Remaining to be addressed
	What are the processes that control the dynamics of the aurora?				
	Relate the aurora to magnetospheric drivers	**THEMIS**			
	Relationship of Alfvén and electrostatic acceleration mechanisms and how they evolve		LWS #8		
	Characterize signatures of auroral types and identify acceleration regions and acceleration processes				Remaining to be addressed
	Determine whether auroral conjugacy reflects the magnetic configuration of the Earth's magnetosphere as it responds to external drivers				Remaining to be addressed
What is responsible for the dramatic variability of the ionosphere-thermosphere-mesosphere region? *Associated RFAs: (F3, F4, H2, J1, J4)*	*Discover the connections between spatial and temporal scales in the ionosphere-thermosphere system*				
	Energy transfer, redistribution, and radiative transport effects driven by minor constituent chemistry	AIM			
	Understand the global scale response of the Earth's thermosphere and ionosphere				Remaining to be addressed
	Multipoint low altitude in situ properties				Remaining to be addressed
	Determine the seasonal dynamics of the ionosphere-thermosphere system driven by lower atmosphere processes				
	Discover how winds and the composition of the upper atmosphere drive the electrical fields and chemical reactions that control the Earth's ionosphere				
	Understand the electrodynamics that couple the magnetosphere and ionosphere-thermosphere				Remaining to be addressed

Appendix A

Science Investigations	*Open Issues*/Priority Objectives	In Flight	Development	Next Priority	Future
How do the magnetosphere and the ionosphere-thermosphere systems interact with each other? *Associated RFAs: (F3, H2)*	*How does energy and momentum from the solar wind propagate downward through geospace to Earth?*				
	Magnetospheric storage and release of solar wind energy (SMC vs load/unload)	THEMIS			
	Understand how magnetospheric dynamics provides energy into the coupled thermosphere-ionosphere-magnetosphere system			**LWS #8**	
	Interaction/competition of solar wind electric fields and internal magnetic fields				Remaining to be addressed
	High-speed solar wind streams effects on the I-T-M system magnetospheric, solar wind, solar radiation energy inputs into lower atmosphere and its response				Remaining to be addressed
	How does energy, mass, and momentum propagate upward through geospace?				
	Lower-atmospheric forcing of ionosphere-thermosphere system				Remaining to be addressed
	Poleward transport of ionospheric plasma energizing magnetic storms				Remaining to be addressed
	Temporal/spatial distribution of ion outflow				Remaining to be addressed
	Dependence of heating rates/outflow on scale size of magnetospheric input, solar flux				Remaining to be addressed
How do long-term variations in solar energy output affect Earth's climate? *Associated RFA: (H3)*	*Measure the total solar irradiance and solar spectral irradiance as a function of wavelength and solar cycle*				
	Solar ultraviolet spectral variation and total solar irradiance variation	**SORCE** SOHO	**GLORY**		
	Solar x-ray and EUV spectral variation	SOHO, TIMED	SDO		
	Quantify solar cycle and secular change in the middle atmosphere, thermosphere, and ionosphere				
	Response of mesosphere-lower thermosphere to solar cycle and global change	TIMED			
	Determine why polar mesospheric clouds form and vary	**AIM**			
	Determine the depth of penetration of solar variability effects through the middle atmosphere and how mechanisms of transmission of middle atmosphere variations transfer to the troposphere				Remaining to be addressed
	Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport				
	Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on ozone			**LWS #7**	
	Understand whether the solar modulation of galactic cosmic rays affect cloud nucleation processes				
	Determine whether cloud nucleation processes are affected by GCRs and quantify the solar/secular changes in albedo, if any				Remaining to be addressed

Appendix B—Prioritization Process

Science Prioritization Logic Flow

Review Strategic Guidance
NRC Decadal Survey
Current Strategic NASA Documents

Link With Heliophysics Objectives
Frontier, Home, Journey
Research Focus Areas
Priority Investigations
Open Science Questions

Update: Identify Open Science Questions and Other Issues
Important questions not addressed by operating missions or missions in development

Assign Science Questions
Assign science questions to LWS and STP strategic lines

Use Community Input as Reference Missions. Establish Notional Implementations
Notional missions as placeholders for addressing research gaps

Evaluate and Prioritize Science Targets
Rank science targets with NPR 7120.5D mission cost categories based on scientific merit

Identify Launch Frequencies for Each Mission Size Category
Mission cost recommendations determined by weighing strategic guidance and science evaluation

Establish Science Target Timelines for LWS and STP
Science queue in context of out-year budgets for Heliophysics mission lines

The roadmap team developed a new scientific prioritization process that starts out at overarching science goals and leads to a science queue. The science queue offers the flexibility in implementation that is needed to ensure a robust science strategy for the future of heliophysics.

How Our New Process Establishes a Science Queue

We recommend a new, flexible heliophysics research strategy with a science-based launch queue. The science targets in the queue do not have fixed point designs as their implementation strategies. They are simply the recommended science objectives for future missions. These science targets have been evaluated based on specific factors that determine their science value and associated cost. It is anticipated that this approach will help NASA select and fly the best mission to meet the science objectives within cost. This process is not only a departure from former approaches listing a queue of mission designs, but it establishes a novel process created by the roadmap team that provides the Heliophysics Division with flexibility that enables a more far-reaching, robust science program for the future.

NRC and Agency Goals Guide Roadmap Strategy

The roadmap's science queue is founded on the NRC's Decadal Survey and on current NASA strategic objectives. At this time, the Decadal Survey recommendations already date back 6 years and the predecessor heliophysics roadmap 3 full years. New missions have become operational since or are now under development. New observations and discoveries have been made that have impact on the future directions of our science and the theoretical foundations of heliophysics have progressed. The proposed strategy has accounted for recent progress and has the flexibility to accommodate future discoveries.

Science Update and Situational Awareness

We have reviewed and updated the heliophysics strategic objectives and research focus areas that link heliophysics goals with the 2003 Decadal Survey Integrated Research Strategy and Decadal Challenges (Chapter 1). Chapter 2 summarizes and highlights the major accomplishments. Other changes have recently occurred, namely the increase of launch costs and the loss of Delta II class of launch vehicles that have been so important for heliophysics science missions.

Open Science Questions

The Heliophysics Division's Strategic Objectives are parsed into three general areas: Open the Frontier to Space Environment Prediction (Frontier), Understand the Nature of our Home in Space (Home), and Safeguard the Journey of Exploration (Journey). Four RFAs comprise each. From these flow priority investigations, a set of 18 more narrowly defined science topics. These topics do not map directly to the RFAs but are derived from the RFAs and the 2003 Decadal Survey Challenges. The priority investigations are further separated into those appropriate for funding through the STP mission line addressing fundamental processes, and the LWS mission line addressing science having societal impact.

The team's analysis of past and recent progress resulted in a comprehensive list of currently open science questions that fall under each of the priority investigations. Operating missions and missions now in formulation or development are expected to address a subset of the open science questions as shown in Chapter 3. The priority investigations and open science questions are listed in Appendix A on page 94. The remaining open science questions constituted the raw material of the prioritization process.

Science Community Input

The science community has, in large numbers, attended and contributed to the 2008 Heliophysics Town Hall meeting through the submission of mission implementation ideas addressing important heliophysics problems. These new implementation ideas, along with other implementation strategies of the Decadal Survey, missions published in the 2006 Heliophysics Roadmap, and those suggested by roadmap team members provided background for the roadmap team deliberations and served as examples of possible implementation concepts for science targets, called reference missions. Reference missions were identified with a cost category and their implementation readiness. Many of the reference missions have been identified as addressing one or more questions in the list of open science questions.

Evaluation and Prioritization of Science Investigations

Within the 18 priority investigations, the roadmap team had the task of ranking science targets that address the open science questions. The scientific merit of an investigation is evaluated against the following five criteria:

- Is the science compelling and urgent?
- Does the science address vital national objectives?
- Would the science transform the knowledge base?
- Does the science have discovery potential?
- Does the science enable exploration?

Recommendation No.2
Strive to meet a launch frequency of two to three per decade for each of its STP and LWS strategic lines, allowing the entire range of most urgent scientific problems to be addressed and advancing a system-level understanding of Heliophysics.

The implementation factor has been taken into account by analyzing one or more design reference missions as the technical solutions as they are currently known:

- Technical Readiness and Feasibility.
- Launcher Availability.
- Development Cost Category.
- Launch Cadence.

Cost categories are consistent with the guidelines of NPR 7120.5D (NASA Space Flight Program and Project Management Requirements), where the project life cycle cost category covering $250 M to $1 B has been divided into four subcategories:

- Light Missions (<$250 M).
- Small Missions (<$500 M).
- Medium Missions (<$750 M).
- Large Missions (<$1 B).

Launch Cadence

The frequency of new missions is critical to the development of our science objectives, which encompass fundamental processes and a study of interconnected physical processes over vast dimensions in both time and space. The resulting system science requires the conduct of investigations that ensure progress across the broad frontier of key unresolved science questions. These considerations have led us to recommend a launch frequency model of two to three missions per decade for each of the strategic mission lines STP and LWS, excluding Explorer and LCAS launches.

In a constrained budget scenario, the number of missions that can be launched within a period of time is determined by the size distribution of the missions. A large number of small missions per decade can be launched and operated almost simultaneously, but their scope and their applicability across the subdisciplines within heliophysics would be very limited. Very few large missions can be launched, but these would operate in isolation if the launch cadence is small so that missions do not survive until the next large mission is being launched. These principles dictated the recommended launch queue and the cost boxes for the science targets.

Establishing Science Queues for LWS and STP Strategic Lines

The roadmap team has combined the science and implementation evaluation factors to identify the six highest priority science targets in cost categories (i.e., light, small, medium, and large) and placed them into a science queue in either the STP or the LWS funding lines consistent with the goals of each. The timing of the projects was based on the required launch frequency and the FY 2009 President's budget with 1% inflation rate per year beyond the 5-year horizon of the budget. Besides the science queue, the team identified one high-priority science target for a potential international partnership, and identified other existing international partnership opportunities. All science targets have been described to the extent that the science queue warrants, i.e., without prescribing an implementation (Chapters 3 and 4).

Appendix C—Cost Control Concepts and Recommendations

This roadmap recommends that the science imperatives of heliophysics be addressed with cost-capped missions. To implement these missions in the timeframe of the roadmap and to meet the recommended launch frequency, the serious threat of cost growth must be mediated. This applies to missions presently in prephase A and any future missions. In recognition of the problems attendant with cost escalation, the roadmap team strongly recommends that the following prime cost drivers be addressed in the management and procurement of heliophysics missions.

Recommendation No.3
Reduce cost growth to help meet launch frequency requirements of the science.

Recommendation No.3b
The time span between mission definition and procurement be minimized. Procure what is planned and implement what is procured.

Recommendation No.3a
Peer review competition at the time of formulation be used to define the implementation of strategic missions to best address the recommended science goals within the resources available.

Recommendation No.3c
Establishment of policies and procedures to minimize and control implementation costs during all phases of mission formulation and development. Avoid a "full mission science regardless of cost" mentality.

Procure what we plan, implement what we procure.

- The SMD AO process is used to procure science investigations, not build-to-requirement instrumentation. Thus, this roadmap recommends a plan for priority science investigations, leaving the definition of specific mission architecture to the procurement process. In addition, the roadmap recommends that the implementation of strategic missions, whether Center-led or PI mission mode, adheres to the requirements and recommended architectures of the peer-reviewed, selected investigation.

Minimize the time interval between mission definition and implementation.

- The science queue approach described in this roadmap purposely postpones the definition of the mission architecture as long as possible to minimize requirements creep during the often long period between mission preformulation and development.

Compete the architectures of new missions.

- The roadmap team strongly recommends that all strategic missions compete the mission architecture and design requirements at the time of the science investigation procurement. Mission implementation is then most responsive to the latest science innovations, technology breakthroughs, and budget/launcher cost-benefit trades. Heliophysics has been successful controlling costs on Explorer Program PI missions. Strategic missions could be implemented likewise. Other models (e.g., competitive Science and Technology Definition Teams) could be utilized.

Avoid the current disconnect between the technical design of a new mission carried out at the Centers and the procurement of the science package carried out by Headquarters.

- The introduction of competition in the definition of the mission would allow all elements of the mission, including the flight and ground segments, to be defined and procured as a unit. Mission architectures are established at the outset consistent with expected funding.

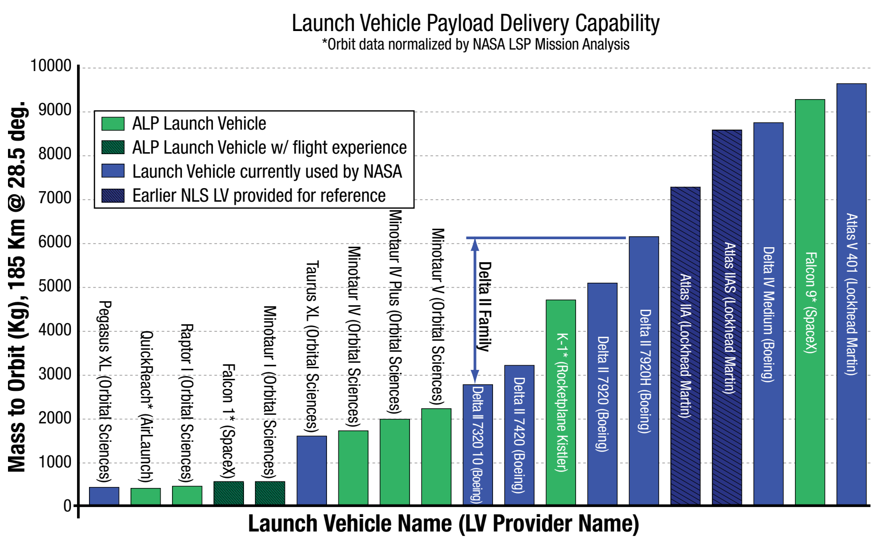
Other implementation issues that have been identified as significant cost drivers

- Avoid early optimism in formulation that inevitably leads to over optimistic estimates of cost growth during implementation.
- Invest sufficient time and money in phase A/B for adequate systems engineering studies to more fully understand the requirements and risks.
- Provide a stable and adequate budget profile to avoid costly reprogramming and schedule delays.
- Avoid requirements creep, especially NASA-imposed changes in requirements (without a commensurate reduction in risk).
- Make and enforce descope options.

Appendix D—Launch Vehicle Availability

The launch vehicle options for heliophysics missions have been reduced over the recent years, causing the implementation of many proposed missions to be no longer viable. The launch vehicle problem is punctuated by the phasing out, for NASA use, of the Delta II launch vehicle line. The decision by DoD to transition to the EELV class vehicle has required NASA to bear the increased share of the infrastructure costs. This has made the Delta II unaffordable for NASA. The Delta II launch vehicle was considered the workhorse in the stable of rockets for heliophysics missions. Its capability, cost, and reliability matched many of the previous roadmap missions.

The unavailability of the Delta II vehicle prompted an assessment of alternate launch providers. The conclusion is that launch capability has bifurcated. The options are either a launch vehicle with small capacity or the very large EELV class. The graphic below illustrates that the launch capabilities of available vehicles are either half the capacity or 2 to 3 times the capacity provided by the Delta II.



The Alternate Launch Vehicle Payload (ALP) delivery capability showing mass to 185 km orbit with a 28.5° inclination as a function of launch vehicle.

The low-capacity vehicles (Pegasus XL, Taurus, and Minotaur) will meet the needs of a subset of heliophysics missions, specifically missions requiring low-Earth orbits or very small payloads in high-altitude orbits. Missions requiring a larger capacity will be very expensive because of the cost of the EELV.

Other options that have been considered to address the limited access to space are as follows:

1. Comanifesting payloads with other missions requires significant early planning. The risk of schedule delay or changing requirements has historically been a significant impediment to this option.
2. International partnerships have had success in the past and can be a viable option. However, significant coordination and consistent long-term commitment are required by all agencies for success.

3. New launch providers in the private sector are being developed. However, this has proven to be a difficult undertaking, proving that access to space is neither easy nor inexpensive.
4. Restrictions on use of DoD and foreign launch vehicles make those options difficult to acquire (DoD) or not available (foreign).

In conclusion, the current near-term launch options for future heliophysics missions limit the mission capability and frequency of missions. The development of a reliable, low-cost launch option to fill the void left by the Delta II would be of tremendous benefit in supporting the heliophysics mission of understanding the integrated-coupled system.

Appendix E—Mission Quad Charts

Appendix E-1—HSO Currently Operating Missions

Appendix E-2—Missions in Formulation/Development

Appendix E-3—Heliophysics Town Hall 2008: Mission Concepts

Please click here to view Quad Charts

Appendix F—Acronyms

ACE	Advanced Composition Explorer
AIM	Aeronomy of the Ice in the Mesosphere
ALP	Alternate Launch Vehicle Payload
AO	Announcement of Opportunity
BARREL	Balloon Array for RBSP Relativistic Electron Losses
CCMC	Community Coordinated Modeling Center
CINDI	Coupled Ion Neutral Dynamic Investigation
CISM	Center for Integrated Space Weather Modeling
CISR	Climate Impacts of Space Radiation
CME	Coronal Mass Ejection
CMOS	Complementary Metal Oxide Semiconductor
C/NOFS	Communications/Navigation Outage Forecasting System
COMSTAC	Commercial Space Transportation Advisory Committee
CSA	Canadian Space Agency
CSEM	Center for Space Environment Modeling
DGC	Dynamic Geospace Coupling
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DSN	Deep Space Network
DSX	Deployable Structures Experiment
EELV	Evolved Expendable Launch Vehicle
EIT	EUV Imaging Telescope
ENA	Energetic Neutral Atom
EOS	Earth Observing System
E/PO	Education and Public Outreach
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate
EUNIS	Extreme Ultraviolet Normal Incidence Spectrograph
EUV	Extreme Ultraviolet
EVA	Extravehicular Activities
FAA	Federal Aviation Administration
FAST	Fast Aurora Snapshot
FIP	First Ionization Potential
FUV	Far Ultraviolet
GCR	Galactic Cosmic Ray
GEC	Geospace Electrodynamic Connections
GI	Guest Investigation
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HEIDI	High Energy Imaging Device
HIREGS	HIgh REsolution Gamma-ray and hard X-ray Spectrometer
HIREX	High Resolution X-ray
HMag	Heliospheric Magnetics

HSO	Heliophysics System Observatory
IACG	Interagency Consultative Group
IBEX	Interstellar Boundary Explorer
ILWS	International Living With a Star
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMP	Interplanetary Monitoring Platform
INCA	Ion-Neutral Coupling in the Atmosphere
IR	Infrared
ISM	Interstellar Medium
ISTP	International Solar-Terrestrial Program
I-T	Ionosphere-Thermosphere
ITM	Ionosphere-Thermosphere-Mesosphere
ITSP	Ionosphere-Thermosphere Storm Probes
JAXA	Japan Aerospace Exploration Agency
LADEE	Lunar Atmosphere Dust Environment Explorer
LASCO	Large-Angle Spectroscopic Coronagraph
LCAS	Low-Cost Access to Space
LCC	Lifecycle Cost
LEAG	Lunar Exploration Analysis Group
LISM	Local Interstellar Medium
LRO	Lunar Reconnaissance Orbiter
LWS	Living With a Star
MAP	Mission Archive Plan
MAVEN	Mars Atmosphere and Volatile EvolutioN
MHD	Magnetohydrodynamics
MDI	Michelson Doppler Imager
MIDEX	Mid-size Explorer
MLTI	Mesosphere-Lower Thermosphere-Ionosphere
MMS	Magnetospheric Multiscale
MO&DA	Mission Operations and Data Analysis
MSL	Mars Science Laboratory
NAC	National Advisory Council
NAS	National Academy of Science
NLC	Noctilucent Cloud
NO	Nitric Oxide
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NWS	National Weather Service
ONEP	Origins of Near-Earth Plasma
ORBITALS	Outer Radiation Belt Injection, Transport, Acceleration, and Loss Satellite
PI	Principal Investigator
R&A	Research and Analysis
RASA	Russian Aviation and Space Agency
RBSP	Radiation Belt Storm Probe
REP	Relativistic Electron Precipitation
RFA	Research Focus Area
RFT	Research Focus Target
RHESSI	Reuven Ramaty High-Energy Solar Spectroscopic Imager
ROSES	Research Opportunities In Space and Earth Sciences
SCOPE	Scale Coupling in the Plasma Universe
SDO	Solar Dynamics Observatory
SEP	Solar Energetic Particle
SEPAT	Solar Energetic Particle Acceleration and Transport
SET	Space Environment Testbed

SMC	Steady Magnetospheric Convection
SMD	Science Mission Directorate
SMEX	Small Explorer
SO	Solar Orbiter
SOHO	Solar and Heliospheric Observatory
SORCE	Solar Radiation and Climate Experiment
SP+	Solar Probe Plus
SR&T	Supporting Research and Technology
STEM	Science, Technology, Engineering, and Mathematics
STEREO	Solar Terrestrial Relations Observatory
STP	Solar Terrestrial Probe
SWOT	Strengths, Weaknesses, Opportunities, Threats
TDRSS	Tracking and Data Relay Satellite System
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIMED	Thermosphere-Ionosphere-Mesosphere Energetic and Dynamics
TRACE	Transition Region and Coronal Explorer
TR&T	Targeted Research and Technology
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers
U.S.	United States
UV	Ultraviolet
VHO	Virtual Heliospheric Observatory
VO	Virtual Observatory

National Aeronautics and Space Administration

George C. Marshall Space Flight Center
Huntsville, AL 35812
www.nasa.gov/marshall

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NP-2009-08-76-MSFC
8-402847