National Aeronautics and Space Administration

The New Science of the Sun-Solar System Connection

Recommended Roadmap for Science and Technology 2005-2035

heliophysics

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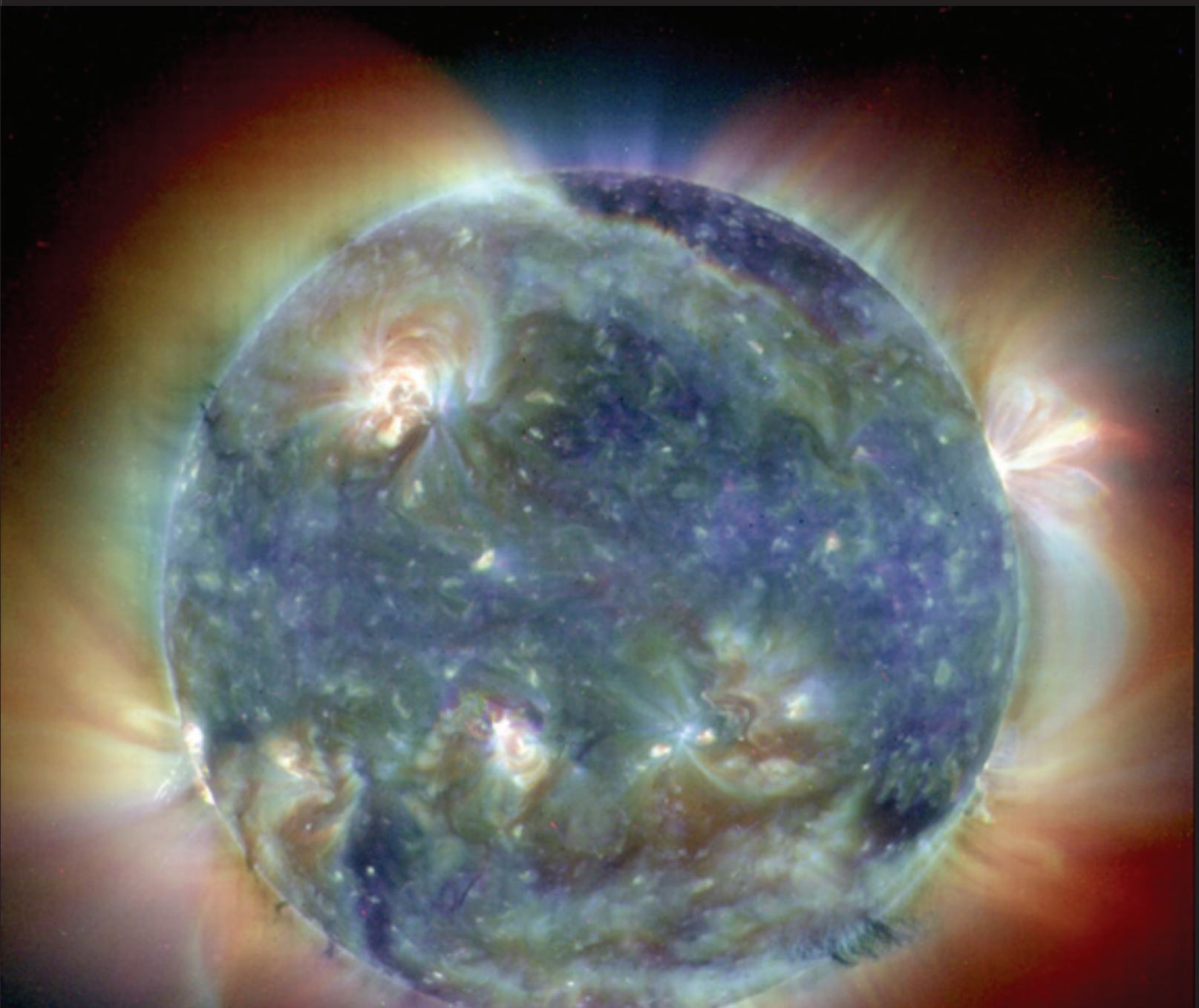
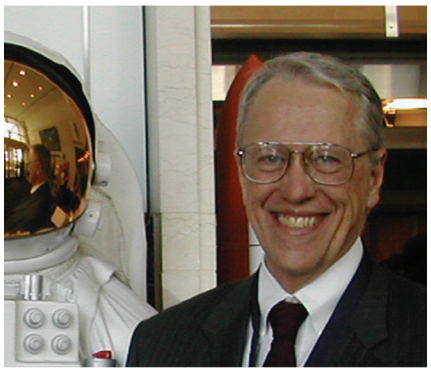
How and Why Does the Sun Vary?

How Do Planetary Systems Respond?

What Are the Impacts on Humanity?



The SOHO and TRACE missions reveal intricate structures above the bright active regions strewn across the Sun's surface, which would otherwise appear as groups of dark sunspots in ordinary visible light. Colorized extreme-ultraviolet images have been melded to show that the magnetic field in the Sun's upper atmosphere confines gas at widely differing temperatures virtually side by side. The Solar Dynamics Observatory, to be launched in 2008, will image the entire Sun every few seconds in several temperatures and measure surface velocity and magnetic field. SDO data will dramatically advance our ability to determine the origins of these structures and understand how they change.



"Thought Generates Action" -
- *C. Hobbs, Time Power (1987)*

It is a pleasure to accept the 2005 Heliophysics Roadmap from our nation's science community. It describes a renewed strategic outlook to provide essential space environment knowledge for the benefit of society and for space exploration. It communicates our progress made to date, our plans for the future, and our opportunities for supporting the Agency's vision and mission.

The field of Space Physics has made rapid and spectacular advances over the past few years. Utilization of combinations of missions, each one with its own complement of instruments, has been vital to the emergence of a new view of the Sun and Solar System as a connected system. There will be further dramatic advances as observational techniques, new missions, and a new understanding of how microphysical processes influence broad-scale dynamics emerge in the not-too-distant future. Each discovery impels us to ask new questions or regard old ones in new ways. How and why does the Sun vary? How do planetary systems respond? What are the impacts on humanity?

This roadmap outlines a common groundwork of inquiry spanning all the space physics branches of learning. It is anticipated that this will lead to a unification of long-separated fields of inquiry; thereby enabling the emergence of new and significant scientific insights. I believe that we are on the cusp of a flowing together of knowledge that will merge these various disciplines of research, and that the results of this process will have not only cultural and intellectual value but will also be vital to the optimization of economic and political activities in the 21st Century.

This is our community's most ambitious roadmap plan to date. The program includes forefront research and technology development as well as the development of the most complex flight missions conceived. The program is a balanced portfolio of small missions and larger spacecraft with the goal of obtaining the best science at the lowest cost that meet NASA's standards for mission success. I am confident that the passage of time will validate the wisdom and choices of this roadmap committee and their consultants. It has been a privilege to associate with the people who have contributed their time and energy to the construction of this document.

To those involved, I extend my warmest gratitude and my admiration for a comprehensive and articulate statement. I invite you, the reader, to join this fascinating future journey of discovery.

Richard R. Fisher
Director, Earth-Sun Systems Division

Heliophysics

helio-, pref.,
of the Sun and environs; from the Greek helios, ἥλιος.

physics, n.,
the science of matter and energy and their interactions.

Heliophysics concentrates on the Sun and its effects on Earth, the other planets of the solar system, and the changing conditions in space.

Heliophysics studies the magnetosphere, ionosphere, thermosphere, mesosphere, and upper atmosphere of the Earth and other planets.

Heliophysics combines the science of the Sun, corona, heliosphere and geospace.

Heliophysics encompasses cosmic rays and particle acceleration, space weather and radiation, dust and magnetic reconnection, solar activity and stellar cycles, aeronomy and space plasmas, magnetic fields and global change, and the interactions of the solar system with our galaxy.

Heliophysics: The New Science of the Sun-Solar System Connection

Recommended Roadmap for Science and Technology 2005-2035

Exploration and Fundamental Science

" Something hidden. Go and find it. Go and look behind the Ranges---"
- Rudyard Kipling (1865-1936), *"The Explorers"* (1903)

The primary goal of the Vision for Space Exploration is the implementation of "a sustained and affordable human and robotic program to explore the solar system and beyond." This simple statement has profound consequences on how to prioritize the science programs that are needed to accomplish the new vision. How is the Heliophysics community to respond, when its traditional culture has been to emphasize the scientific investigation of processes fundamental to space physics? Advice came recently from the Space Studies Board of the National Academy of Sciences who offered five guiding principles, the first of which was:

Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. Exploration done properly is a form of science.

The answer for the Heliophysics community becomes clear when we realize that the converse of the guiding principle also holds: Exploration cannot be done properly without science.

Exploration must be well planned; history is rife with narratives of expeditions that ended fruitlessly or, even worse, tragically. In reality, properly implies safely, efficiently, and economically. There are many examples of pragmatic problems facing the successful implementation of the Exploration Vision, ranging from the prediction of the space radiation environment to the design of the critical entry of a Crew Exploration Vehicle into the Martian atmosphere. In both cases, the science that enables exploration activities is drawn from the same science that is used to investigate the fundamental processes on the Sun, the planets, and in the heliosphere, from its inner boundary to the outer boundary with the interstellar medium.

The pursuit of fundamental science not only enables Exploration but it also transforms our understanding of how the universe works. Current Heliophysics missions are producing a steady stream of transformational science that is rewriting the textbooks of past decades. Some recent examples:

• Direct evidence from IMAGE and Cluster that magnetic reconnection in the Earth's protective magnetosphere can open "holes" that allow solar wind to leak through continuously for hours – much longer than theorists predicted.

• Surprising information from SOHO about the hidden workings of the subsurface solar dynamo that generates the Sun's magnetic field.

• A new understanding of the acceleration sites of solar energetic particles based on RHESSI gamma ray observations.

• The puzzling complexities of the outer boundary of the solar wind discovered by the Voyager-1 spacecraft, our most distant explorer.

The new pragmatic challenges of the Vision for Space Exploration will dictate re-focused and intensified scientific exploration. This exploration will bring forth exciting discoveries, but only if it has the same broad scientific base that has nurtured the Heliophysics community to its current maturity. Why? Because space science is replete with pivotal discoveries that came from unexpected quarters, from areas of sound but seemingly tangential research. We would not now be understanding the details of the acceleration of solar energetic particles revealed by RHESSI if space scientists in the 1970's had not worked out the details of gamma-ray line emission in the solar atmosphere (a subject that struck many as esoteric in those days).

This Heliophysics Roadmap differs from its predecessors in that it clearly responds to the new priorities in space science. Nonetheless, it preserves the momentum of our community's achievements and maintains continuity with past strategic planning. Appropriate missions recommended by previous studies are carried forward, while new missions are put forward that will produce the science required for the success of the Vision for the Moon (2020) and Mars (2035). Each of these new missions is soundly conceived in fundamental science objectives while being efficiently designed to do the science that will support the Vision of Space Exploration. Well-planned science cannot help but generate exciting discoveries while still delivering the promised results.

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The Heliophysics Roadmap to Discovery and Exploration of the Sun-Solar System Connection

This is a Roadmap to understanding the environment of our Earth, from its life-sustaining Sun out past the frontiers of the solar system. A collection of spacecraft now patrols this space, revealing not a placid star and isolated planets, but an immense, dynamic, interconnected system within which our home planet is embedded and through which space explorers must journey.

These spacecraft already form a great observatory with which the Heliophysics program can study the Sun, the heliosphere, the Earth, and other planetary environments as elements of a system - one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar variability. NASA continually evolves the Heliophysics Great Observatory by adding new missions and instruments in order to answer the challenging questions confronting us now and in the future as humans explore the solar system.

The three scientific and exploration objectives listed on the facing page require sustained research programs that depend on combining new data, theory, analysis, simulation, and modeling. Our program pursues a deeper understanding of the fundamental physical processes that underlie the exotic phenomena of space, such as magnetic reconnection, while at the same time targeting specific hazards, such as solar energetic particles. The result will represent not just a grand intellectual accomplishment; it will also provide the predictive capabilities essential to future human and robotic exploration of space and will serve important societal needs.

Over the next ten years NASA will launch spacecraft to investigate the dynamo deep within the Sun, image its roiling surface, and perhaps even probe the intricate structures of its torrid atmosphere. Constellations of spacecraft, separating variations in time and space, will measure the complex responses of the upper atmospheres of the Earth and Mars, Jupiter, and even the Sun. Observations of unique regions near Earth will allow us to understand the key physical processes regulating our local environment.

Later activities will push the limits of our technological capabilities. The power of the Heliophysics Great Observatory will expand so that new-found understanding can be used to predict hazardous events wherever explorers may travel. A high-speed probe will directly measure the current interstellar environment from which the heliosphere shields us. Resolved images of other stars will provide amazing insights into the varying activity of our own Sun. External influences affecting the habitability of planets, including our own, will be understood.

How can this all be accomplished?

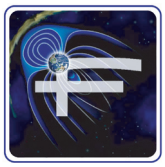
The Heliophysics endeavor relies on five major mission programs. The Solar Terrestrial Probes focus primarily on fundamental science questions. Living With a Star missions and partnerships target knowledge of processes that directly affect life and society. The flexible Explorer program provides an efficient means of achieving urgent strategic goals that is highly responsive to new knowledge, technology and priorities. Challenging Flagship and Partnership missions address important goals that cannot be funded in the baseline program. The Heliophysics Great Observatory coordinates new and existing mission elements to confront broader problems.

Implementation of this ambitious program requires a comprehensive approach. The missions described in the Roadmap will be effective only with strengthened programs of supporting research and technology to develop the models, theories, and new instrumentation necessary to continuously redirect and reform future science and exploration activities. Virtual observatories and advanced information systems must be developed to provide data access and computing resources. The program cannot be long sustained unless the public appreciates the important benefits of NASA's Heliophysics program and new scientists and engineers enter the field, for example through the Low Cost Access to Space program.

The Heliophysics Roadmap Committee derived these objectives with a set of targeted achievements to support the highest level of objectives of the U.S.A. for NASA's program. Prioritizing investigations from the rich set of options was a difficult task.

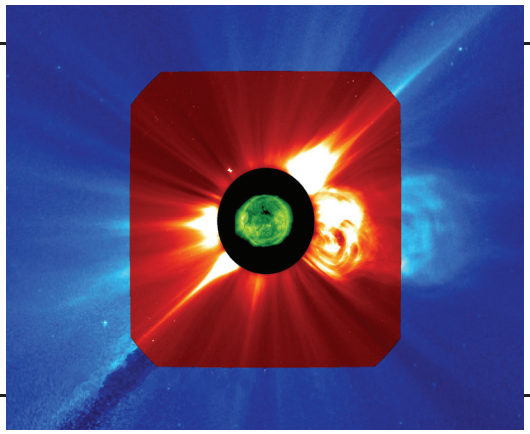
Join us on this exciting path of exploration, discovery, and service to humanity.

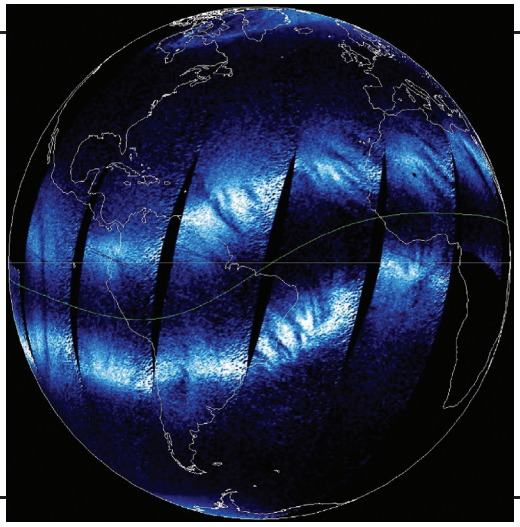
Heliophysics Science Objectives:



Open the Frontier to Space Environment Prediction

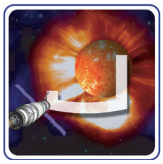
Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium





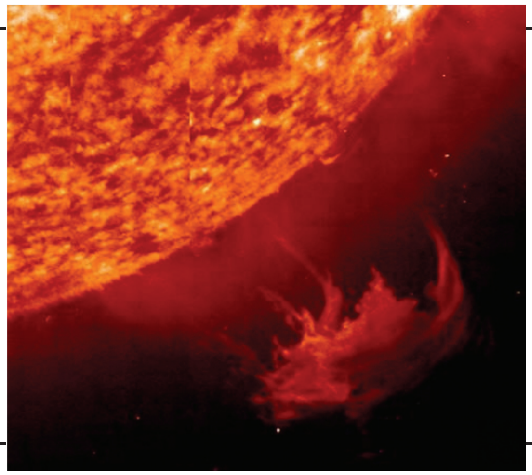
Understand the Nature of Our Home in Space

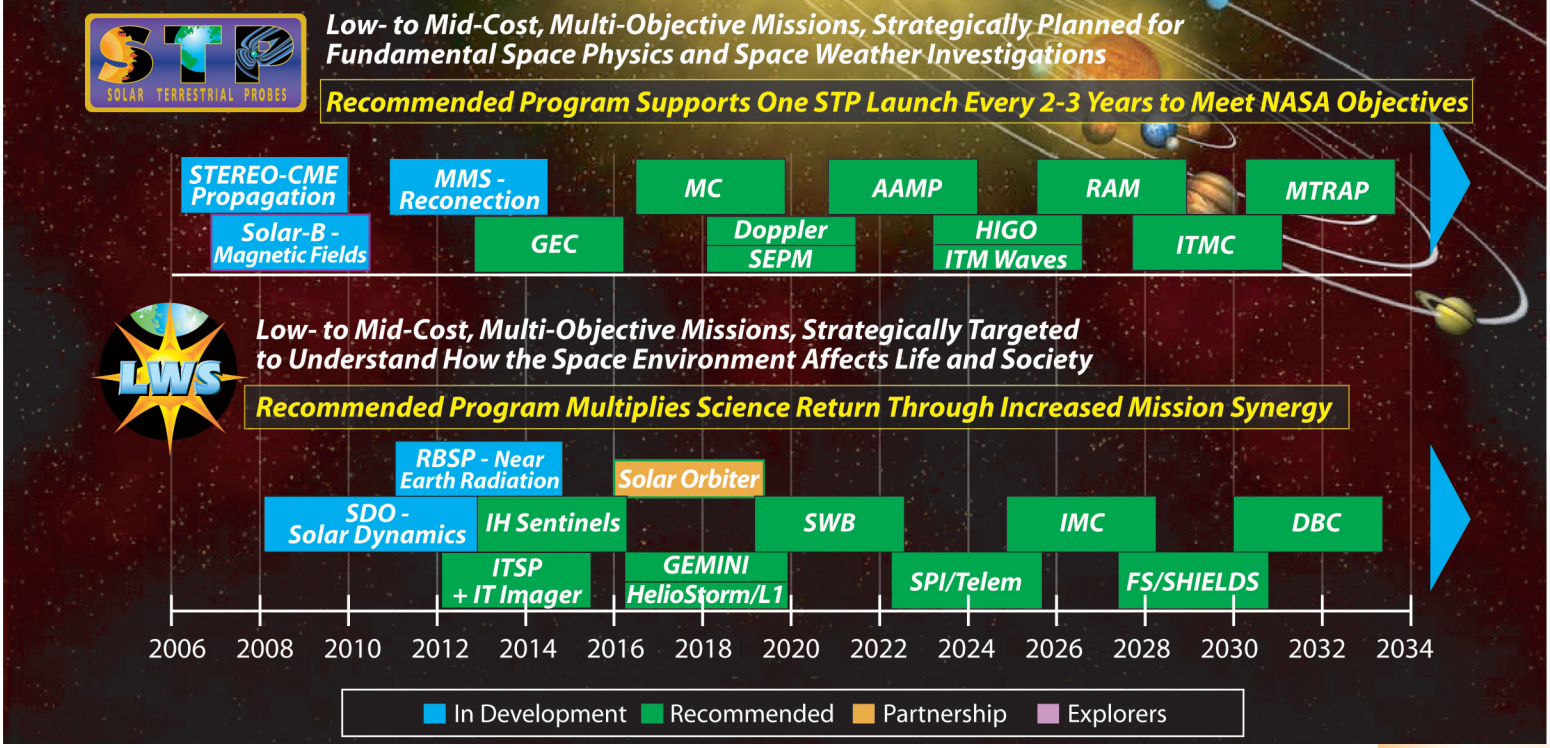
Understand how human society, technological systems, and the habitability of planets are affected by solar variability interacting with planetary magnetic fields and atmospheres.

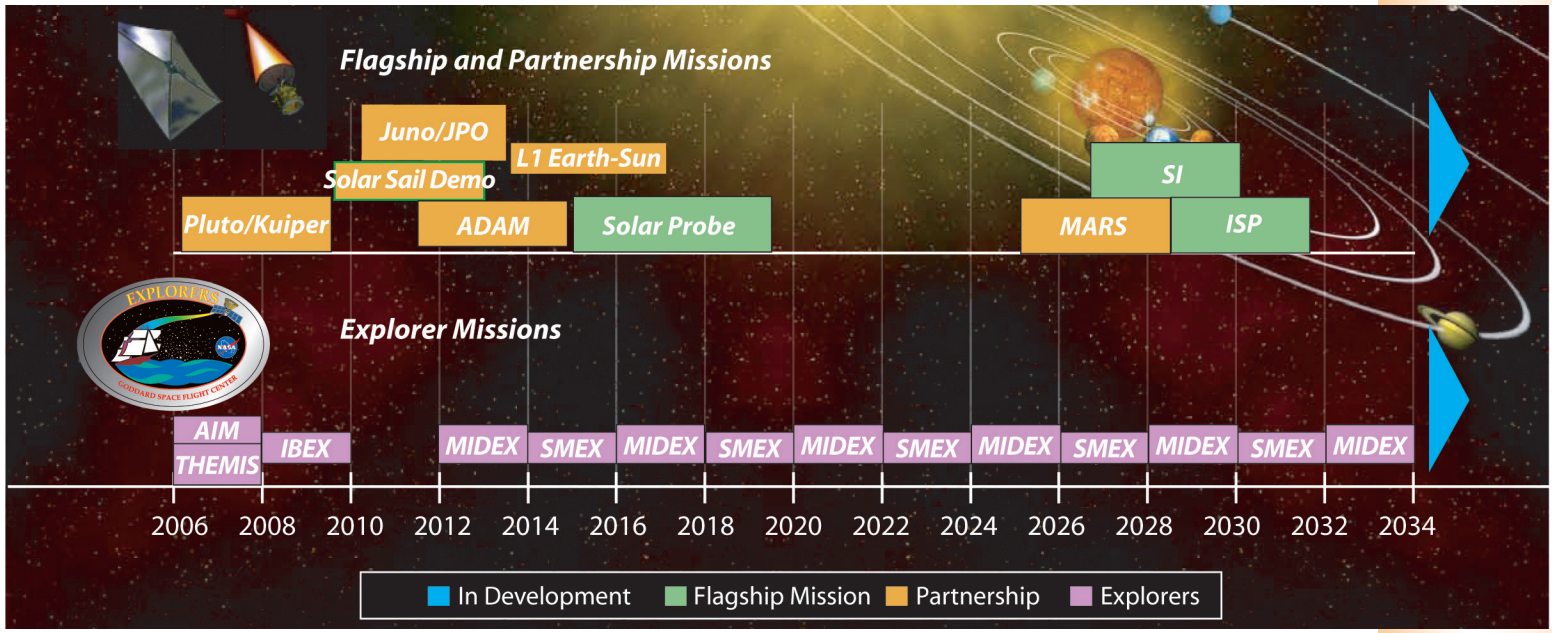


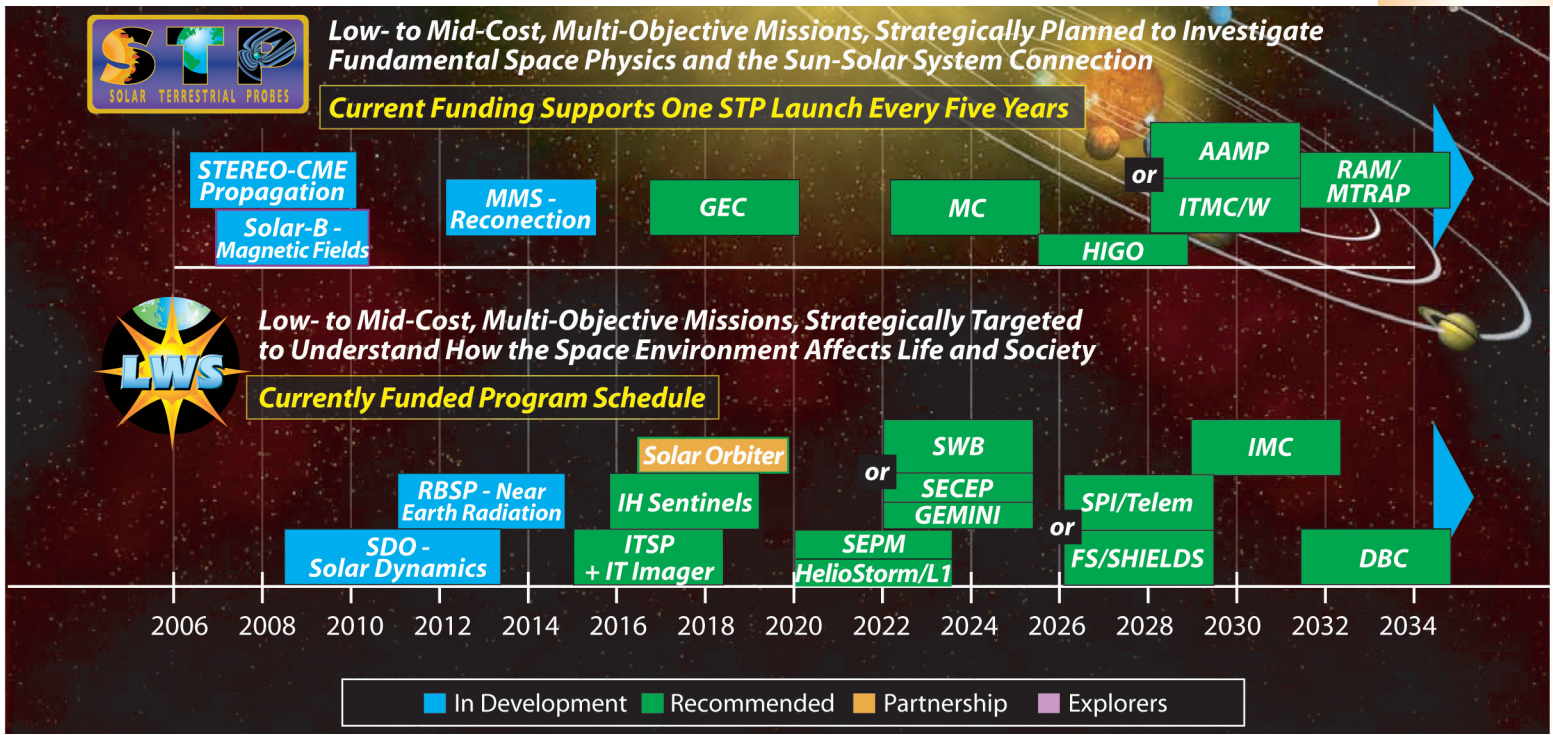
Safeguard the Journey of Exploration

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




Low- to Mid-Cost, Multi-Objective Missions, Strategically Planned for Fundamental Space Physics and Space Weather Investigations
Recommended Program Supports One STP Launch Every 2-3 Years to Meet NASA Objectives
STEREO-CME Propagation
Solar-B - Magnetic Fields
MMS - Reconection
GEC
MC
Doppler
SEPM
AAMP
HIGO
ITM Waves
RAM
ITMC
MTRAP
Low- to Mid-Cost, Multi-Objective Missions, Strategically Targeted to Understand How the Space Environment Affects Life and Society
Recommended Program Multiplies Science Return Through Increased Mission Synergy
RBSP - Near Earth Radiation
SDO - Solar Dynamics
IH Sentinels
Solar Orbiter
ITSP + IT Imager
GEMINI HelioStorm/L1
SWB
SPI/Telem
IMC
FS/SHIELDS
DBC
2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030 2032 2034
In Development
Recommended
Partnership
Explorers


Flagship and Partnership Missions
Juno/JPO
Solar Sail Demo
L1 Earth-Sun
Pluto/Kuiper
ADAM
Solar Probe
SI
MARS
ISP
Explorer Missions
AIM
THEMIS
IBEX
MIDEX
SMEX
2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030 2032 2034
In Development
Flagship Mission
Partnership
Explorers


Low- to Mid-Cost, Multi-Objective Missions, Strategically Planned to Investigate Fundamental Space Physics and the Sun-Solar System Connection
Current Funding Supports One STP Launch Every Five Years
STEREO-CME Propagation
Solar-B - Magnetic Fields
MMS - Reconection
GEC
MC
HIGO
or
AAMP
ITMC/W
RAM/ MTRAP
Low- to Mid-Cost, Multi-Objective Missions, Strategically Targeted to Understand How the Space Environment Affects Life and Society
Currently Funded Program Schedule
RBSP - Near Earth Radiation
SDO - Solar Dynamics
IH Sentinels
Solar Orbiter
ITSP + IT Imager
or
SWB
SECEP
GEMINI
SEPM HelioStorm/L1
or
SPI/Telem
FS/SHIELDS
IMC
DBC
2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030 2032 2034
In Development
Recommended
Partnership
Explorers

Executive Summary

We live in an exciting environment: the heliosphere, the exotic outer atmosphere of a star. The space beyond Earth's protective atmospheric cocoon is highly variable and far from benign. It is the one part of the cosmos accessible to direct scientific investigation, our only hands-on astrophysical laboratory. Our technological society is increasingly susceptible to space weather disturbances in this curious region. A host of interconnected physical processes, strongly influenced by solar variability, affect the health and safety of travelers in space and the habitability of alien environments. We call the science of the Sun-Solar System Connections 'heliophysics.'

Building on NASA's rich history of exploration of the Earth's neighborhood and distant planetary systems, we are poised to develop the quantitative knowledge needed to help assure the safety of the new generation of human and robotic explorers. The Heliophysics Program has been completely reevaluated to address the needs of the Vision for Space Exploration.

NASA's future research and exploration within its Heliophysics program aims to "explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by explorers, and to demonstrate technologies that can improve future operational systems." We have unfolded this articulated strategic goal into the three broad science and exploration objectives.

• ***Open the Frontier to Space Weather Prediction:*** Understand the fundamental physical processes of the space environment – from the Sun to Earth, to other planets, and beyond to the interstellar medium.

• ***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.

These will be accomplished by studying the Sun, the heliosphere, and planetary environments as elements of a single inter-connected system, one that contains dynamic space weather and evolves in response to solar, planetary and interstellar conditions. Focused research programs addressing specific space environmental hazards will help guide the design and operations 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. Such an understanding will represent not just a grand intellectual accomplishment for our times - it will also provide knowledge and predictive capabilities essential to future human and robotic exploration of space and will serve key societal objectives in important ways. Herein, we describe current plans for NASA's research programs in this area and the guiding principles we will follow in pursuit of forthcoming exploration challenges.

This scientific exploration will target the highly coupled system that stretches from the Sun's interior to planetary neighborhoods and the vast expanses of interplanetary space. We are already transforming human understanding of this fascinating global system of systems, so closely connected that a single explosive event on the Sun can produce power outages on the Earth, degradation of solar panels on interplanetary spacecraft, fatal damage to instrumentation in Mars orbit, and auroral displays at Saturn – effects that span the entire

Heliophysics Mission Roadmap - Recommended and Currently Funded. The figure on page 8 illustrates the prioritized mission schedule through 2035. The top panel shows the recommendations for the Solar Terrestrial Probes and Living With a Star programs. Slots for competitively selected Explorers that contribute to our strategic objectives along with the partnership and flagship missions that require additional funding appear in the center. The bottom panel shows the endorsed schedule for the STP and LWS programs assuming the current budget level. See page 55 for details.

Anticipated Heliophysics Science and Exploration Achievements

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

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

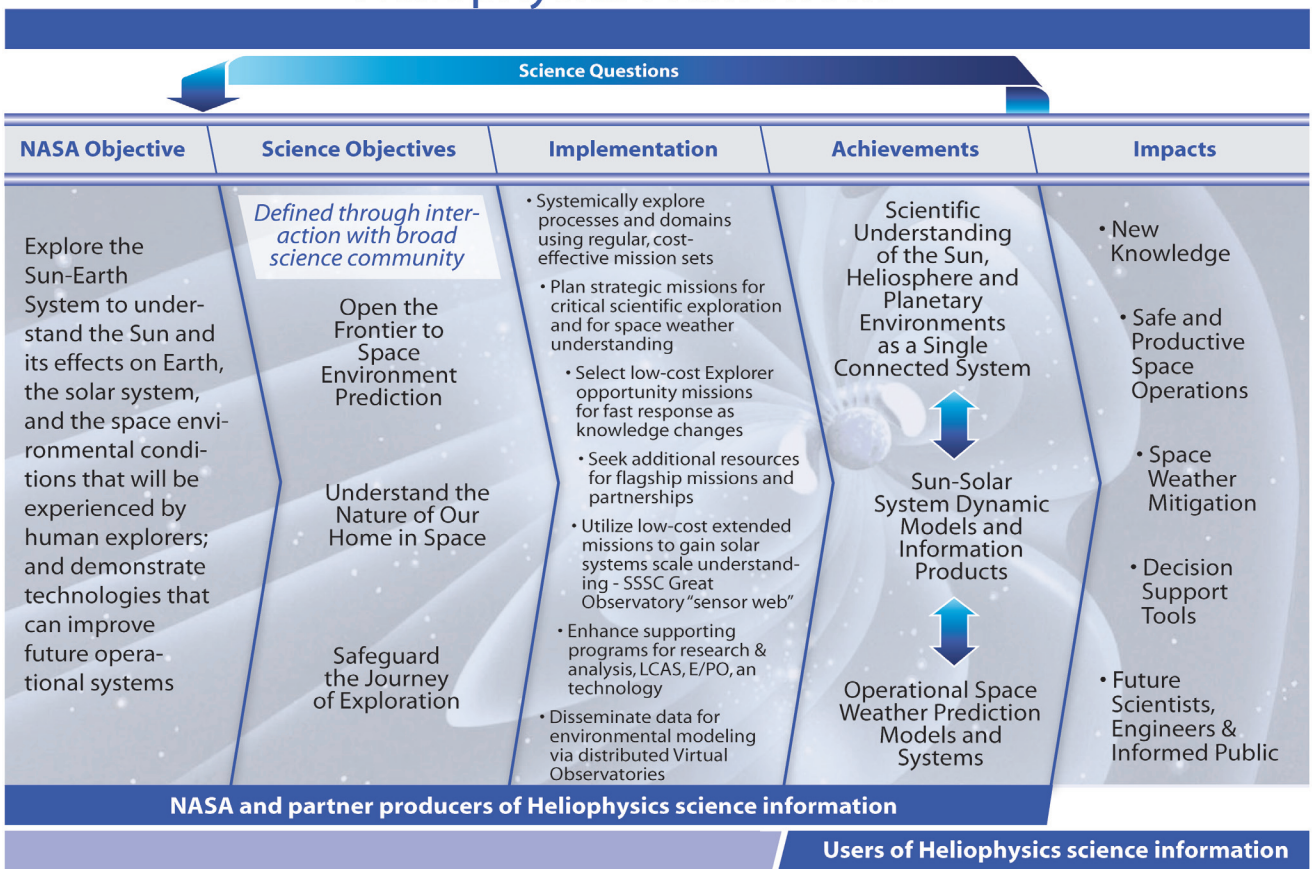
Each anticipated achievement in the table has been developed from the Heliophysics research focus areas. Each targeted outcome requires advances in understanding of physical processes. Measurement capabilities must be available to develop that knowledge. Deployment of missions, development of theoretical understanding, and availability of infrastructure systems are required to provide that measurement capability.

solar system. By expanding and deepening that understanding, we will not only develop a predictive capability to address hazards to space travelers and to important technological assets closer to home, but we will learn how the fundamental space processes interact to affect the habitability of other distant environments, beyond our own solar system.

In keeping with our requirements driven approach, each objective has been associated with research focus areas and scientific investigations. Targeted outcomes for each decade have been identified for each objective and these have led to our prioritized recommendation for missions. Our goals will be achieved by pursuing three groups of strategic missions and the rapid-response Explorer Program, all supported by programs for research and analysis, technology development, and education and public outreach. Investigations supported by missions that can launch in the next ten years are described below. Subsequent mission candidates for each line are described in the report.

The **Solar-Terrestrial Probe** (STP) missions address fundamental science questions about the physics of space plasmas and the flow of mass and energy through the solar system. Three STP missions already begun can be launched in the next decade. Solar–B, a partnership mission led by Japan, will be launched in 2006 to observe how magnetic fields on the Sun's surface interact with the Sun's outer at-

Heliophysics Framework



This figure illustrates the flow of requirements from an overarching strategic goal to principal science objectives, through implementation, to anticipated achievements, and impacts relative to the goal and objectives.

mosphere, which extends millions of miles into space. The STEREO mission, also to be launched in 2006, will provide an unprecedented three-dimensional view of the magnetic field and particle flows throughout the inner heliosphere. Third, the Magnetospheric Multiscale (MMS) mission, to be launched in 2011, will explore the fundamental physical processes responsible for the transfer of energy from the solar wind to Earth's magnetosphere and the explosive release of energy during solar flares.

The **Living With a Star** (LWS) missions will enhance knowledge of the Earth–Sun system that directly affects life and society. The budget enables the launch of four synergistic missions by 2015. The Solar Dynamics Observatory (SDO), to be launched in 2008, will observe the Sun's interior, surface, and atmosphere continuously to determine the physical causes of solar variability. The Radiation Belt Storm Probes (RBSP), to be launched in 2011, will determine how space plasmas are accelerated to hazardous energies, thereby enabling scientists to predict changes to planetary radiation environments and protect space explorers. The Ionospheric Thermospheric Storm Probes and Imager (ITSP), to be launched in 2015, will help scientists understand, to the point of acquiring a predictive capability, the effects of geomagnetic storms on the ionosphere / thermosphere – the region of the atmosphere approximately 50 to 800 miles above Earth's surface. Last, the Inner Heliospheric Sentinels IH Sentinels), also to be launched in 2015, will provide understanding of the propagation and evolution of eruptions and flares from the Sun to the planetary environments. Partnership is crucial to LWS and we recommend collaboration on ESA's Solar Orbiter mission in this time frame. The LWS Space Environment Testbeds provide a valuable opportunity for technological partnerships with spacecraft designers.

Flagship and Partnership Missions address highly challenging and important goals, but are not part of the baseline funded program. Flagship missions cannot be afforded

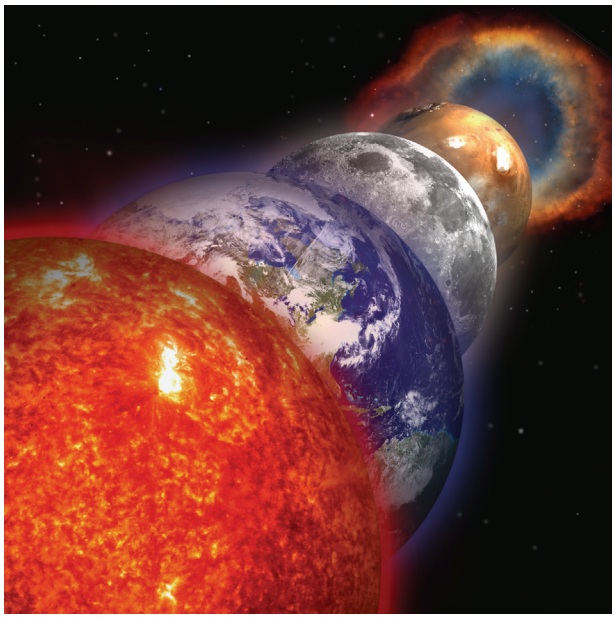
without additional resources. The Solar Probe mission will explore the inner frontier of our solar system; the mission is ready to fly and is our highest priority for new resources. Much later flagships are an interstellar probe and a stellar imager. Partnerships must leverage opportunities available in other programs. The Pluto/Kuiper mission already includes space plasma instrumentation to examine solar wind interactions out to the most remote bodies in our solar system. The Solar Sail Demo mission will enable future missions of much higher delta-V capability. A Jupiter Polar Orbiter (Juno) mission will enable us to compare the solar wind interaction with a rapidly rotating magnetosphere to that of Earth. The Aeronomy and Dynamics at Mars (ADAM) mission, a potential Mars Scout, will provide information about the Martian atmosphere in support of human and robotic exploration of Mars.

The **Explorer Program** provides a vital and effective means of achieving urgent strategic goals in a timely way. Explorers are highly responsive to new knowledge, new technology, and updated scientific priorities by supporting smaller missions that are conceived and executed in a relatively short development cycle, based on open solicitation of concepts from the entire community. The program also enables participation in missions-of-opportunity provided by other national or international agencies. Three Explorers currently in development are relevant to this Roadmap. AIM will determine why polar mesospheric clouds form and why they vary and will determine the mesospheric response to solar energy deposition and coupling among atmospheric regions. The five-spacecraft THEMIS mission will elucidate the mechanisms of transport and explosive release of solar wind energy within the magnetosphere and is a technology precursor to future 'constellation' missions. The recently selected IBEX mission will image the edge of our solar system to examine galactic cosmic rays and particle acceleration at the heliopause.

The connected system we study cannot be adequately measured by single missions. The currently operating spacecraft missions supporting Sun-Solar System connections research collectively constitute a Great Observatory that can address the fundamental challenge for heliophysics science. The **Heliophysics Great Observatory** (page 66) provides the simultaneous measurements in multiple locations needed to resolve temporal and spatial changes and to understand the interactions of complex systems of regimes. As we progress in the exploration of space, this essential capability must evolve to support ever more comprehensive understanding and predictive capabilities. In the years ahead, portions of this spacecraft fleet will be configured into "smart" constellations - sets of strategically-located satellites that provide data to virtual observatories. Researchers will work together to provide the timely, on-demand data and analysis to users who enable the practical benefits for scientific research, national policymaking, economic growth, hazard mitigation, and the exploration of other planets in this solar system and beyond.

New knowledge of this system enables safe and productive exploration. Exploration enables new scientific understanding. The knowledge has utility for society. Our high priority science and exploration objectives address each of these needs. The program is vital, compelling and urgent.

Several smaller but no less crucial program elements support the implementation of the Heliophysics program. The **Low Cost Access to Space (LCAS)** program uses ever



Sun, Earth, Moon, Mars, and Beyond...

more capable rockets and balloons to provide unique science, community development, and technology and instrument development. The interplay among **observation, simulation, modeling, and theory** is essential for the vitality of our space science program. A model or simulation often provides specific predictions to spur the course of future observation. Unexplained observations have led to the development of new theories and the creation of entirely new models. Heliophysics must continue supporting fundamental theory, modeling, data assimilation, and simulation programs, the development of space weather modeling frameworks, and the transition to applications-based codes necessary for space weather operational predictions. The burgeoning maturity of current, comprehensive theoretical modeling systems, spanning many regions and times scales, provides the essential underpinnings for NASA's effort to integrate and synthesize knowledge of the complete system of systems.

As an essential element of its plan to meet these challenging requirements, NASA will invite active participation by **international and national partners** to support the exploration and research program

Education and public outreach have become a natural part of Heliophysics activities. Building on this foundation, we recommend that E/PO activities stemming from the science achievements or milestones be developed to support the following five messages:

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

Heliophysics embraces the development, infusion, and study of **new technology**, both for its stimulating effect on science and because of the key role that understanding and predicting the space environment presents for the safety of other NASA missions and of our global infrastructure that is increasingly space-based. Continuing progress requires technological development in a number of key areas.

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

This proposed Heliophysics program has been derived directly from NASA's new priorities. Still, it should not be surprising that the new plan is largely consistent with previous recommendations. The long-term goals and the near-term budget have shifted since the solar and space physics strategy was presented in the National Research Council's 2002 decadal report, *The Sun to the Earth – and Beyond*. However, as noted in the 2004 NRC update, *Solar and Space Physics and Its Role in Space Exploration*, "the basic priorities of the decadal strategy are still valid for the simple reason that the fundamental principles used in constructing the strategy were the need for a balanced program of basic and applied research that endeavors to recognize the solar-planetary environment for the complex system that it is. We do not know enough today to perform the predictive task required of us by the exploration initiative, and only by pursuing fundamental knowledge and employing a system-level approach can we hope to succeed."

Our present generation of space researchers has inherited a fantastic legacy from the exploratory missions and discoveries of earlier decades. Our success in conducting a robust program of exploration at new scientific frontiers will leave to future generations a similar gift of achievement and inspiration. Because the purpose of exploration is to understand the unknown, the precise benefits of their future space research and their path to success defy prediction. We do know that progress will require constant adaptation to exciting diversions and new directions.

The Heliophysics Great Observatory in Action

The 2003 Halloween Storms

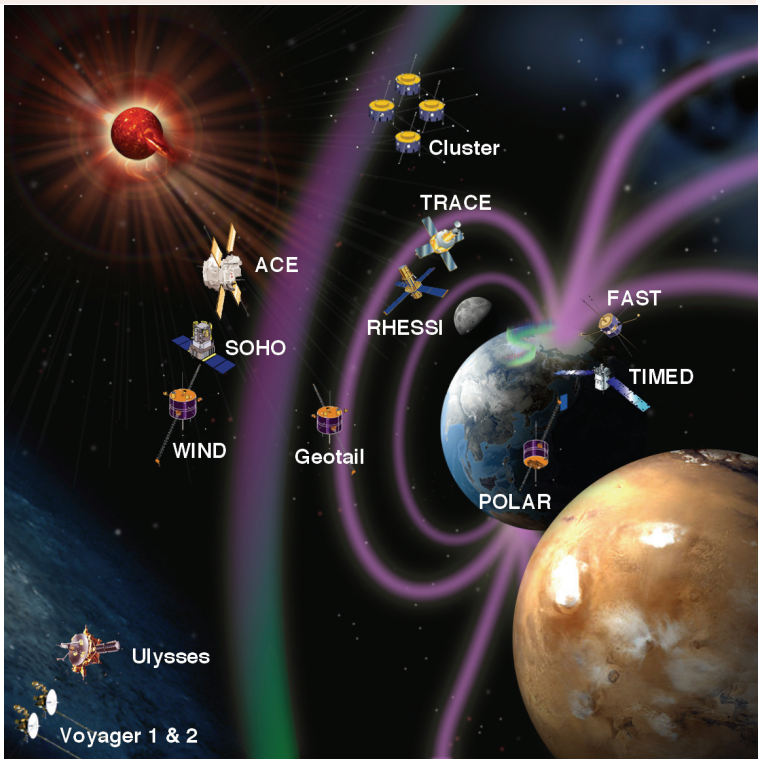
In late October and early November 2003 a large cluster of active regions on the Sun produced a extended series of Coronal Mass Ejections (CMEs) that caused the most spectacular set of events ever observed to flow through the solar system. The solar storms, referred to as the 2003 Halloween Storms, drove a blast wave that pushed the solar system boundary about 1.5 billion miles deeper into interstellar space and expanded the volume of the Sun's corner of the galaxy by almost a third.

Only recently have enough research spacecraft been in place to track such blast waves as they propagate through the solar system revealing that solar storms are both universal and ubiquitous in their influence. This fleet of spacecraft, NASA's Great Observatory for the Sun-Solar System connection, observed the Halloween Storms as they blasted by Earth within a day and past Mars just a few hours later, they detected radio bursts from colliding CMEs as the storms streamed past Jupiter and Saturn. The most distant observations were taken at the outer edge of the solar system by the Voyager spacecraft almost eight months later.

At Earth within a few days the storms produced half as much of the deadly 30-50 MeV particle radiation as the total emitted from the Sun in the previous 10 years and created a new radiation belt at Earth that lasted for several weeks. Southern Sweden experienced a blackout, surge currents were observed in Swedish pipelines, GPS signals were degraded or occluded, and several Mount Everest teams reported interference in high-frequency radio communications. The storms caused aircraft to be rerouted and spacecraft operators reported electronic upsets, data noise, significant proton degradation to solar arrays, orbit degradation, high levels of accumulated radiation, and proton heating. Fortunately, no NASA satellites near Earth were severely damaged, a tribute to advance planning and engineering, although the Mars Radiation Environment Experiment (MARIE) instrument on the Mars Odyssey spacecraft was disabled by radiation at Mar's orbit.

The Sun regularly sends massive explosions of radiative plasma hurtling through the solar system, some with as much energy as a billion megaton bomb. Scientists have identified just 13 other events as extreme as the Halloween storms, including the historic Carrington event of September 1, 1859.

Such events, in addition to being disruptive to society, are important from a research point of view. Because they offer clearer signatures of the solar source mechanisms and propagation characteristics, the ensuing planetary effects and consequences can be unambiguously determined. The plasma, particle and electromagnetic consequences of such events are the focus of this roadmap. The goal of which is to understand the Sun, heliosphere and planetary environments as a single connected system and to apply this knowledge for the benefit of society and the exploration of the solar system. We will reach this goal by strategically evolving the distributed network of spacecraft we call the Heliophysics Great Observatory.



Today's Heliophysics Great Observatory

Chapter 1.
A New Science for the Age of Exploration: Heliophysics

As We Leave the Protective Cocoon of the Earth System, Our Explorers Will Move from a Gravitationally Dominated to a Magnetically Driven Environment

Gravitationally Driven

Familiar Physics - Two Forces:

- Gravity
- Pressure

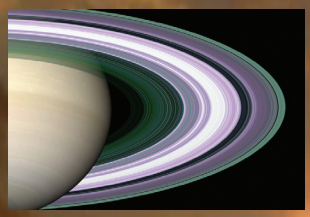
Magnetically Driven

Heliophysics - Three Forces:

- Gravity
- Pressure
- Magnetism

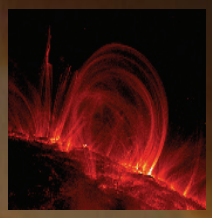
Galaxies

Planets



Heliosphere

Stellar Magnetism

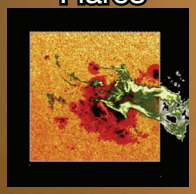


Space Weather

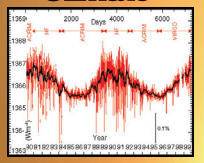
Stars/Sun:

CMEs

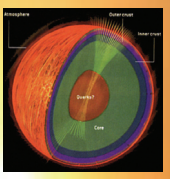
Flares



Total Solar Irradiance & Climate

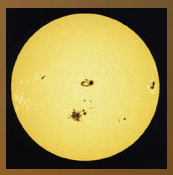


Magnetars



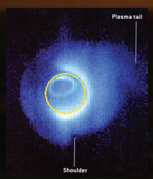
Shocks

Solar Variability



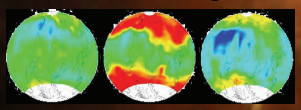
Planets:

Aurorae

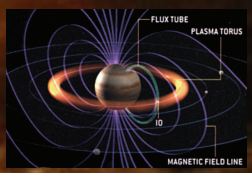


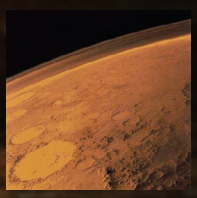
Ionospheres

Atmospheric Chemistry



Planetary Magnetospheres & Atmospheres





The dynamic interplay between the three forces (pressure, gravity, and electromagnetism) in the various venues of the solar system - the Sun's atmosphere; the relationship between the Sun and the heliosphere; the interfaces between planets, their magnetospheres and the heliosphere; and the boundary between the solar system and the galaxy

Chapter 1

A New Science for the Age of Exploration: Heliophysics

Space exploration has transformed our understanding of the solar system. It has revealed a fascinating nested system of systems, so closely connected that an explosive event on the Sun produces measurable effects that span the entire solar system. Through judicious use of a number of operating missions, we have achieved system surveillance over parts of the heliosphere and have been able to examine causal linkages between its elements. In late 2003 we observed an event that caused spectacular coronal mass ejections, power outages on the Earth, degradation of spacecraft solar panels and circuits, destruction of atmospheric ozone, inflation and ablation of planetary upper atmospheres, fatal damage to instrumentation in Mars orbit, auroral displays on Saturn, and, months later, radio disturbances at the edge of the solar system where it meets the interstellar medium. In short, we have observed that space contains weather and that it can affect us (pg 6 & 14).

Recognizing that comprehensive study of this cohesive system has no name, the division has coined the term "Heliophysics" to unite the disciplines that study the linked phenomena in the region of space influenced by the Sun, our star. This chapter highlight some of the key contributions of heliophysics.

Classically, the structure and processes of our environment had been understood in terms of gravitation and pressure. Since space exploration began in 1957, we have learned that space is filled with matter and electromagnetic fields whose importance is belied by their invisibility. Unsheltered from the Sun's pervasive ultraviolet radiation, matter in space enters the fourth state: a conducting plasma of electrically charged electrons and ions, flowing and reacting to highly variable electromagnetic forces. Common human experience provides little experience or intuition about the behavior of such plasma atmospheres.

Owing to its conductivity, moving plasmas generate electrical currents and magnetic fields. Many exotic phenomena ensue, some of which resemble turbulent fluid flows, but impart significant energy to a subset of particles; so much that they can be dangerous to semiconductor circuits or living tissue. Magnetic field lines act to organize their source plasmas into coherent cells, much as droplets of water are defined by surface tension. When such cells come into contact, their magnetic fields may reconnect, creating a coupling between them so that motions of one drive motions of the other. Electrical currents flow to generate

Our program will help assure the safety and productivity of the next generation of human and robotic explorers.

At the same time we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space.

We will develop a predictive capability to address hazards to important technological assets closer to home and discover how fundamental space processes may affect the habitability of other distant environments beyond our own solar system.

the coupling forces, charged particles are accelerated, sometimes explosively as in solar flares.

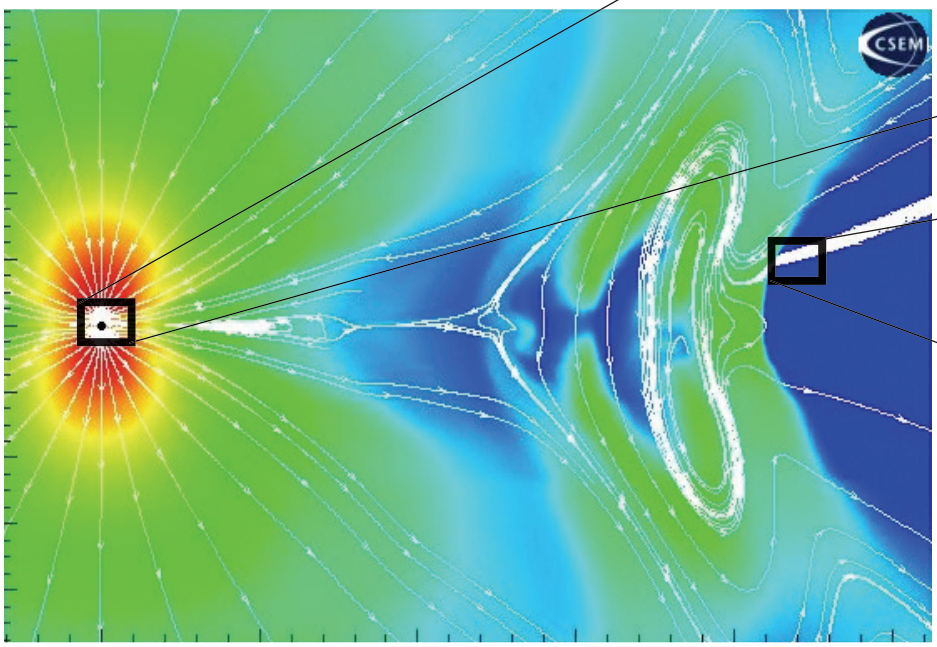
Such electromagnetically driven processes act at the center of every stellar system. Our own solar system is controlled by the Sun, a magnetically variable star. Because our solar system is the one part of the cosmos accessible to direct scientific investigation, it provides our only hands-on astrophysical laboratory for understanding these universal processes.

Heliophysics is the new science for the age of exploration. Implementing the Vision for Space Exploration will eventually free humankind from the gravitational forces that have held us through history. Space explorers will learn to live within the magnetically controlled space environment and, through our NASA exploration missions, every citizen will be able to see and experience these things.

The Earth and Sun are linked together to form the system that has given origin and sustenance to our lives. The story of how this came to be over the history of the solar system is one of the most compelling mysteries faced by humankind. The physical processes and the evolutionary paths embedded in this combined system are studied in the Earth-Sun System Division of NASA's Science Mission Directorate. We examine the Earth and Sun system today for insights into questions concerning how the system evolved so as to produce and sustain life, what will happen to this unique environment through the course of time, and how it will affect us.

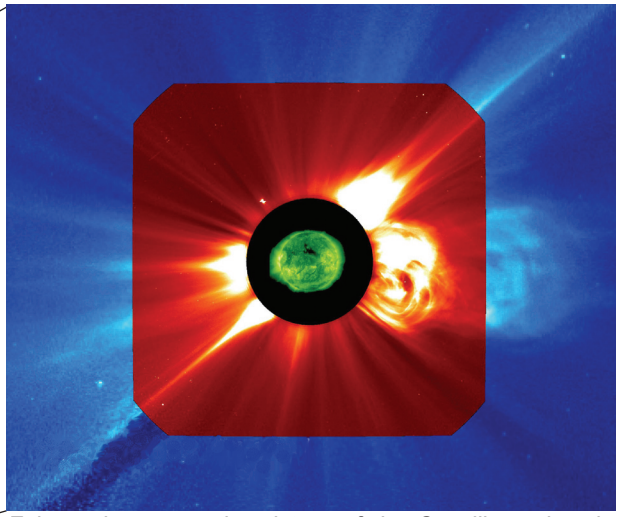
With human space activity confined to low Earth orbit since the mid-1970's, we have been reconnoitering the solar system (and beyond) using robotic spacecraft and telescopes. In 2005, Voyager passed through the solar wind termination shock and into the heliosheath, nearing the outer edge of the solar system. Though we have not yet probed the inner boundary of the solar atmosphere directly, the Sun is bright enough to reveal a great deal about itself through remote imaging, spectroscopy, and polarimetry.

With the first general survey of the solar system nearly complete, explorers are now beginning to revisit the planets, including Earth, for studies of greater depth. The region around the Earth remains an important astrophysical laboratory for the study of the physical processes that are of broad relevance to astrophysics. Moreover, these processes are by now known to have influenced the habitability of the Earth

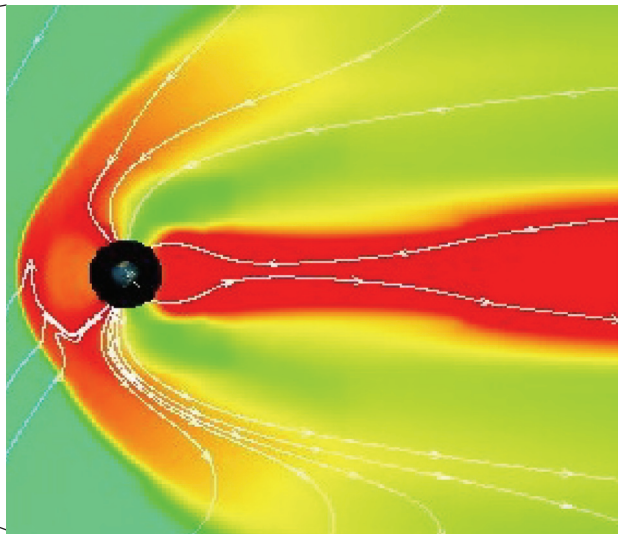


Several kinds of space plasma simulation models have been developed to provide a theoretical understanding of the flow of energy from the Sun through interplanetary space to the Earth's magnetosphere. This first frame illustrates the progression of a coronal mass ejection (CME). Shown are magnetic field lines (white) and magnetic field strength (low = blue to high = red) 20 hours into an event. The sun is the small black dot at the center of the red glow to the left. The CME is at the right riding on top of the expanding flow of the solar wind at speeds up to 2,000 kilometers per second.

in time and so are relevant to the possible existence of life elsewhere in the solar system or the universe. Investigators have barely begun to scratch the surface of the history of our solar system over geologic time and have only recently determined that planets are commonplace around other stars. In at least one such case observers can discern the signature of an atmosphere being ablated by a stellar wind. In another case, X rays are emitted from a young star that is not fully ignited, showing that electromagnetic and plasma processes become active very early in the life of a planetary system.



False color composite picture of the Sun illustrating the source of the disturbance shown in the simulation. The Sun observed in extreme UV is the center object colored in green. The areas in red and blue are views of the Sun's atmosphere (corona) where the CME can be seen as white areas moving rapidly away from the Sun.



This frame is a continuation of the same simulation as the CME impacts the Earth's magnetosphere creating a geomagnetic storm, which first manifests itself as large, episodic variations in the Earth's magnetic field. The electromagnetic pulses can produce a new radiation belt in minutes, not days, as normally occurs.

The United States is now embarking on an ambitious new journey of exploration to the Moon, Mars, and beyond. NASA has been challenged to establish a sustained presence on the Moon by the end of the next decade with the purpose of enabling Martian exploration thereafter. The will to achieve this Vision for Space Exploration presents the agency with great opportunity and sobering demands.

Success in this venture requires advanced understanding of the complex physical systems that link the variable star at the center of our solar system with the Earth and other planets. The harsh and dynamic conditions in space must be characterized and understood in some detail if robots and humans are to safely and productively travel to and explore the Moon and Mars.

The biological effects of the energetic particle radiation environment outside of low-Earth orbit remain largely unknown. Astronauts aboard the International Space Station (ISS) accumulate significant radiation exposure and energetic particle events impact space station operations. Travel outside Earth's protective magnetic cocoon, whether to the Moon or Mars, will require new predictive capability for solar particle events. Even well designed hardware is damaged or degraded by extreme conditions in space. And astronauts spending more than a few days in space will need a way to take shelter from episodic exposure to debilitating doses of solar energetic particles.

Equally important is the need to investigate the space weather and solar variability that affect critical technologies used on Earth. For example, satellite communications, navigation, remote sensing, and power distribution are subject to problems because of variations in the Earth's ionosphere that are not currently understood. Increasing reliance on vulnerable global systems demands active management in response to variations in the space environment. In many ways, our space weather approach resembles earlier steps taken by scientists to understand and predict weather in the Earth's atmosphere. We too must ob-

serve and understand the detailed phenomena, generate theoretical models that can be validated and verified against observed reality, build data-assimilative predictive systems, and then develop operational decision support systems closely tailored to the needs of end-users and rigorously tested and improved over time. In this way and by these means, NASA's Heliophysics program will bring sound science to serve society.

Space weather is in some ways analogous to the tropospheric weather that is so familiar to us, yet remains difficult to predict beyond a few days. In other ways it is fundamentally different. It is analogous in its nonlinear complexity, though across an even greater range of physical and temporal scales. Systems this large simply cannot be reduced to a linear combination of interacting parts, no matter how detailed the study of those parts. Space weather is fundamentally different in that electricity and magnetism are at least as important as the more familiar forces of gravity and pressure. Measuring, characterizing, and understanding these processes cannot be accomplished with images and common intuition. Localized measurements cannot merely be interpreted to generate a global picture. Conversely, the global picture does not provide insight into the small-scale physical processes of the system. For example, the magnetic reconnection that regulates much of the interaction between the solar wind and the Earth's magnetosphere cannot be observed remotely and it takes place in a rapidly moving location several Earth radii above the planet on a spatial scale of a few kilometers and temporal scale of several milliseconds.

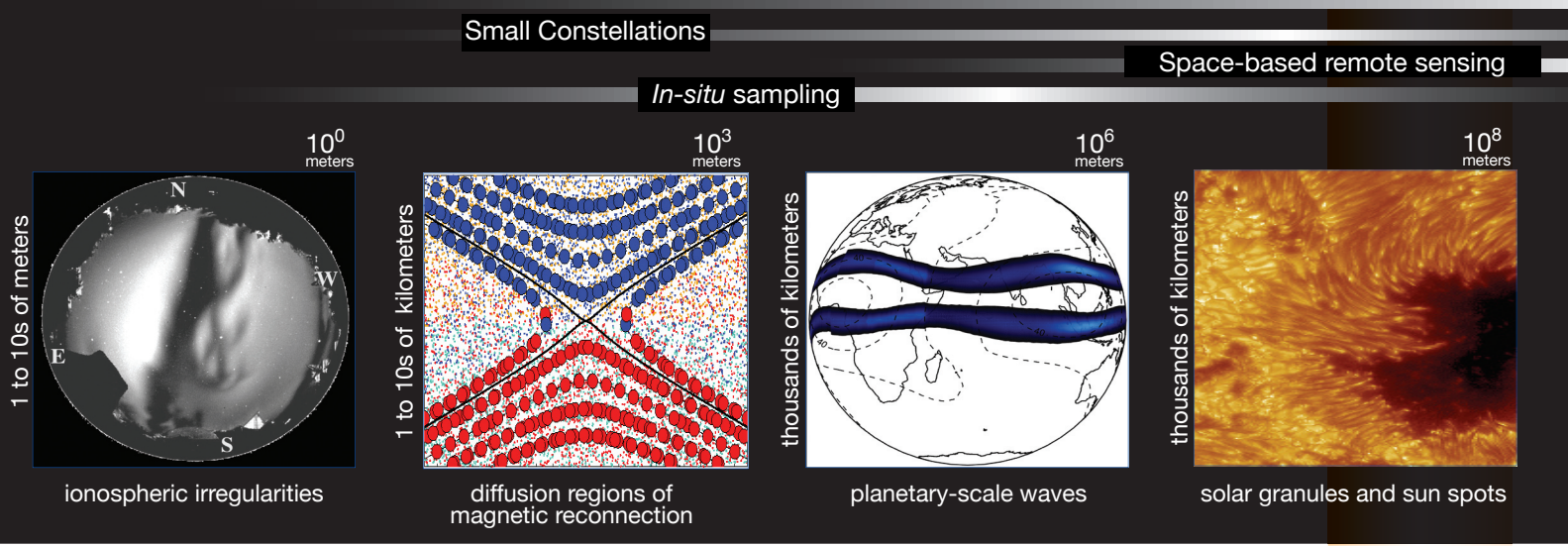
Our approach to experimentally probing this vast system of systems is three-fold:

- Identify the weakest links in our understanding of the coupled system and deploy targeted missions to resolve those science questions.
- Utilize all NASA deployed assets as a distributed sensor net to sample large-scale phenomena.
- Combine these necessarily sparse data with modeling and theory to achieve system-wide understanding.

Answering a specific science and/or exploration question often requires a narrowly focused mission to a particular location with a unique instrument. For example, measuring flows in the solar interior requires a long, continuous series of simultaneous velocity measurements at millions of locations on the solar disk. However, Sun – Solar System connection science increasingly depends on combining multi-point *in situ* measurements with remote sensing. Again, by analogy with meteorology, combining a network of distributed local observations with global measurements (a meteorological Great Observatory) enables the development and testing of predictive models that improve with time and experience.

Currently the **Heliophysics Great Observatory** includes satellites that (for example) hover

Interacting Powers of Ten: Our work over the past few decades have taught us enough about our local space environment to know that our task to produce reliable space weather predictions is a formidable challenge



near L1 – a million miles upstream in the solar wind, circle over the Sun's poles, orbit the Earth in various configurations, and have just reached the first boundary between the interstellar medium and the Sun's domain, the termination shock.

As each set of scientific problems is resolved, new mysteries emerge and the Heliophysics Great Observatory evolves with the addition of new spacecraft. Solar-B will help understand the creation and destruction of solar surface magnetic fields, variations in solar luminosity, and the dynamics of the solar atmosphere. Soon the two STEREO spacecraft will drift away from Earth to provide the first stereoscopic views of the Sun and inner heliosphere. The Solar Dynamics Observatory (SDO) will image the Sun's interior, surface, and atmosphere from geosynchronous orbit. Observing the terrestrial response, the Radiation Belt Storm Probes (RBSP) will investigate the processes that accelerate particles to hazardous radiation levels, and the four Magnetospheric Multi-Scale (MMS) spacecraft will fly in tight formation to explore the multiple scales of reconnection, turbulence, and particle acceleration in the magnetosphere of the Earth. Solar Probe, when funded, will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity.

This recommended science and exploration roadmap for the Heliophysics Division elaborates the strategic planning consequences of a stated U.S. national objective for NASA:

Challenges to achieving a quantitative, predictive understanding of this complex "system of systems"

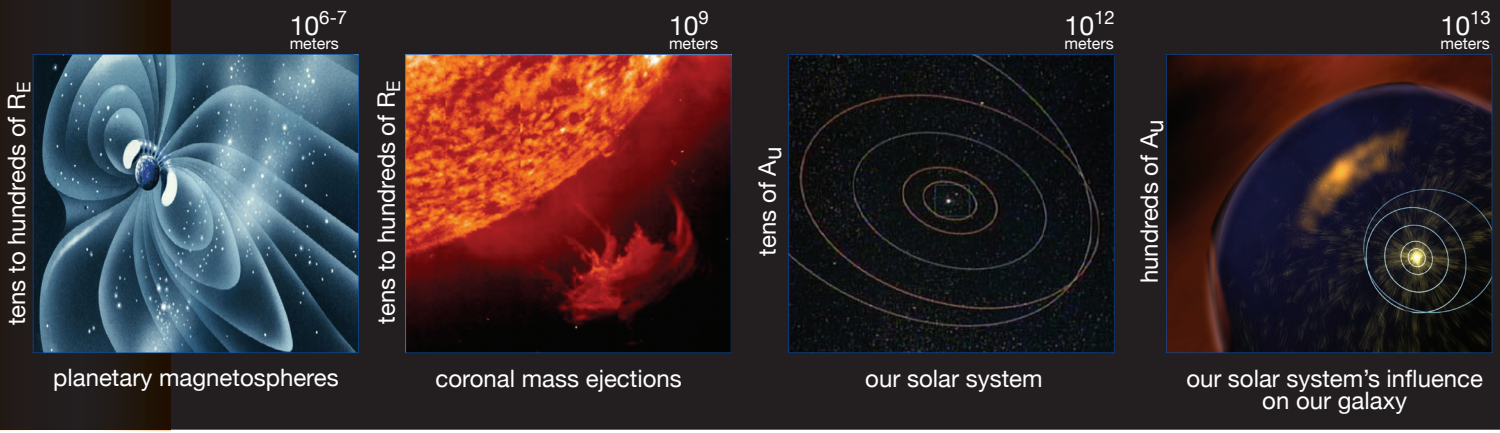
- Regulation of global and interplanetary structures by microphysical processes
- Multi-constituent plasmas and complex photo chemistry
- Non-linear dynamic response
- Integration and synthesis of multipoint observations
- Development of data assimilative models and theory
- Amalgamation of interdisciplinary communities and tools

"Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human and robotic explorers, and demonstrate technologies that can improve future operational systems." The resulting science and explorations objectives are explained in the next chapter. Implementation plans follow that span the next 30 years. The document concludes with an explanation of the links to other NASA activities.

New knowledge of this system enables safe and productive exploration. Exploration enables new scientific discovery and understanding. The knowledge has utility for society. Our high priority science and exploration objectives address each of these needs. The program is vital, compelling, and urgent.

Observations of solar system-scale and planetary- scale phenomena, and of microphysical plasma processes, will be required. This requires a range of observational techniques: *in situ*, imaging, constellations, and the Heliophysics Great Observatory.

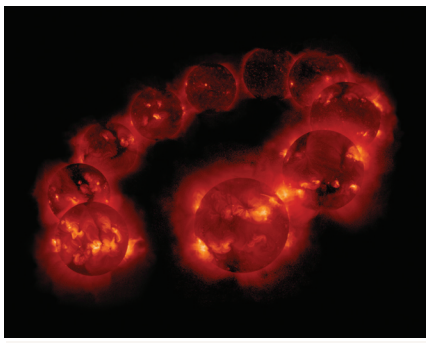
Solar System Great Observatory



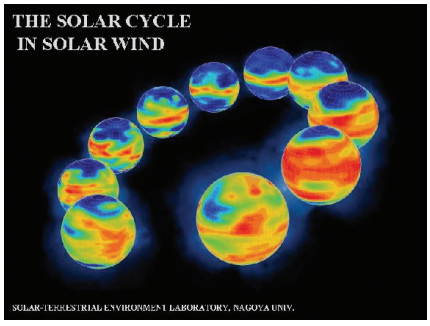
The Calm Between the Storms

Powerful events such as the 2003 Halloween space storms (page 6) obviously affect astronauts, satellites, communication and electrical power systems. But it may seem that the space environment is usually benign and unimportant because such storms are rare. In fact, the constant variation of the space environment makes the time between storms anything but calm.

Magnetic active regions on the Sun emerge and decay over days to weeks. The numbers of active regions varies regularly with the 11-year solar cycle and erratically over longer time scales - up to centuries. The patchy distribution of regions over the Sun produces variation at the 27-day solar rotation period.



Annual soft x-ray images from Yohkoh (above) show dramatic changes over an 11-year solar cycle. Less regular, but equally large, changes can occur on shorter (27-day) and much longer (millennial) time scales. The solar wind velocity distribution (below) follows a similar pattern. Fast (blue) solar wind originates in dark x-ray coronal holes.



Many phenomena – emission of visible light, intensity of short wavelength radiation, solar wind characteristics, and blocking of galactic cosmic rays – vary significantly with the time scales of the solar magnetism, even without storms.

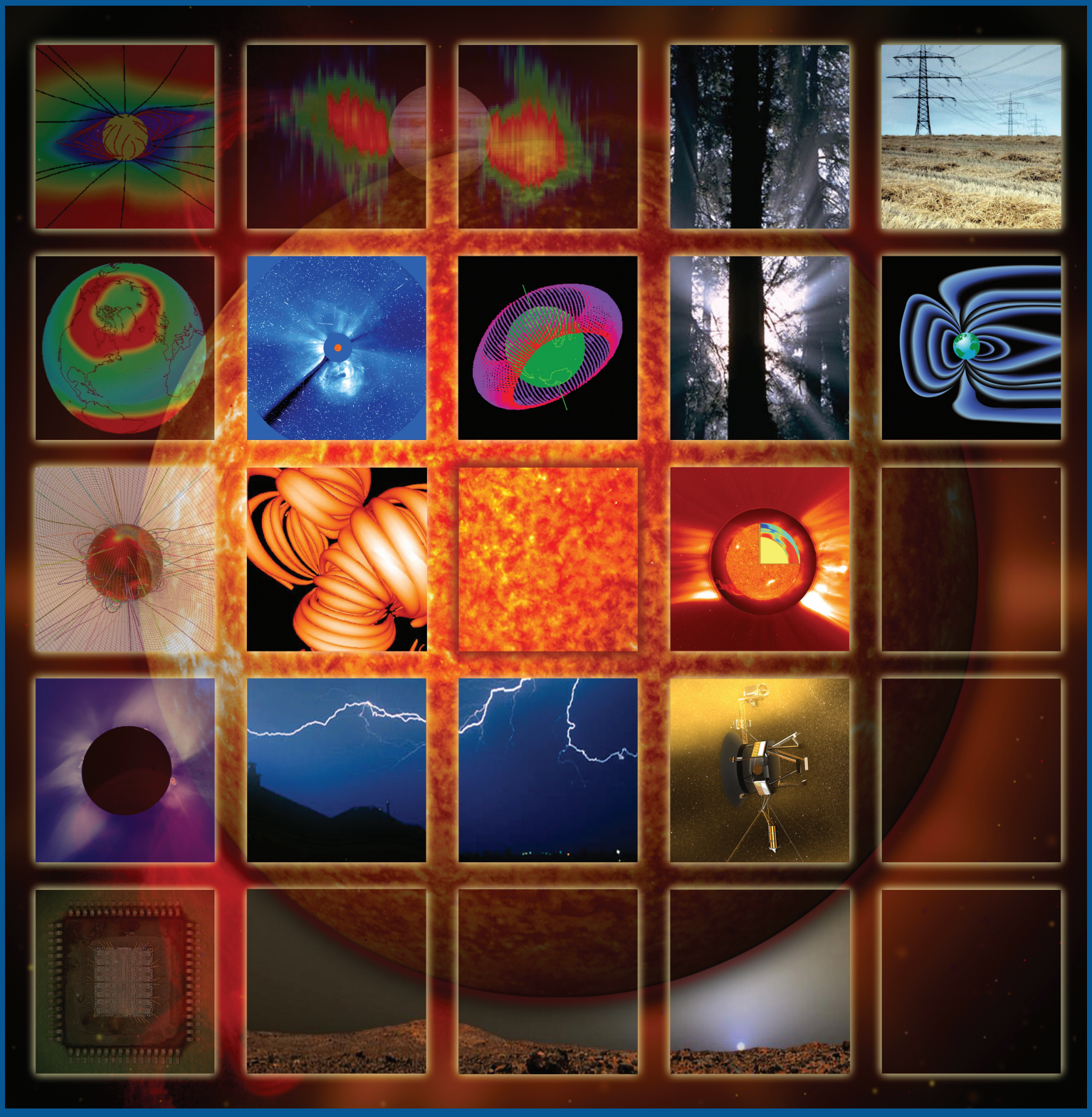
Light from the solar surface directly heats the Earth's surface and lower atmosphere. Dark sunspots and bright faculae in magnetic regions alter the emission of light from the surface enough to affect the climate over long intervals.

The corona above magnetic regions is heated to millions of degrees and emits strong and variable amounts of X-rays, EUV, and UV radiation. The radiation heats, dissociates, and ionizes the atmospheres of Earth and other planets, producing our ozone layer, the ionosphere, and the thermosphere. It alters atmospheric chemistry and temperature, which in turn modifies the mixing of molecules over height and latitude. As these layers heat and cool, they become more and less dense, changing the drag that slows satellites until they reenter.

The solar wind, striking Earth's magnetic field, drives the acceleration of energetic particles that fill the radiation belts. By contrast, Mars has no global magnetic field, and the solar wind directly impacts and strips away Mars' upper atmosphere. The wind's magnetic field, constantly reshaped by change on the Sun even in absence of solar events, can power intense geomagnetic storms, with the whole array of energetic particle acceleration, aurora, and disturbances of satellites systems.

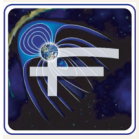
Coronal holes above stable solar areas power the solar wind, which carries magnetic fields with it. The magnetized solar wind, filling the heliosphere, deflects many of the cosmic ray particles that fill the rest of the galaxy.

Understanding the varying space environment on all timescales is the motive for our Heliophysics Great Observatory and for the new missions planned in this Roadmap. From the climate of Sun and Earth, to travel to other planets, and out to the space between the stars, the Heliophysics program seeks to predict these variations that we know – and those we have yet to discover.



Chapter 2.
Heliophysics: The Science

HELIOPHYSICS SCIENCE & EXPLORATION RESEARCH FOCUS AREAS:



Open the Frontier to Space Environment Prediction

Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium.

F1. Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.

F2. Understand the plasma processes that accelerate and transport particles.

F3. Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system.

F4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

Understand the Nature of Our Home in Space

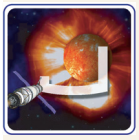
Understand how human society, technological systems, and the habitability of planets are affected by solar variability interacting with planetary magnetic fields and atmospheres.

H1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment.

H2. Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

H3. Understand the role of the Sun as an energy source to Earth's atmosphere and, in particular, the role of solar variability in driving change.

H4. Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.



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.

J1. Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

J2. Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

J3. Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

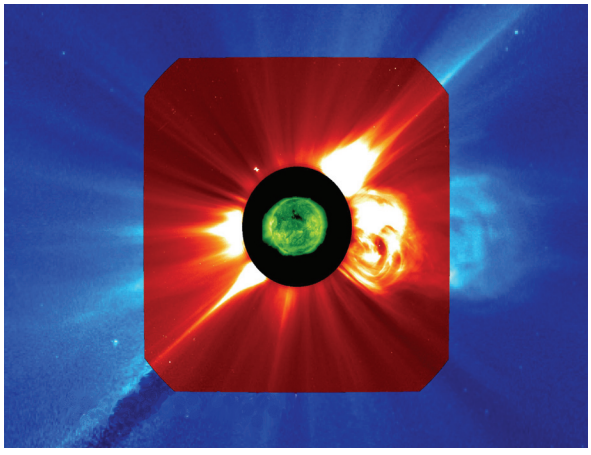
J4. Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

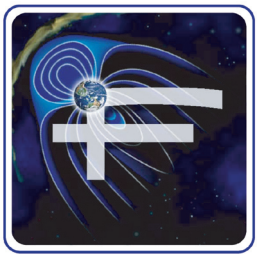
Chapter 2

Heliophysics: The Science

This generation of space researchers has inherited a fantastic legacy from the exploratory missions and discoveries of earlier decades. Our success in conducting a robust program of exploration at new scientific frontiers will leave to future generations a similar gift of achievement and inspiration. Because the purpose of exploration is to understand the unknown, the precise benefits of their future space research and their path to success defy prediction. We do know that progress will require constant adaptation to exciting diversions and new directions.

Building on this rich history of exploration, we now seek to transform human understanding of this fascinating system of systems that are so closely connected (page 14). We will not only develop a predictive capability to address hazards to space travelers and important technological assets closer to home, but we will also learn how the interplay of fundamental space processes affects the habitability of other distant environments. The strategic plan for the future of heliophysics consists of three encompassing scientific and exploration objectives we designate F, H, and J for Frontier, Home, and Journey.





Open the Frontier to Space Environment Prediction

Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium.

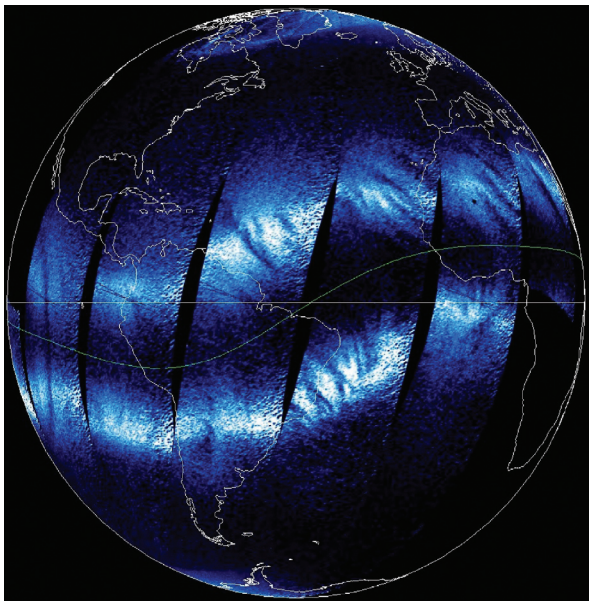
Earth's upper atmosphere, the Sun, our solar system, and the universe consist primarily of plasma, resulting in a rich set of interacting physical processes and regimes, including intricate exchanges with the neutral environment. We will encounter hazardous conditions on our return to the Moon and our journey to Mars. Technological systems are disrupted and we must develop a complete understanding of the many processes that occur within these systems with such a wide range of parameters and boundary conditions.

As the foundation for our long-term research program, we must develop a comprehensive understanding of the fundamental physical processes of our space environment–from the Sun to the Earth, to other planets, and beyond to the interstellar medium. We will systematically examine similar processes in widely different regimes with a range of diagnostics techniques to both test our developing knowledge and to enhance overall understanding. The universal themes of energy conversion and transfer, cross-scale coupling, turbulence and nonlinear physics have been chosen as near-term priority targets. The five fundamental processes that have been identified as the critical imme-

diate steps are magnetic reconnection, particle acceleration and transport, the generation and variability of magnetic fields, cross-scale coupling across boundaries and large structures, and nonlinear energy and momentum transport and coupling in atmospheres. Both *in situ* and remote sensing observations will be required, together with modeling to provide a three dimensional large-scale perspective as well as a detailed small-scale microphysics point of view. With our increasingly sophisticated understanding of such basic processes, we will open the frontier of predictive modeling across the solar system.

Understand the Nature of Our Home in Space

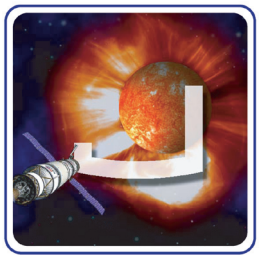
Understand how human society, technological systems, and the habitability of planets are affected by solar variability interacting with planetary magnetic fields and atmospheres.



Humankind does not live in isolation; we are intimately coupled with the space environment -through our technological needs, the habitability of the planets and 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.

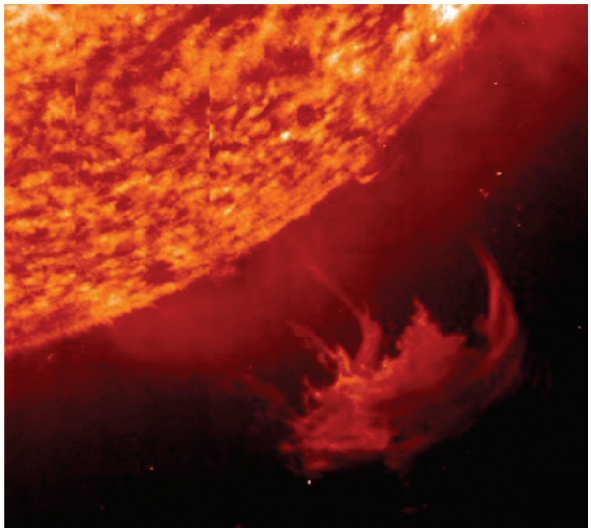
We plan to better understand our place in the Solar System by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. Building on our new knowledge of fundamental processes, we plan to characterize and develop a predictive knowledge of the impact of the space environment on society, technology, and our planet. This will be accomplished both by direct investigation of the local environment and by what can be learned about life on Earth through studying other environments. Human life and society provide the context in which these investigations are conducted.

As we extend our robotic and human presence throughout the solar system, we will be increasingly interested in the planetary environments that await us and how the lessons learned can be applied to our home on Earth. Much can also be learned by studying our own atmosphere and applying that knowledge to the exploration of other planets. 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. We believe we know some of the features that make planets habitable, but there is much more to be understood.



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 great variety of space environment conditions will have a significant impact on our future space explorers, both robotic and human. We plan to pursue, with all due vigilance, the research necessary to assure the safety and the maximum productivity of our explorers. We plan to develop the capability to predict space environment conditions from low Earth orbit to the Moon and Mars. Addressing space weather issues is necessary for optimizing the design of habitats, spacecraft, and instrumentation, and for planning mission and operations scenarios, ultimately contributing to mission success.

Building on our knowledge of fundamental processes, we plan to understand those aspects of the space environment essential for enabling and securing space travel. Useful engineering data are already flowing into exploration-oriented planning and implementations because the Heliophysics community has long been exploring useful scientific directions. Our heliophysics research community is poised to provide the next generation of measurements, simulations, and models that will be useful to the implementation of manned and robotic missions to the Moon, Mars, and other planetary bodies. Such parameterizations of the space environment will be essential inputs for overcoming the challenging engineering problems that must be solved for successful and economical exploration activities.

The remainder of this chapter explains the research focus areas and lists the investigations that flow from these three objectives. The Connection to missions is developed in later chapters. See the table at the beginning of Chapter 4 for mission details.

Objective

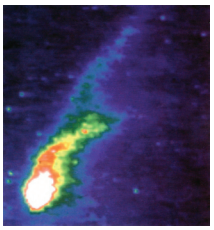
Open the Frontier to Space Environment Prediction

Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium.

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 some of these 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 – from the Sun to the Earth, to other planets, and beyond to the interstellar medium. We must be able to predict the behavior of the complex systems that influence the inimical conditions we will encounter on our return to the Moon and journeys to Mars.



The processes of interest occur in many locations, though with vastly different magnitudes of energy, size, and time. The same processes rule the seething atmosphere and interior of our Sun, the supersonic wind of particles that our star flings outward into space, Earth's cocoon-like magnetosphere, the highly variable terrestrial ionosphere, the tenuous upper atmosphere of Mars, and even the fantastically energetic spinning pulsars that spray out beams of x rays.

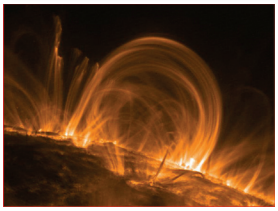
By quantitatively examining similar phenomena occurring in different regimes with a variety of measurement techniques, we can ultimately identify the important controlling mechanisms and more rigorously test our developing knowledge. Both remote sensing and *in situ* observations must be utilized to provide the complementary three-dimensional large-scale perspective and the detailed small-scale microphysics view necessary to see the complete picture.

Prediction provides the ultimate test for scientific understanding.

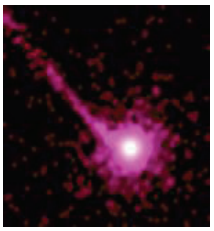
The strategy for prioritizing this first science objective focuses on the knowledge gaps most vital to safe and productive exploration via the development of accurate forecasting of the space environment. Four fundamental processes have been identified as crucial immediate steps: magnetic reconnection, particle acceleration, the physics of plasma and neutral interactions, and the generation and variability of magnetic fields with their coupling to structures throughout the heliosphere. Each of these research focus areas (RFA's) involves the universal themes of energy conversion and transport, cross-scale coupling, turbulence, and nonlinear physics – concepts that are fundamental to the understanding of space and planetary systems. In addition they all include processes that can be influenced by

large-scale boundaries or by coupling between regions with very different conditions (for example, cold, dense neutral atmospheres with energetic particles).

Plasmas are conductive assemblies of charged particles and neutrals that exhibit unfamiliar collective effects. Plasma systems carry electrical currents, generate magnetic fields, and can interact explosively. The solar system is the only directly accessible laboratory for exploring the behavior of astrophysical plasmas. We must prepare our space explorers to live and work in this harsh alien environment.

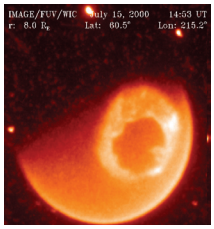


Magnetic Reconnection: Magnetic reconnection occurs in highly localized regions when interacting magnetic fields "snap" to a new, lower energy configuration, as if a pair of twisted rubber bands broke and relinked to form two new relaxed bands. Magnetic reconnections can release vast amounts of stored energy and are responsible for solar flares, CME's and geospace storms. An explosive release of energy can be potentially devastating to space assets and voyaging humans, and can seriously affect worldwide communications. Although we have developed an initial picture of where reconnection may occur and the observable results, the detailed physical mechanisms, in particular the microphysical processes and the role of large-scale topology, are not understood. This focus area (RFA F.1) will deliver a fundamental understanding of this universal process in the very different regimes where it occurs.



Particle Acceleration: By far the most distinguishing characteristic of plasmas, in contrast to the neutral states of matter of planets, is that plasmas produce prodigious amounts of radiation. Because energetic particle radiation has the most direct impact on human and robotic space explorers, detailed understanding of the particle acceleration processes that produce radiation, the regions in which these processes operate, and the boundary conditions that control them is crucial to the exploration of space. RFA F.2 will investigate the mechanisms that accelerate particles within the solar system, including small-scale waves, shocks, and quasi-static electric fields. Radiation can be produced almost instantaneously through explosive processes, but also built up step-wise by processes acting under more benign conditions. Providing essential predictions of the radiation environment along the end-to-end path of space explorers will involve accounting for particle acceleration in all its forms and locations, from Earth's aurora to the solar corona.

Plasma-Neutral Interactions: Heliophysics requires understanding of the fundamental physics of plasma and neutral particle coupling. This coupling encompasses a variety of mechanisms and regions from turbulence and charge exchange in the solar wind to electrodynamic processes in the ionosphere and thermosphere to gravity waves and chemical/collisional interactions in planetary atmospheres. Space plasmas are often in a non-equilibrium state and they can be a highly nonlinear medium. Many of the techniques developed for understanding nonlinear systems ensue from basic plasma research – chaos theory is one example; another is the understanding of turbulence, which is so important to safer air travel. The goal of RFA F.3 is a comprehensive understanding of how nonlinear processes influence plasma-neutral interactions from atmospheric to heliospheric scales. This work has specific applicability to the operation of satellites in the Martian atmosphere, the mitigation of the effects of global change, as well understanding how habitable planets retain their atmospheres.



Magnetic Dynamos: Understanding the variations of the magnetic fields of the Sun and planets on both long and short time scales is the key element of the Sun-Solar System connection addressed by RFA F.4. The creation of these fields – the magnetic dynamo problem – remains one of the outstanding problems in

physics. How dynamos operate in such widely disparate systems – from stellar interiors to planetary cores – is poorly understood. Dynamos determine the characteristics of the solar activity cycle. The Sun's magnetic field controls the structure of the heliosphere and, thus, regulates the entry of galactic cosmic rays into the solar system. Therefore, it is imperative that we understand the origin and variability of solar magnetism. The Earth's interior dynamo sustains the geomagnetic field and provides the shield that enables life to flourish in the harsh radiation environment of space. Understanding how dynamos are created and sustained, how they affect the nearby space environment, how to predict their variations and ultimately their demise lies at the heart of understanding our own destiny.

With our increasingly sophisticated understanding of these fundamental physics process, we will open the frontier to the development of truly predictive space weather models.

Objective F: Open the Frontier to Space Environment Prediction

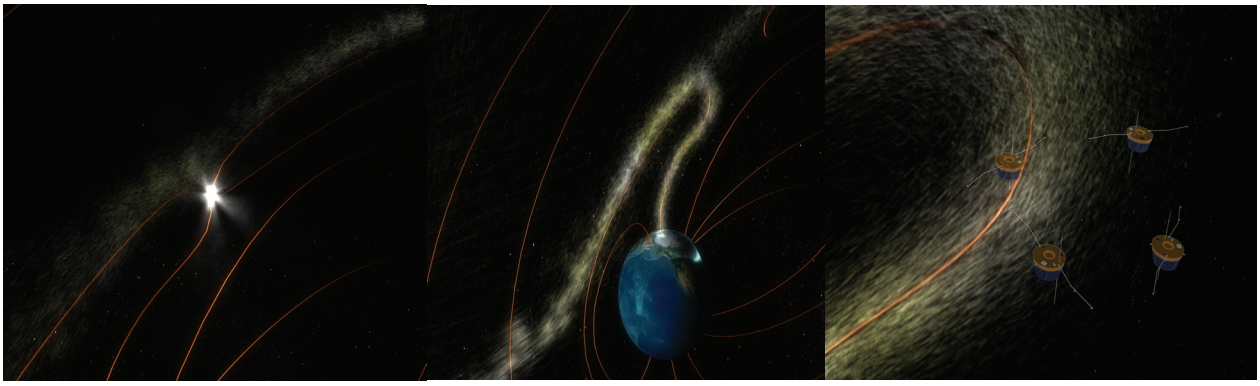
Priority Research Focus Areas & Associated Investigations

F1. Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.
1. What are the fundamental physical processes of reconnection on the small scales where particles decouple from the magnetic field?
2. What is the magnetic field topology for reconnection at the Earth and at what size scales does magnetic reconnection occur on the Sun?

F2. Understand the plasma processes that accelerate and transport particles.
1. How are charged particles accelerated to high energies?
2. How are energized particles transported?
3. How is the solar wind accelerated and how does it evolve?
4. How are planetary thermal plasmas accelerated and transported?

F3. Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system.
1. What governs the coupling of neutral and ionized species at various spatial and temporal scales?
2. How do energetic particles chemically modify planetary environments?
3. How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?
4. How do the heliosphere and the interstellar medium interact?
5. How does the neutral environment in planetary and cometary systems affect their global morphology through charge exchange and mass loading processes?

F4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.
1. How do subsurface flows drive the solar dynamo and produce the solar cycle?
2. How do solar and stellar dynamos evolve on both short and long-term time scales?
3. How are open flux regions produced on the Sun, and how do variations in open flux topology and magnitude affect heliospheric structure?
4. How do planetary dynamos function and why do they vary so widely across the solar system?



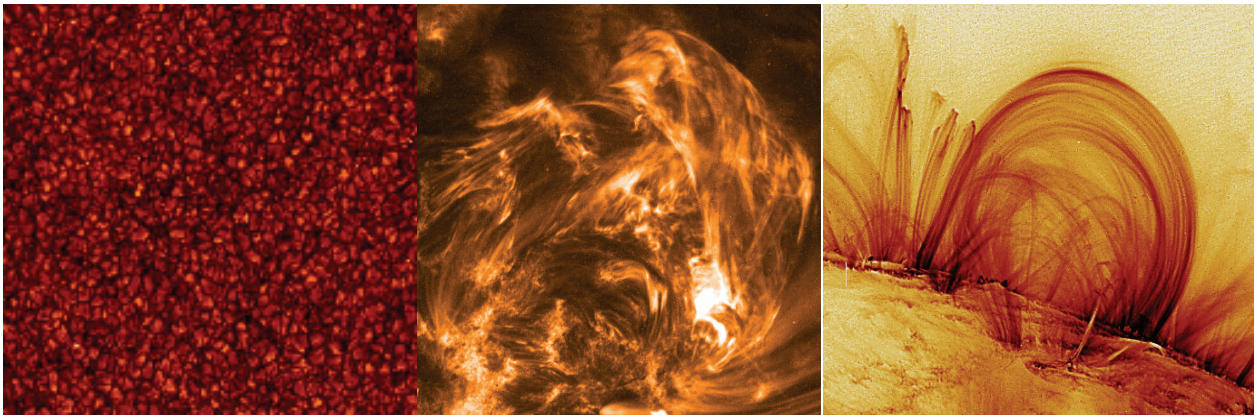
One type of reconnection takes place when the Earth's usually impenetrable magnetic field fractures and has to find a new stable configuration. Until the field mends itself, solar protons leak through the gap and jet into Earth's atmosphere, precipitating aurora and ionospheric currents. For a predictive capability, very high time-resolution, 3D measurements of particles and fields from multiple satellites with variable separations are needed reveal the micro- to meso-scale processes needed to directly probe the electron diffusion region.

RFA F.1: Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.

Reconnection typically results in the rapid conversion of magnetic energy into particle energy. It is an important, cross-scale coupling process in a variety of space plasmas ranging from the magnetotail of the Earth to solar flares. Reconnection can accelerate particles to very high energies and, because it changes the magnetic field topology, it can dramatically alter the regions of space that are accessible to those particles. In the corona reconnection can sever large clouds of dense plasma from the magnetic fields that anchored them. Solar flares, coronal mass ejections, and geospace storms are all initiated and energized by reconnection – often with potentially devastating effects for space systems.

The explosive conversion of magnetic energy originates in a volume of space known as the diffusion region. This region is very small when compared to the large scales in space. For example, reconnection at the Earth's magnetopause surface (the boundary separating the solar wind and terrestrial magnetic fields) occurs in a region with an area of the order of hundreds of square kilometers compared to a total surface area of approximately 60 billion square kilometers. While there have been a few encounters with the diffusion region in the near-Earth environment, systematic *in situ* study of this region is just beginning. Current solar imaging is insufficient to resolve the diffusion region associated with solar flares. Thus, the physical processes that initiate and control reconnection remain to be measured.

Most of our basic theoretical understanding of reconnection comes from an MHD (magnetohydrodynamics) perspective. Although this approach has provided important insight, it is inherently limited in that it cannot examine the very small scales on which ions and electrons decouple from the magnetic field or predict the particle energization process. Important questions that remain unanswered include: 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? Is reconnection quasi-steady or bursty? What mechanisms or boundary conditions control the spatial and temporal scales? What is the 3D structure of the reconnection region and how does this structure affect particle acceleration?



Granulation on the solar surface reveals Texas-sized convective cells produced by hot columns of rising gas. (left) The cells originate just below the visible photosphere and only last for about five minutes. The emergence of active regions disrupts this steady state and stores energy in the overlying atmosphere (center) Eventually this leads to dramatic energy releases from coronal loops in the form of flares and coronal mass ejections (right). Various acceleration mechanisms have been proposed to explain the highly efficient energy conversion in these eruptions, including strong electric fields induced by reconnection in current sheets.

RFA F.2: Understand the plasma processes that accelerate and transport particles.

High-energy particles accelerated at the Sun and within interplanetary space, as well as cosmic rays from outside the solar system, pose a serious hazard to the human and robotic exploration of our solar system. 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 are accelerated and how they are transported.

More than one mechanism can operate to produce a given energetic particle population at a given location and the nature of the seed population from which the accelerated particles are drawn is a critical part of the puzzle. Important processes for near-term investigation include quasi-static electric fields parallel to the background magnetic field, wave parallel electric fields, stochastic (Fermi) acceleration, and the drift of particles along a component of the electric field. such as occurs in shocks and the magnetotail. 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.

Energetic particles accelerated both at localized sites (solar flares, magnetotail reconnection sites, auroral acceleration regions), and globally (coronal and interplanetary shocks, corotating interaction regions and global merged interaction regions in the solar wind, and the termination shock) need to be understood. An understanding of the acceleration of thermal plasmas is also vital to meeting NASA objectives. For example, both the interaction of the Sun with planets and the transport of solar energetic particles are mediated by the solar wind. Successful progress on the understanding of solar wind acceleration will significantly improve the predictive capability for determining the severity of solar wind disturbances. The origin of the solar wind is not well understood and represents a large gap in our knowledge of fundamental processes.

RFA F.3: Understand the role of plasma and neutral interactions in the nonlinear coupling of regions throughout the solar system

Plasma populations are embedded in a background neutral gas throughout the solar system, from the solar transition region, to planetary upper atmospheres, to the heliosphere's interface with the interstellar medium. These populations transfer energy and momentum through multi-scale, nonlinear interactions which act to redistribute the bulk flows that, in turn, feed energy back into the original coupling system.

For example, the upper atmospheres of planets, including Earth, are dramatically affected by energetic inputs originating at the Sun in the form of photons, particles, and fields. However, there are many pathways by which that solar energy is transformed and redistributed throughout the atmosphere until the energy is ultimately re-radiated to space. Connected with these processes is much of the inherent variability of the atmosphere over daily to millennial time scales.

The lower atmosphere is periodically pumped and heated, giving rise to a spectrum of small-scale gravity waves and longer-period oscillations. These waves can propagate into the mesosphere and thermosphere depositing momentum. The atmospheric mean circulation is thereby modified, resulting in changes to the temperature structure and redistribution of radiation absorbers and emitters. The mean wind and temperature structures in turn influence the propagation of the waves and the manner in which they couple the lower and upper atmosphere. Similar processes are also key to understanding the upper atmosphere weather and climate on Mars and Venus.

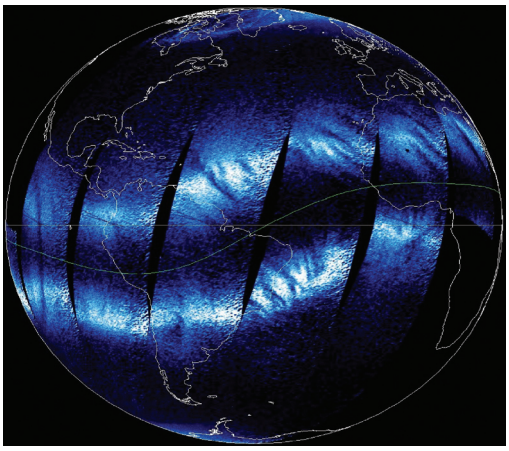


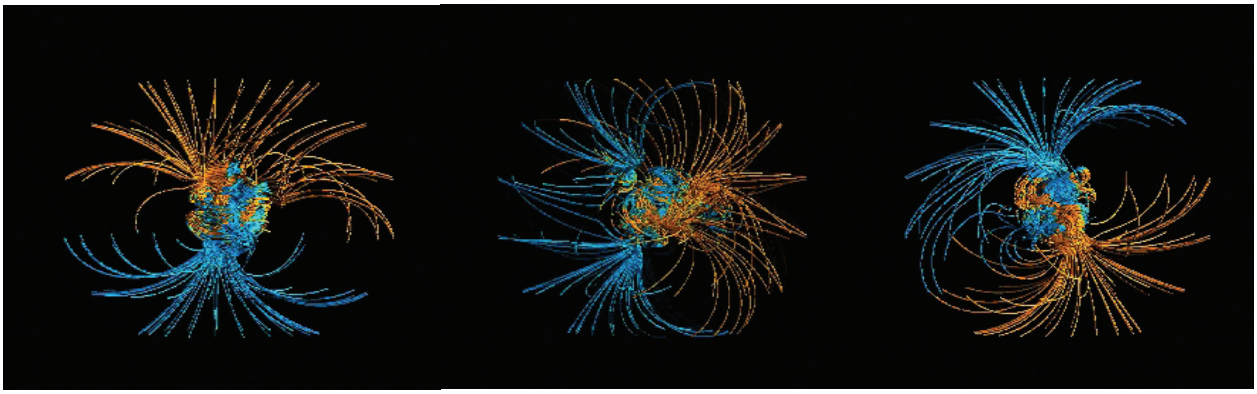
Image of electron density enhancements (equatorial arcs) in the Earth's ionosphere. The transport of plasma away from the equator results in alternating traveling bands of enhanced and depleted density. These exist during the daytime and most of the night and create enhanced media transmission errors in navigation and communication signals.

The ionospheric electron density distribution depends on thermospheric composition and winds, together with electric fields that can be generated within the ionosphere-thermosphere system or imposed from the magnetosphere. In turn, the ionospheric plasma can inhibit or accelerate thermospheric winds that produce electric fields via an electrodynamic interaction. The interactions and feedback mechanisms remain a mystery due to a lack of simultaneous measurements of all the parameters that describe the fully coupled system. These interactions can occur on a global scale, but can also produce mesoscale structures, such as high latitude thermospheric density cells that affect satellite orbits, or mid-latitude electron density enhancements that disrupt aircraft navigation systems being implemented by the FAA. In addition, smaller scale structures cause ionospheric irregularities that degrade communication system performance.

Turbulence is another example of a very important multi-scale, nonlinear process that transports particles and fields effectively, but is not well understood. Numerical simulations and laboratory experiments demonstrate that, in the presence of rotation or magnetic fields, turbulent motions create small-scale and large-scale dissipative structures.

In addition, electrodynamic and mass coupling along magnetic fields are fundamental physical processes that cut across many disciplines of space science. The interface between the heliosphere and the interstellar medium is a coupling region about which we are just beginning to learn.

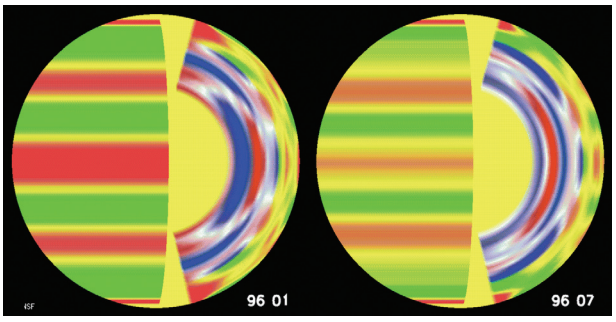
Finally, mass loading through ionization and charge exchange is a phenomenon of broad interest from planetary and cometary atmospheric erosion to energetic particle creation and loss.



Simulated reversal of Earth's magnetic field, with inward (blue) and outward (yellow) directed field lines. The location of the core-mantle boundary is evident where the structure becomes complex. We seek to understand the effects of such magnetic field variations on the formation and retention of planetary atmospheres. *Image credit: Gary Glatzmaier, Los Alamos National Laboratory*

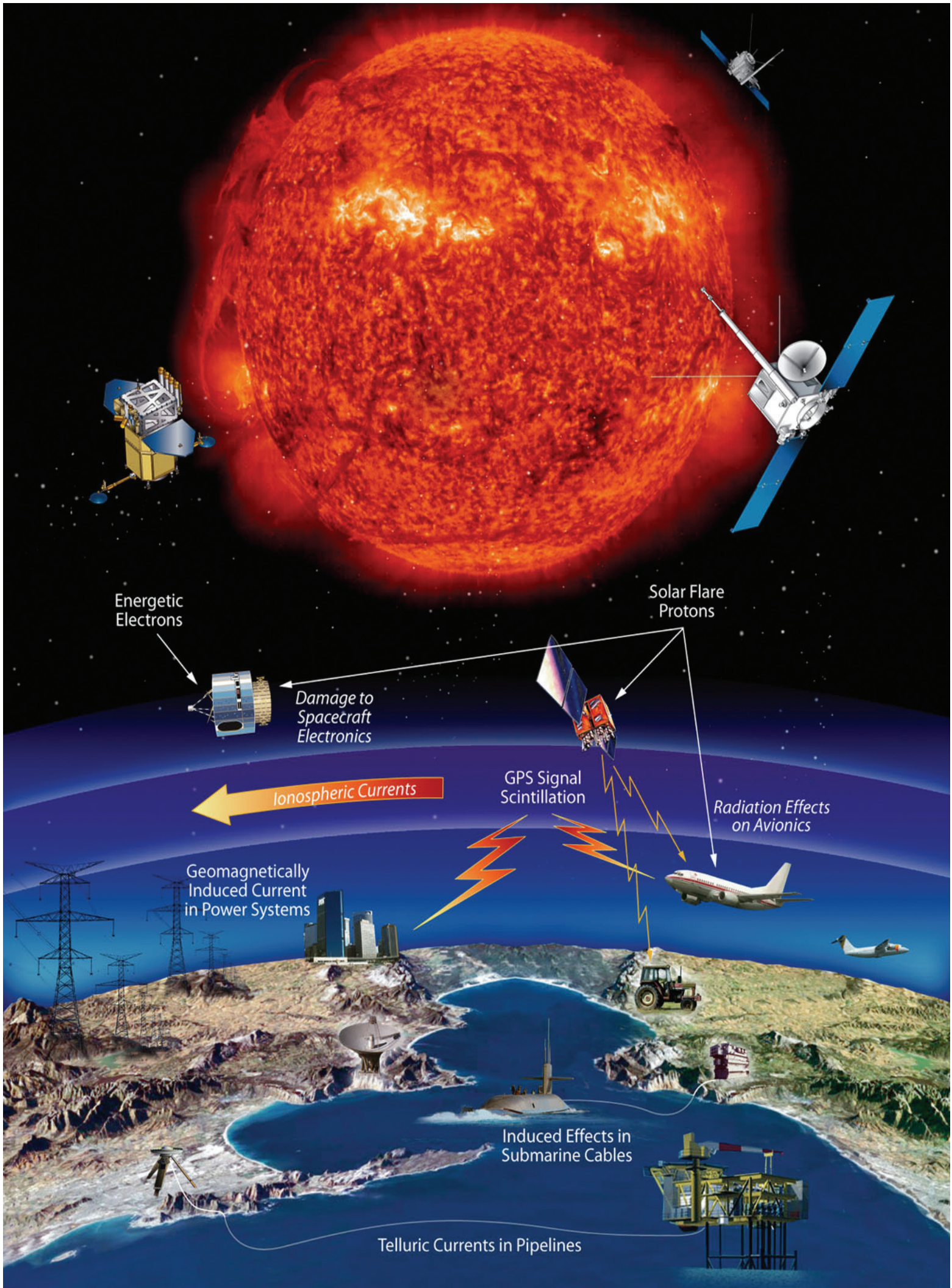
RFA F.4: Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

The Sun's variable magnetic field is the energy source for solar particle acceleration and its structure controls the entry of galactic cosmic rays into the solar system. Helioseismic data from SOHO and ground-based observatories have revolutionized dynamo theories by placing the main solar-cycle dynamo action at the base of the convection zone, in the rotationally sheared layer called the tachocline. Having the correct meridional circulation has proven to be a key ingredient for determining the length of the solar cycle. For the first time models can now use the meridional flow patterns from previous cycles to estimate the length of the next cycle. However, although these dynamo models can now forecast the cycle length, neither the amplitude nor details, such as whether the cycle will be double peaked, are within our predictive capability. For example, we do not know why the last two solar cycles have had relatively small maxima in the sunspot number. 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 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 abnormally reduced solar activity and concomitant affects on terrestrial climate and planetary habitability.



The figure shows the residual solar rotation speed after removing the average differential rotation. The cut-away shows the surface velocity on the left of the disk and a cross-section of the interior on the right. The two figures show how the rotational profile changes over six months.

Closer to home, reversals and other large variations of 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 – 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 planets to 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.

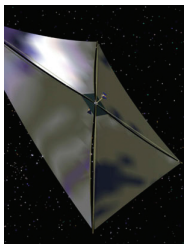

Energetic Electrons
Solar Flare Protons
Damage to Spacecraft Electronics
Ionospheric Currents
GPS Signal Scintillation
Radiation Effects on Avionics
Geomagnetically Induced Current in Power Systems
Induced Effects in Submarine Cables
Telluric Currents in Pipelines

Objective

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.

We do not live in isolation. Our past, present, and future are intimately coupled to the relationship between the Earth and Sun - and with the universe beyond. Increasingly we are sensitive to changing conditions on the Sun and in the space environment because of our technology; increasingly we have a practical interest in the habitability of planets and solar system bodies we plan to explore; and increasingly we recognize how astrophysical phenomena influence life and climate on our home planet. Variability in this environment affects the daily activities that sustain our society, including communication, navigation, and weather monitoring and prediction. We are living with a star.



To meet this objective, Heliophysics investigates the interaction of the space environment with Earth and its impact on us and on our home, either directly or by what can be learned about life on Earth by studying other environments in our solar system and beyond. This effort builds on the understanding of the fundamental physical processes addressed in Objective F. Our scientific goal is to understand the web of linked physical processes connecting Earth with the space environment. Our applied goal is to protect society and its technological infrastructure from space hazards and understand the external drivers of long-term climate change. We will improve technological efficiency of future operational systems by exploiting our understanding of Earth and its place in space. Human life and society provide the context for our investigations.

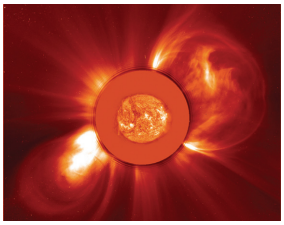
This context is not limiting. As we extend our presence throughout the solar system, we are interested in the planetary environments awaiting us and how the study of these environments can be applied to our home on Earth. Habitability, for humankind in particular, requires a rare convergence of many factors. These factors, especially the role of the Sun as a source of energy to planets and the role of magnetic fields in shielding planetary atmospheres, are a subject of immense importance. We understand some of the features contributing to make planets habitable, but key questions remain.

The interactive couplings of solar system processes, in the Sun and interplanetary space, with the interstellar medium, and throughout the near-Earth environment - require comprehensive study of these linked systems through a series of investigations covering these regions. Investigations of impacts on humankind must begin with the Sun, understand the cause of eruptive events and solar variability over multiple time scales, follow propagation and evolution of solar wind disturbances and acceleration and transport of energetic particles through the heliosphere to Earth, and finally investigate the interaction of solar radiative emission and the solar wind with Earth's coupled magnetosphere-ionosphere-atmosphere system.

Four Research Focus Areas (RFAs) have been formulated to understand: the Sun so we can predict solar variability and the evolution of solar disturbances as they propagate to the Earth; the response of the coupled ionosphere, thermosphere, magnetosphere plasma envi-

ronment and the impacts on society; the role of the Sun as the principal energy source in our atmosphere, including the impact of long-term solar variability on Earth's climate; and, in a broader context than just the Earth, the solar photon and particle impact on other solar system bodies and how stellar activity and magnetic fields affect the evolution of planetary habitability over time.

It is not enough to study just variability and change due to external drivers. Coupled systems also have complex internal forcing, e.g. gravity waves breaking in the upper atmosphere. The internal dynamics of the near-Earth coupled systems that protect us must be understood, even in the absence of solar variability. The program outlined below focuses on both internal linkages and external forcing mechanisms.



Solar Variability & Heliospheric Disturbances. RFA H.1 aims to understand the Sun, determine how predictable solar activity truly is, and develop the capability to forecast solar activity and the evolution of solar disturbances as they propagate to Earth. It focuses on both short-term and long-term variability. X-ray flares can immediately and severely degrade radio communications through ionospheric effects. Precursors to solar disturbances observable above and below the solar surface will initially serve as predictive tools for disruptive events. Coronal mass ejections that create large magnetic storms at Earth evolve significantly over their multi-day travel time to Earth. We will learn how disturbances initiate, propagate, and evolve from the Sun to Earth and incorporate this knowledge into a predictive model of geoeffectiveness at Earth to enable a warning and mitigation system for our technological assets. Solar energetic particle events can pose serious threats to technological assets and astronauts in near-Earth orbit; we will learn how particles are accelerated in the inner heliosphere and how they propagate. We must also understand the long-term changes in total and spectral irradiance and the solar cycle variations that have significant impacts on Earth's climate and human society.

Objective H: Understand the Nature of Our Home in Space

Priority Research Focus Areas & Associated Investigations

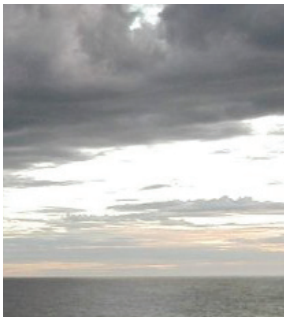
H1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment.
1. How do solar wind disturbances propagate and evolve from the Sun to Earth?
2. What are the precursors to solar disturbances?
3. Predict solar disturbances that impact Earth.

H2. Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.
1. What role does the electrodynamic coupling between the ionosphere and the magnetosphere play in determining the response of geospace to solar disturbances?
2. How do energetic particle spectra, magnetic and electric fields, and currents evolve in response to solar disturbances?
3. How do the coupled middle and upper atmosphere respond to external drivers and to each other?

H3. Understand the role of the Sun as an energy source to Earth's atmosphere and, in particular, the role of solar variability in driving change.
1. How do solar energetic particles influence the chemistry of the atmosphere, including ozone densities
2. What are the dynamical, chemical, and radiative processes that convert and redistribute solar energy and couple atmospheric regions?
3. How do long-term variations in solar energy output affect Earth's climate?

H4. Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.
1. What role do stellar plasmas and magnetic fields play in the formation of planetary systems?
2. What is the role of planetary magnetic fields for the development and sustenance of life?
3. What can the study of planetary interactions with the solar wind tell us about the evolution of planets and the implications of past and future magnetic field reversals at Earth?
4. How do local interstellar conditions influence the Solar System's space environment and what are the implications for the formation, evolution, and future of life in the solar system?

Variability in the magnetosphere, ionosphere, and upper atmosphere. RFA H.2 will develop understanding of the response of the near-Earth plasma regions (magnetosphere, ionosphere, and thermosphere) to space weather. This complex highly coupled system protects Earth from the worst solar disturbances, but it also redistributes energy and mass throughout. A key element involves distinguishing between the responses to external and internal drivers, as well as the impact of ordinary reconfigurations of environmental conditions, such as might be encountered when Earth crosses a magnetic sector boundary in the solar wind. This near-Earth region harbors space assets for communication, navigation, and remote sensing needs; even though conditions there can adversely affect their operation. Ground based systems, such as the power distribution grid, can also be affected by ionospheric and upper atmospheric changes. Investigations emphasize understanding the nature of the electrodynamic coupling throughout geospace (the near-Earth plasma environment), how geospace responds to external and internal drivers, and how the coupled middle and upper atmosphere respond to external forcings and how they interact with each other.



Solar Variability and Atmospheric Responses. RFA H.3 addresses the role of the Sun as the primary energy source for Earth's atmosphere. We seek to understand not only the atmospheric response to solar variability, but also the importance of steady-state processes in maintaining our atmosphere. It also considers long-term climatic impacts of solar variability on humankind. We need to understand the changing inputs - both spectral changes in the electromagnetic radiation and changing levels of energetic particles throughout the atmosphere. Two fundamental problems are first, delineating what processes convert and redistribute solar energy within the atmosphere and second, determining how this is accomplished. Other specific processes can have significant impact on Earth's atmosphere and climate and merit dedicated investigations. For example, the role of energetic particles from aurorae, the radiation belts, and solar flares on ozone chemistry in the upper atmosphere is not well understood. As another example, non-solar external processes, for example cloud nucleation from galactic cosmic rays, may affect Earth's climate but the details of this impact are uncertain.

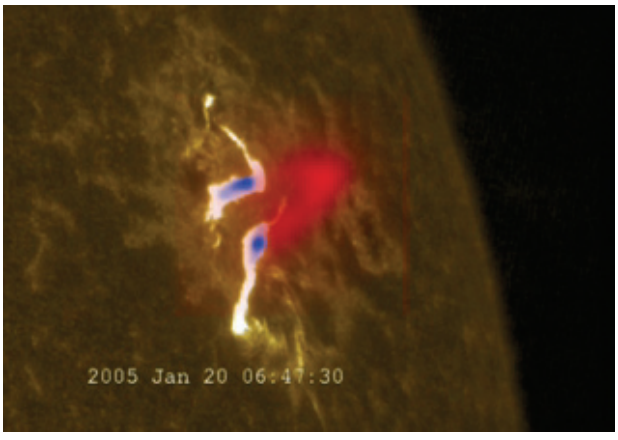
Stellar Variability and Magnetic Shielding. Other planets and other stars provide illuminating perspectives for understanding the Earth and Sun. RFA H.4 addresses the long-term impact of interactions of the solar wind with Earth, other solar system bodies, the local interstellar medium, and the study of activity on stars other than our Sun. We need to understand the role plasmas and magnetic fields play in planetary formation and in the evolution of planetary atmospheres because this relates to the ultimate habitability of planets. A particular goal is to understand the importance of planetary magnetic fields for the development and sustenance of life.

The interaction between the solar wind and the interstellar medium has created boundaries that shield us from most of the hazardous galactic cosmic radiation. The properties of the local interstellar medium and of the solar wind change over the course of time. How do these changes affect the biospheres of planets like Earth? Observing activity on other stars will tell us how conditions change with time. One applied investigation that stems from these studies is to determine the implications of past and future magnetic field reversals at Earth. Such investigations provide important opportunities for linkages with other NASA fields of study.

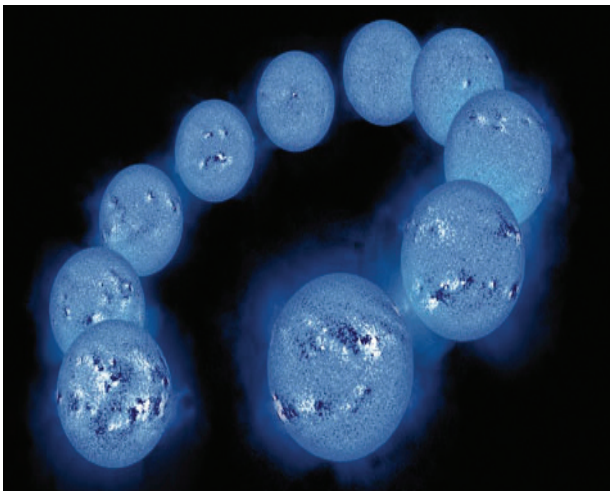
RFA H.1: Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment

The climate and space environment of Earth are primarily determined by the impact of plasma, particle, and electromagnetic radiation outputs from the Sun. The solar output varies on many time scales: from explosive reconnection, to convective turn over, to solar rotation, to the 22-year solar magnetic cycle, and even longer, irregular fluctuations, such as the Maunder minimum. The variability is linked to the emergence of magnetic field from below the photosphere, its transport and destruction on the solar surface, and the eruption into the heliosphere of energy stored in the atmosphere as flares and coronal mass ejections. The large-scale heliosphere also modulates the propagation of incoming galactic cosmic rays. Longer-term changes that can affect Earth's climate include solar total and spectral irradiance.

The solar wind, embedded disturbances, and energetic particle populations evolve as they travel through the heliosphere. Shocks accelerate particles and interact with other irregularities. CME's can even interact with each other. Current observations generally depend only on near-Sun and 1 AU observations. 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.



RHESSI data overlaid on a TRACE image shows gamma-rays (blue) and X-rays (red) thrown off by the hottest part of the 20 January 2005 flare. The gamma rays are made by energetic protons at the Sun.



Sunspots and their associated magnetic fields follow an 11-year activity cycle. This composite image shows ten magnetic maps of the Sun observed approximately one year apart, from one maximum of activity almost to the next. As activity fades, the large regions disappear and only small ones generated near the surface continue to emerge, creating a salt-and-pepper pattern of ephemeral magnetic regions that persists through time. As the next cycle of activity picks up, the magnetic polarities of the active regions that emerge from deep inside the Sun are reversed. This means that although the sunspot number and the coronal activity have an eleven-year cycle, the full magnetic cycle is actually twenty-two years. *Images: Kitt Peak telescope of the National Solar Observatory.*

Precursors will provide useful information about solar and interplanetary events; however more complete predictive models based on physical principles are required. Like terrestrial weather, it is not yet clear how long in advance solar activity is predictable. Improved continuous observations of the solar vector magnetic field and high-resolution observations of the atmosphere are as critical for resolving this question as helioseismology is for revealing the subsurface conditions.

RFA H.2: Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

The near-Earth space environment, geospace, is unique in the solar system and central to the protection of Earth and its inhabitants. This region includes the magnetosphere, ionosphere, and thermosphere (MIT) bound together as a tightly coupled system that interacts with the neutral atmosphere below and the Sun and heliosphere above. The variability within geospace and the nearby interplanetary environment is our local space weather. Much of space weather is driven by the external processes discussed in the previous section. In addition, internal drivers of the MIT region, such as the upward propagation of gravity waves, greenhouse gases generated in the troposphere, wave-particle interactions, and auroral current systems, are equally important and must be investigated. The consequences of internal drivers include both the natural variability of the MIT system and anthropogenic effects.

Geospace is also the location of most of our space activities. Communication, navigation, Earth weather and remote sensing, emergency location, defense reconnaissance, and NASA missions are all affected by space weather. Space weather also causes disturbances of electric power grids and sensitive electronic systems on the ground. The technological systems sensitive to disturbances in geospace are increasing in importance and urgency to human society.

The electromagnetic, dynamical, and aeronomic processes that couple the inner and outer regimes of geospace remain unresolved. The exchange of mass and energy between these regions during both quiescent conditions and disturbed times must be understood before predictive capabilities, or strategies to mitigate adverse space weather effects, can be developed. Energetic solar and magnetospheric particles penetrate below the MIT domain into the middle and lower atmosphere, and establish the need to better understand the chemical and dynamical effects on the whole atmosphere.

Noctilucent clouds, also known as polar mesospheric clouds, are rare, bright cloud-like atmospheric phenomena visible in a deep twilight. Most commonly observed in the summer months at latitudes between 50° and 60°, they are the highest clouds in the Earth's atmosphere, being located in the mesosphere at altitudes of around 85 kilometers. They are visible only when illuminated by sunlight from below the horizon while lower layers of the atmosphere are in the Earth's shadow; otherwise they are too faint to be seen.

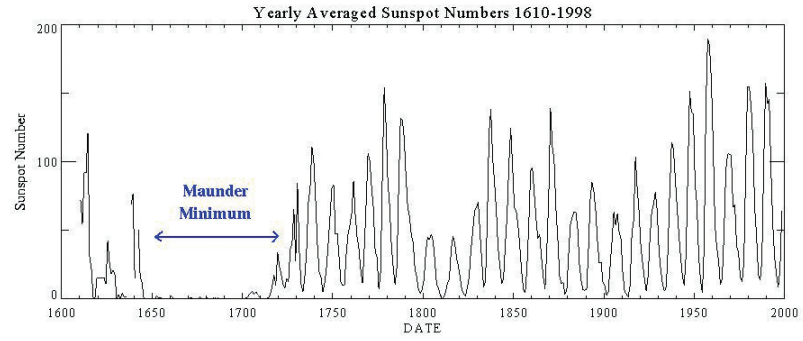
These clouds are not well understood. In most meteorological concepts, clouds generally can not reach such great altitudes, especially at such low air pressures. It was once proposed that they were composed of volcanic or meteoric dust, but they are now known to be primarily composed of water ice. They appear to be a relatively recent phenomenon - they were first reported in 1885, shortly after the eruption of Krakatoa - and it has been suggested that they may be related to climate change. Recent evidence also suggests that many noctilucent clouds today are created by water exhaust from manned spaceflight, such as the Space Shuttle.

Noctilucent clouds can be studied from the ground, from space, and by sounding rockets, but they are too high to be reached by weather balloons. The AIM Explorer satellite, scheduled for launch in 2006, is dedicated to research into noctilucent clouds.

RFA H.3: Understand the role of the Sun as an energy source to Earth's atmosphere and, in particular, the role of solar variability in driving change.

Solar energy in the form of photons and particles drives the chemical and physical structure of Earth's atmosphere. For example, ultraviolet and even more energetic 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 world wide effect due to dynamical processes that transport energy around the globe. 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 energy may be transported to lower altitudes where it can destroy ozone. The ionosphere-thermosphere plays an equally important role in protecting life on Earth, since it is the atmosphere's shield against solar EUV radiation.

Because life depends on the atmosphere and its climate, study of solar energy driven atmospheric variations is critically important. Solar energy and its changes have effects throughout the atmosphere including the troposphere where humans live. 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 deposition measurements of the atmospheric response, as well as theory and modeling of dynamical processes that distribute effects of solar energy.

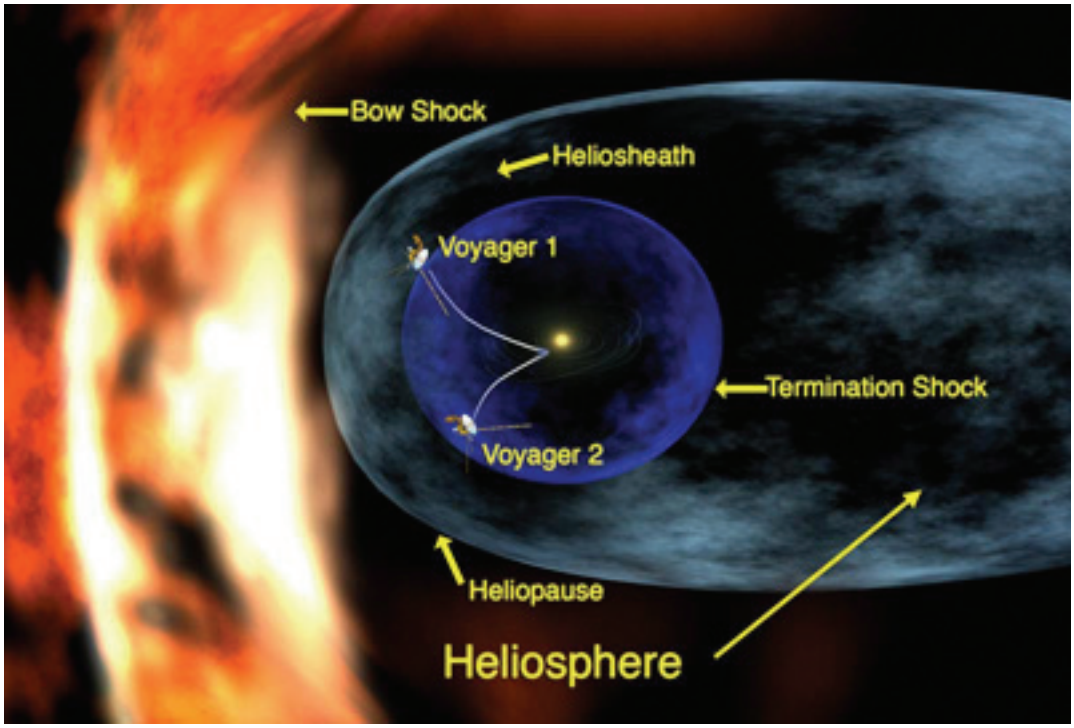


The solar surface varies fairly regularly, with an average period of 11-years. However, if we look at the variation of the sunspot number with time, we find that for a period of about 70 years, from A.D. 1645 to 1715, practically no sunspots were observed. In other words, during this time the solar cycle was interrupted. This period of time is called the Maunder Minimum. It is one of several such intervals revealed in cosmic ray records. Other sun-like stars appear to have similar cycles.

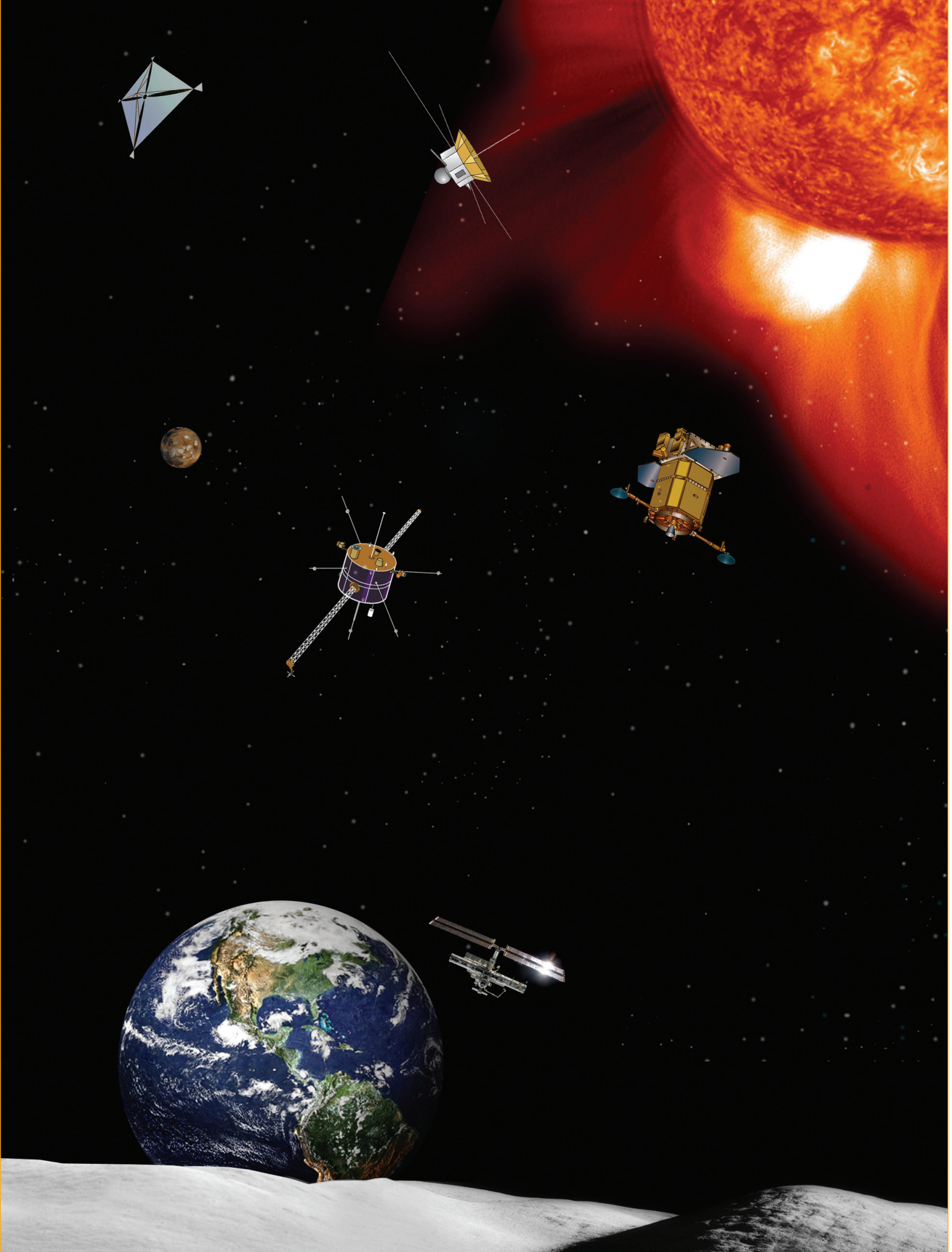
The Maunder minimum also coincided in time with an period of very cold weather in Western Europe (and perhaps all over the world). This era is often called the "Little Ice Age". During this time it got so cold that rivers and lakes that were normally ice-free froze over and the snow did not melt all year round even at low latitudes. In the middle of the 17th century temperatures dropped so low that the Baltic sea and the Thames River froze over regularly. The ice on the Thames in London was so thick that people organized winter festivals with skating parties and carnivals on the river. One of these festivals on the Thames was painted by the Dutch painter Abraham Hondius in December 1676.

RFA H.4: Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.

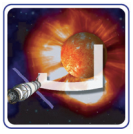
Plasmas and their embedded magnetic fields affect the formation, evolution and destiny of planets and planetary systems. The heliosphere shields the solar system from galactic cosmic radiation. Our habitable planet is shielded by its magnetic field, protecting it from solar and cosmic particle radiation 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 local interstellar medium (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 ultraviolet 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.



On May 24, 2005 NASA's Voyager 1 spacecraft had traveled far enough outward through our Solar System that it reached the heliosheath. This is an area just past the termination shock region, where the solar wind crashes into the thin interstellar gas of the galaxy.



Objective



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.

Harsh conditions in the space environment pose significant risks for the journey of exploration. Like seafaring voyagers, space explorers must be constantly aware of the current space weather and be prepared to handle the most extreme conditions that might be encountered. The important considerations include sudden changes in energetic particle and electromagnetic radiation, encounters with plasmas that cause spacecraft charging and discharging, and the uncertain response of neutral atmospheres to variable energy inputs.

The first step toward safeguarding astronauts and robotic assets in space is to characterize the extremes and ranges of variability that can occur in the space environment to help establish appropriate design requirements for vehicles, electronics, and habitats. This requires not only measurements in various locations at different times, but also an understanding of the physical processes that both cause temporal fluctuations and limit the range of responses of the system to those inputs.

The next milestone requires the ability to determine current conditions in key locations from an affordable set of available measurements – nowcasting of the space environment. This provides the critical operational knowledge that productive work can safely be undertaken at the time. The set of observations must be carefully chosen and the physical system must be modeled well enough to give confidence that the results can be extrapolated to the relevant locations.

Humans will work with robots and vehicles on Mars. Safe and productive expedition activity will depend on accurate forecasting of surface and space weather conditions in order to mitigate risks but avoid false alarms.

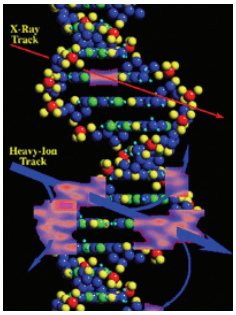
Finally, we must develop the capability to forecast the dynamic conditions in space. Forecasting quiet times may be as useful as forecasting disturbances. Initial reliance on empirical relationships will give way to high-fidelity physics. As our understanding of the fundamental processes improves, through comparison of predictive models with actual events, we will gradually improve the accuracy and extend the range of our predictions, and provide key support to implementing the Vision for Space Exploration. As with terrestrial weather in the past several decades, progress will be made, but it will be difficult because the systems are more diverse, the measurements are more sparse, and the physics is more complex.

These steps are not necessarily sequential and some capability already exists in each area. One of the first major challenges is to determine more precisely what capabilities are needed and when. Our Objective J focuses on the science necessary to ensure safety and maximize productivity of both human and robotic space explorers. This objective includes both near-Earth and planetary environments, especially as they affect the robotic and technological systems that support human space flight. Benefits of addressing these issues include the optimization of spacecraft and in-

strument design, improved planning of mission and operations scenarios, ensuring the safety and maximizing the success and productivity of both robotic and human exploration.

Though much of the dramatic variability in the space environment is driven by solar activity, such as flares and coronal mass ejections or energetic particles accelerated by shocks in the heliosphere, understanding the more routine variations driven by rotation or slowly evolving structures is also important. For example the changing density of the Martian upper atmosphere depends on many uncertain factors in addition to solar activity. The underlying thread that links all three of the Heliophysics roadmap objectives is working to achieve a detailed understanding of the basic physical processes required to enable prediction. While Objective H focuses on the science needed to understand the processes in the near-Earth space environment that affect life and society, Objective J emphasizes understanding the variability of the space environment and its potential hazards with the purpose of enabling and securing human and robotic space travel across the inner solar system.

Objective J is divided into four priority Research Focus Areas (RFAs). The first aims to adequately characterize the important environments. The second and third build on the first and focus on developing the capability to predict solar activity and understand the propagation and evolution of consequential events in the inner heliosphere. The final RFA targets the environmental variability at planets (Earth and Mars) that impact exploration activities.



Characterization of Space Environments. RFA J.1 focuses on determining the full range of extreme conditions that may occur in the inhospitable environments that human and robotic explorers will encounter. Learning these limits takes more than just observational surveys; it requires basic understanding of the dynamics of each space environment. This entails developing an understanding of the internal mechanisms, the critical boundary conditions, and the exter-

Objective J: Safeguard the Journey of Exploration

Priority Research Focus Areas & Associated Investigations

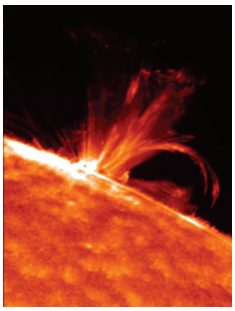
J1. Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.
1. What are the variability and extremes of the radiation and space environment that will be encountered by future human and robotic explorers, both in space and on the surface of target bodies?
2. How does the radiation environment vary as a function of time and position, and how should it be sampled to provide situational awareness for future human explorers?
3. What is the relative contribution to the space radiation environment from solar energetic particles and galactic cosmic rays and how does this balance vary in time?

J2. Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.
1. What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?
2. What heliospheric observations, and empirical models are needed to enhance the predictive capability required by future human and robotic explorers?

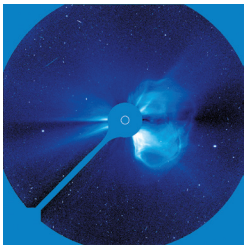
J3. Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.
1. How are solar energetic particles created and how do they evolve from their coronal source regions into interplanetary space?
2. How do solar magnetic fields and solar wind plasma connect to the inner heliosphere and what is the nature of the near-Sun solar wind through which solar disturbances propagate?
3. How are energetic particles modulated by large-scale structures in the heliosphere and what determines the variations in the observed particle fluxes?

J4. Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.
1. To what extent does the hazardous near-Earth radiation environment impact human and robotic explorer's safety and productivity?
2. What level of characterization and understanding of the dynamics of the atmosphere is necessary to ensure safe aerobraking, aerocapture and EDL operations at Mars?
3. To what extent do ionospheric instability, seasonal and solar induced variability affect communication system requirements and operation at Earth and Mars?
4. What are the effects of energetic particle radiation on the chemistry and the energy balance of the Martian atmosphere?
5. What are the dominant mechanisms of dust charging and transport on the Moon and Mars that impact human and robotic safety and productivity?

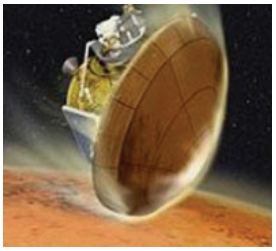
nal drivers – the sources of external variability at the Sun and the interplanetary medium that modulates its extremes. This knowledge feeds into the design of exploration activities and equipment. Practical understanding of the physical conditions and processes that modulate various space environments will lead to a capability to nowcast and forecast both benign and hazardous intervals.



Prediction of Hazardous Solar Activity. RFA J.2 aims to develop the capability to forecast solar activity and the onset of the solar disturbances that are sources of potentially hazardous space weather. Successful prediction begins with reliable characterization of impulsive solar disturbances and their global effects on the corona and solar wind through which they propagate. Presently solar flares and CME's are little more predictable than earthquakes or volcanic eruptions. Complex active regions and other features with high potential for eruption can be identified on the visible solar disk and, absent such regions, it is quite feasible to announce "all clear" periods, when sensitive activities can be safely accomplished. However, during most of the 11-year solar activity cycle, when active regions are almost continuously present or could emerge at any time, even short-term forecasting is unreliable with our current level of knowledge. On longer time scales, we need to develop the ability to predict when and where active regions will arise, when the magnetic field will become unstable, and what the heliospheric consequences will be. This requires spacecraft observations of the entire solar surface both to follow the evolution of active regions over the full solar disk and to observe complex active regions that may be magnetically connected to human or robotic explorers far from Earth.



Propagation to Explorers. RFA J.3 entails development of an understanding of coronal and heliospheric acceleration mechanisms, the propagation of solar disturbances, and local acceleration of particles by plasma interactions in the disturbed solar wind. All are needed for a practical predictive understanding of these events. Disturbances interact with the solar wind. Particles and fields can be swept up and shocks associated with CME's can accelerate particles to dangerous energies. We need to develop observational and modeling tools to more accurately predict the arrival times, durations, and severity of solar energetic particle impacts. In addition, exposure to high-energy galactic cosmic rays accumulates over long intervals to dangerous doses. Cosmic rays are modulated by the large-scale field and diverted by disturbances in the outer heliosphere, so they are of less concern during intervals of high solar activity.



Space Weather Effects on Planets. Hazards in planetary environments must also be understood, characterized, and mitigated. RFA J.4 targets how space weather impacts planetary environments in ways that affect exploration activities, such as spacecraft staging in low Earth orbit, or entry, descent, and landing (EDL) at Earth and Mars. Reliable communications and navigation for spacecraft and surface crews will require improved understanding of terrestrial and martian ionospheres. While the Sun and its variability drive these environments, many internal processes must also be understood. Planetary space weather develops through the interaction of the solar wind with the planetary magnetic fields and plasmas, the interaction of solar photons with plasma and neutral gas populations, interactions with the lower atmosphere, and via internal processes such as dynamos, wave interactions, magnetic reconnection, electric fields, transport, and chemistry. Because geospace is the site of initial staging activities and transport of human and robotic explorers, as well as their return to Earth, understanding this environment is particularly important.

RFA J.1: Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

Mitigating future risks to long-duration space flight requires knowledge of two elements for operational planning: the anticipated background environment and the worst-case transient event environment. The primary goal of space environment characterization is to establish the range of variability both for system design purposes as well as to develop and refine comprehensive models for predictive capabilities. This characterization must be conducted over a sufficiently long time frame. We also need to be able to nowcast the space environment in real time, so astronaut explorers can react to current conditions.

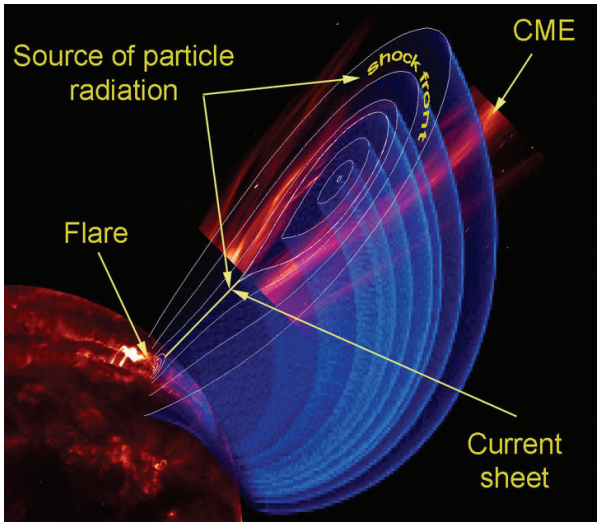
Energetic particles from the Sun generally propagate along the spiral magnetic field embedded in the solar wind. However, CMEs routinely disrupt the field lines and solar wind flow. Further complicating our understanding of this relatively straightforward view are recent observations of significantly elevated proton levels without any activity observed on the Earth-facing side of Sun. Activity on the far side of Sun can have effects throughout the inner heliosphere. Future spacecraft in transit to Mars will endure a 6-9 month cruise phases far from either Earth or Mars, requiring them to have their own support, characterization, and forecasting capability at their own, remote location, independent of Earth-local forecasting. Measurements from a wide range of heliospheric longitudes will be required to accurately characterize, and ultimately predict the conditions throughout this region of the inner solar system.

Understanding the near-Sun source region of the space environment is ultimately required to provide the boundary conditions to enable accurate predictive modeling. This region produces solar energetic particles with energies as high as 1 GeV/nucleon. Above 15 solar radii, the solar wind speed is higher than any of the embedded wave speeds, so it is not possible to extrapolate back from *in situ* measurements made outside this region to determine the physical mechanisms at work there. A near-Sun mission is the only way to provide the direct observations necessary to understand the physics of this critical region.

The continuous galactic cosmic ray background radiation is modulated by the heliosphere. Progress in understanding the modulation requires measurements far from the ecliptic plane and from the inner and outer reaches of the heliosphere.

Because the near-Earth geospace region is the launch and staging point for outbound missions, the landing point for return missions, and the site of much of our space-based communications and logistical infrastructure, characterizing the variability of extremes of the hazardous radiation environment within the Earth's magnetosphere is critically important for safeguarding exploration activities. For example, we are currently unable to distinguish among a growing number of theories relating to the function and evolution of new radiation belts, how energetic and hazardous they can become, or the relative importance of several particle acceleration and loss mechanisms.

After a day on the lunar surface, Apollo 17 astronaut Gene Cernan communicates with ground controllers from inside the lunar module Challenger. Note the condition of his spacesuit and the smudges of dust on his face. *Photo credit: Jack Schmitt.*



One of the most difficult problems in space weather is the prediction of solar energetic particles. These relatively rare events travel from the Sun to Earth in about an hour, giving astronauts and spacecraft operators little time to prepare. New theoretical models are providing information about the precise source region of the energetic particles. Instead of blasting outward from the flare itself, many of these particles may arise in a thin electrified sheet of gas that stretches from the flare site to the base of the coronal mass ejection. This current sheet acts much as a particle accelerator, pushing atomic particles to almost the speed of light.

RFA J.2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

The energetic particles in impulsive solar particle events produced near the Sun by flares or by coronal mass ejections in the low corona have 1 AU transit times of minutes to hours, whereas the gradual events associated with interplanetary CME shocks arrive hours or days later. Coronagraph observations of a CME leaving the Sun may give 1-2 days warning of the gradual events. To give warning of the near-relativistic impulsive events or to increase the warning time of CMEs and gradual events will require the capability to forecast the origin and onset of solar activity and disturbances from observations of the Sun itself. Successful forecasting of space weather depends on knowledge of solar disturbances as well as the global corona and solar wind through which they propagate. This RFA focuses on the onset of solar activity; the next RFA focuses on the propagation of the solar disturbances.

We already have some empirical understanding of the regions that generate solar activity: large, complex active regions are likely to produce flares and CMEs. Both CMEs and flares are driven by magnetic energy release, but neither the stabilizing mechanism allowing energy to accumulate, nor the release processes are understood well enough to predict eruption reliably. At present, the best indicators of oncoming geoeffective coronal disturbances are morphological. New physical diagnostic measurements in the photosphere, sub-photosphere, and solar atmosphere may hold the key to more reliable prediction. We need to develop the ability to predict the evolution of active regions and CME-producing regions from observations of the solar and corona magnetic fields. We need to understand how changes in the magnetic configurations lead to flares and CMEs.

Another critical need for exploration will be the capability of predicting “all clear” periods when extravehicular activities (EVAs) can be safely accomplished. This will require spacecraft observations of the entire solar surface, both to follow the evolution of active regions that are otherwise hidden on the back side of Sun and to observe complex active regions that may be magnetically connected to human or robotic explorers far from the Earth-Sun line. On a longer time scale, we need to develop the ability to predict when and where active regions will arise. This will require development of helioseismology techniques and also observation of the Sun from multiple view points. Research focus areas from Objective F provide the foundation for understanding the fundamental processes related to long term variations in solar activity.

In order to develop the methodology and tools required during the first human exploration operations on the Moon, presently scheduled near the solar maximum of 2020, these investigations need to begin at or just after the time of the next solar maximum (2011-2015).

RFA J.3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

Predicting the heliospheric radiation environment requires an understanding of how solar energetic particles (SEPs) are produced, how solar disturbances evolve as they propagate outward, and how solar disturbances modulate galactic cosmic rays. The investigations described below, along with the fundamental physical understanding provided by the Objective F investigations, are the necessary steps required for transitioning to predictive understanding.

Solar energetic particles can be grouped into two classes: impulsive events and gradual events. Impulsive events are associated with flares or current sheets in CMEs. Gradual events are associated with CME shocks and some are produced farther out in the heliosphere by corotating interaction regions (CIRs). Gradual events produce greater risks to explorers because they extend tens of degrees in latitude and longitude and can last for days as a disturbance propagates through the interplanetary medium. We must characterize the coronal and interplanetary SEP source regions and the properties of the resulting SEPs in order to understand the important factors that determine their composition, flux, energy spectrum, and duration. *In situ* measurements within 0.3 AU are needed in order to characterize the particles before they are scattered in the interplanetary medium.

The evolution of solar disturbances depends on the pre-existing state of the solar wind and the background magnetic fields through which they propagate. Knowledge of the bulk properties of the solar wind is important for determining the strengths of shocks involved in energetic particle acceleration. On smaller spatial scales, wave turbulence processes play a role in particle heating and acceleration. Remote sensing measurements, both spectroscopic and imaging, can tell us much about the region nearest the Sun. However, the regions of the outer corona that provide the interface between the inner corona and the heliosphere (solar wind) are best studied with direct *in situ* measurements. *In situ* measurements taken more than about 0.1 AU from the Sun cannot be extrapolated back to determine the physical mechanisms at work in the coronal source regions. Understanding the physics of these critical regions is necessary to predict the radiation environment throughout the solar system.

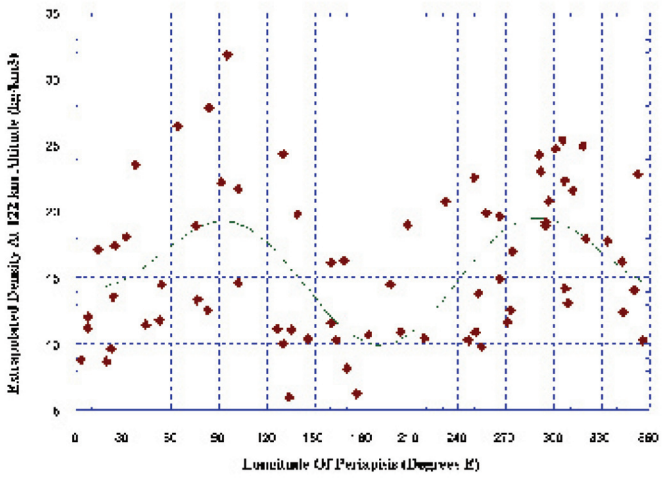
Galactic cosmic rays (GCRs) and other energetic particles are affected by disturbances in the heliosphere. The outer heliosphere shields us from much of the nearly continuous GCR flux, as much as 90% at 100 MeV/nucleon. The remaining flux is modulated by variations in heliospheric structure over the solar cycle and by sporadic events such as coronal mass ejections. Near Earth substantial variability (factors of up to 10 over the solar cycle) is observed in the differential fluxes of GCRs with energies below several hundred MeV/nucleon. The modulation is not completely understood. Global measurements of the heliospheric structure with concurrent measurements of *in situ* energetic particle fluxes are needed. In particular, missions that travel outside of the ecliptic plane and to the inner and outer reaches of the heliosphere provide essential boundary conditions necessary to constrain models.

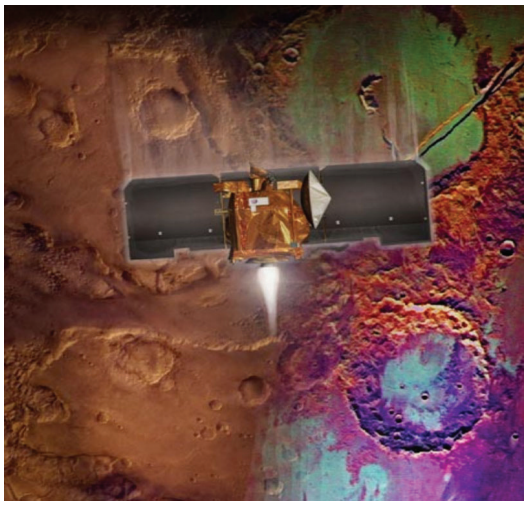
Martian Sunset

RFA J.4: Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

Human and robotic exploration of our solar system will necessarily be influenced by the planetary environments encountered. Both the plasma and neutral atmospheres of the planets, including Earth and Mars, impact exploration activities. Surface-to-orbit and surface-to-surface communications are sensitive to space plasma variability. Spacecraft control in low orbits and aerobraking parking orbits depend on the upper atmospheric density. Asset staging and operations, as well as astronaut health and safety, are impacted by planetary radiation environments. The radiation environment at the Moon varies as it traverses in and out of the Earth's magnetosphere. The plasma and ultraviolet radiation environment at the Moon's surface contributes to recognized problems with lunar dust.

Planetary environmental conditions develop through the interaction of the solar wind with the planetary magnetic fields and plasmas as well as through the interaction of solar photons with plasma and neutral populations and with the atmosphere below. To understand the planetary conditions essential for exploration, scientific investigations target the "near-planet" environments of the Earth and other planetary systems. Because initial staging activities and transit of human and robotic explorers will occur in geospace, including at the Moon, understanding of this environment is particularly important. Furthermore, near-Earth characterization and understanding provides an essential baseline for modeling the impact of space weather in other planetary environments. As exploration proceeds at other planets, our understanding of the near-Earth environment will guide the development of follow-on planetary missions. In addition, comparison with other planetary environments will inform our understanding of our home planet. Understanding and characterizing the effects of near planet interactions and environments is essential to maximize the safety, productivity, and risk mitigation of hazardous conditions for exploration activities. A human mission to Mars will require some combination of both orbiting and landing crews. Improved knowledge of the Mars atmosphere for aerocapture, entry, descent, and landing and improved knowledge of densities in the aerobraking regime (90 - 170 km), and





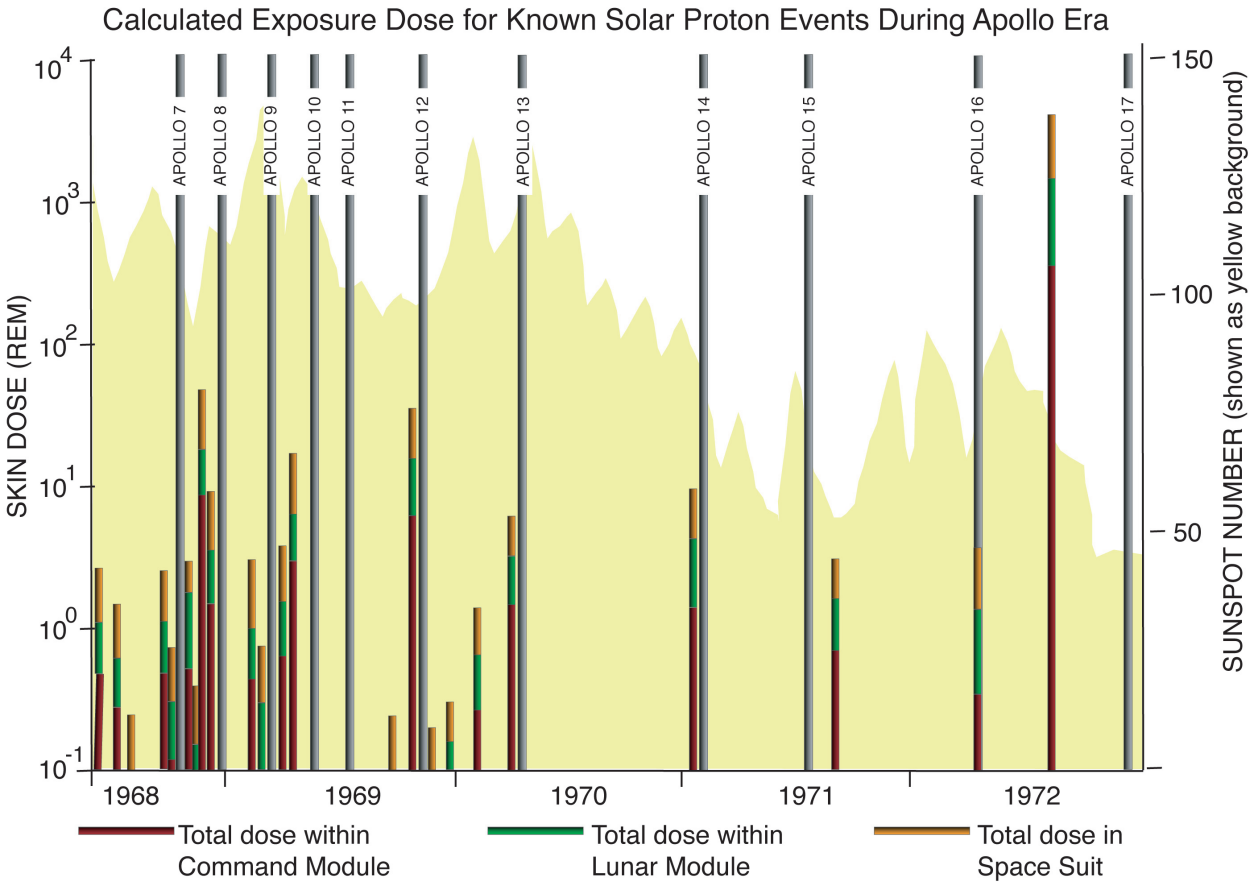
The atmospheric density encountered by the Mars Global Surveyor mission during its aerobraking phase. The density varied by an order of magnitude relative to the predictions, illustrating why current atmospheric prediction science makes for a very tricky implementation of aerobraking and aerocapture. MGS required far more thruster operation than anticipated as a result of this uncertainty in atmospheric drag, and may have suffered minor damage to appendages. Human landings on Mars will require significantly better knowledge of its atmospheric structure and dynamics to minimize fuel consumption while assuring safety.

in a possible low-altitude (200-300 km) station orbit are all required for safe operation of spacecraft.

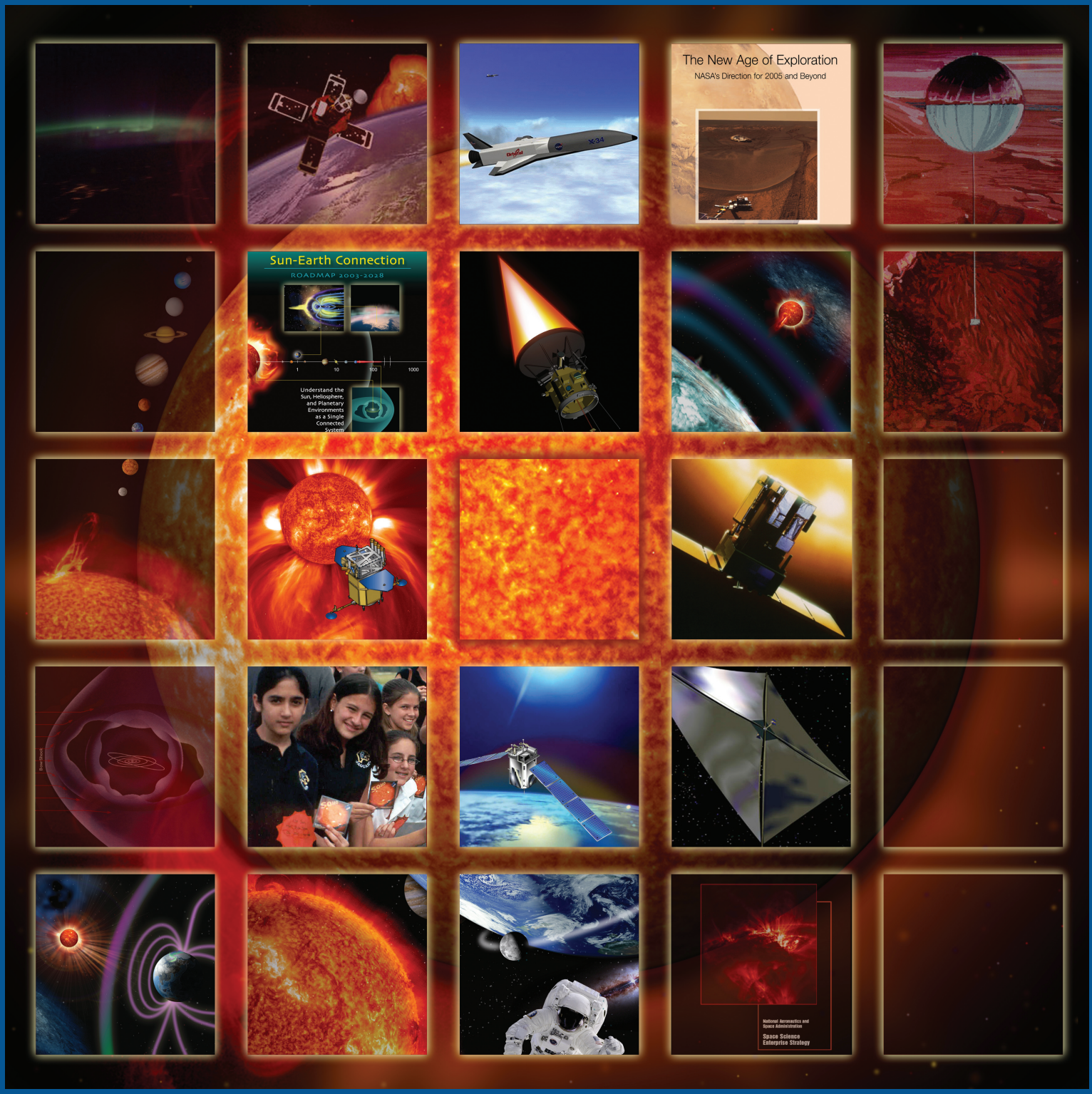
Reliable communications and navigation between orbiting and surface crews, and with Earth, are essential, requiring improved understanding of the Martian ionosphere. Neutral density variability at aerobraking altitudes is predominantly controlled by dynamical influences from below and can be addressed by extending the same basic connections and measurements to higher altitudes.

Orbiting crews may be affected by various space weather effects involving interaction between the solar wind and the partially-magnetized ionosphere and exosphere of Mars. For example, energetic particle events are of concern for astronaut safety, and the variability of radiation dosage when at the surface is poorly constrained.

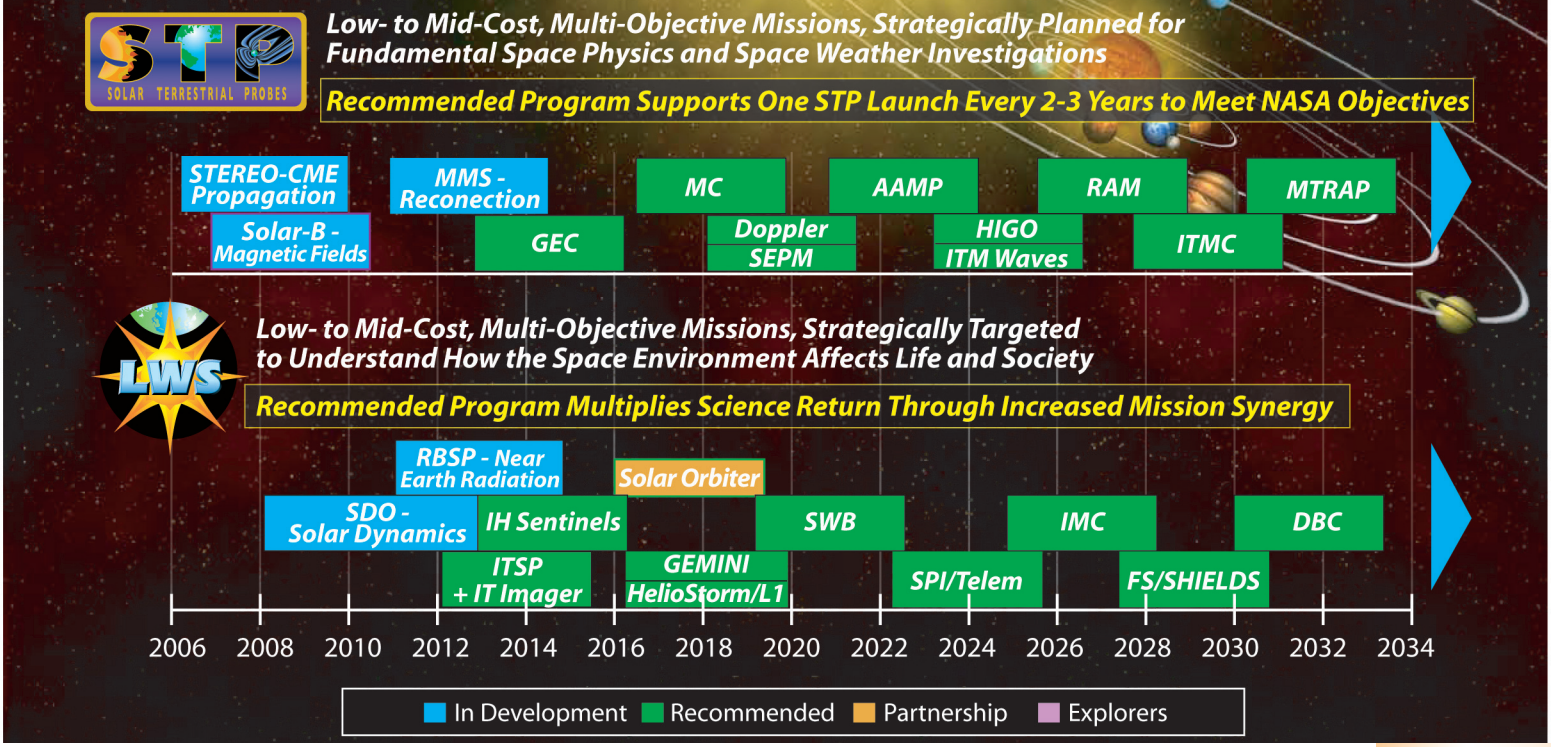
The lunar surface that is encountered by the human and robotic explorers contains fine dust grains. Due to the lack of any appreciable atmosphere, the grains are exposed to a plasma and solar ultraviolet radiation environment. This creates a known problem of dust grain adhesion on astronaut suits and instrumentation that is not fully understood or resolved.

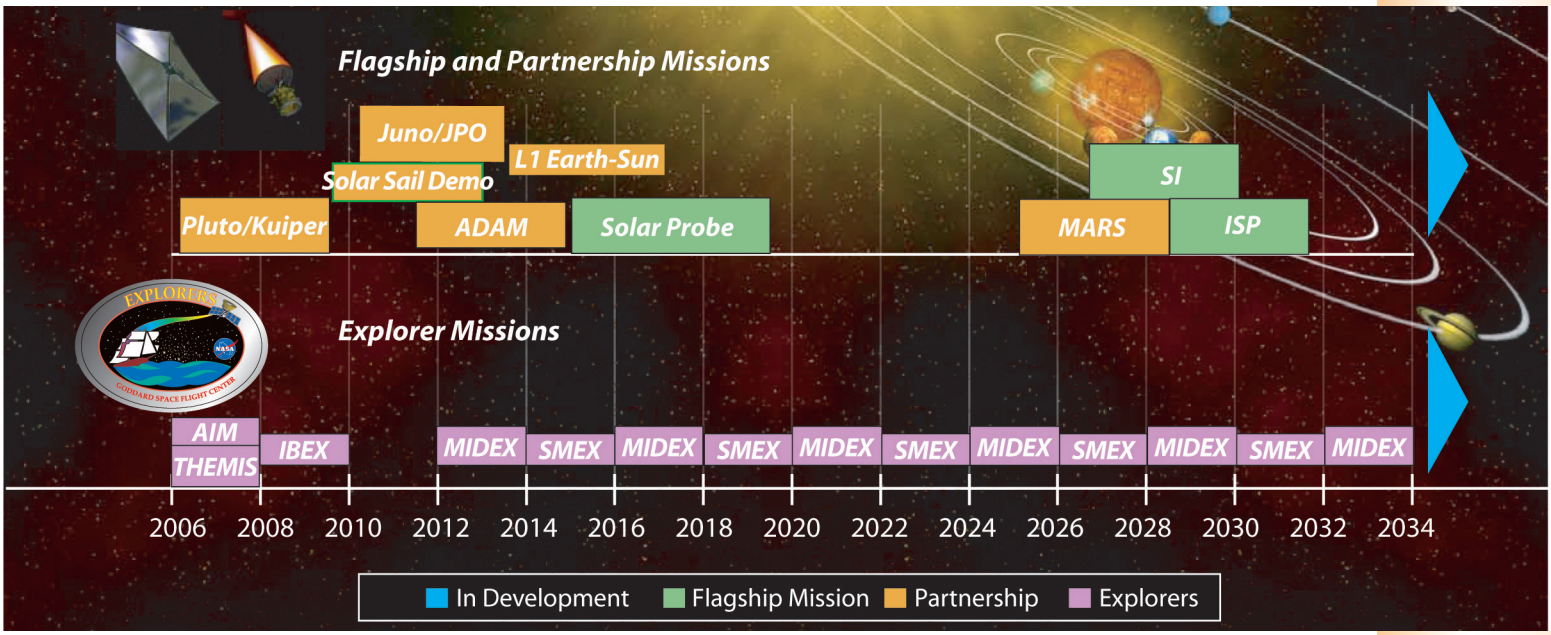


The radiation dose to astronauts during the Apollo era missions is plotted with the sunspot count. This plot graphically highlights the profound difference between short Apollo-like expeditions to the Moon and the longer duration stays anticipated as part of the Vision for Space Exploration, where sporadic risks will become certain events.



Chapter 3. Heliophysics: The Program





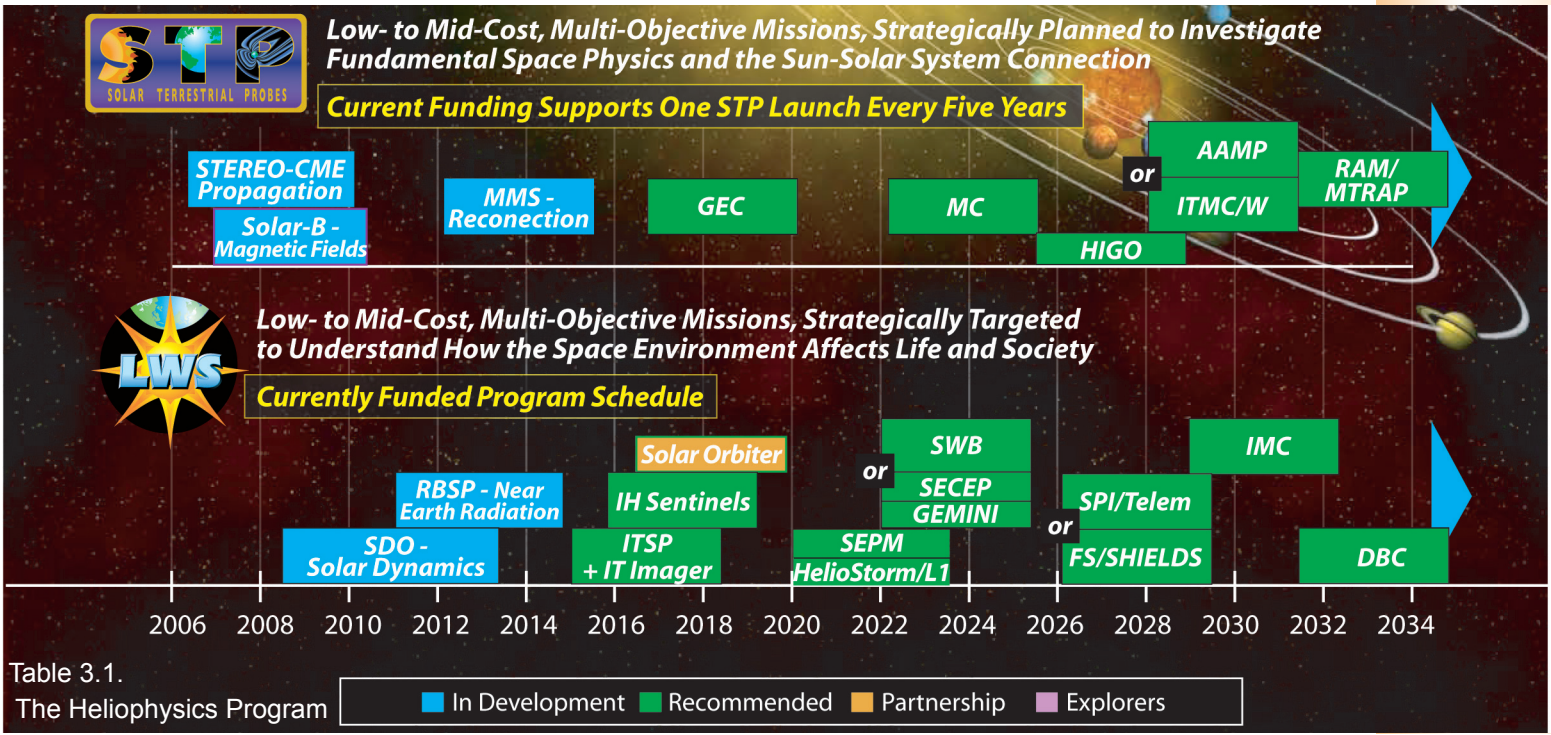


Table 3.1.
The Heliophysics Program

Chapter 3

Heliophysics: The Program

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

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

The Heliophysics program is constructed to address the most important fundamental Sun-solar system science problems with investigations prioritized in order to have the greatest impact on developing understanding of the entire system, from the solar sources to their ultimate consequences.

NASA's Strategic Objective for Heliophysics

Explore the Sun-Earth system to understand the Sun and its effects on Earth, on the Solar System, and on the space environment conditions that will be experienced by explorers, and demonstrate technologies that can improve future operational systems.

Table 3.1. The Heliophysics Program. The figure on the opposite page illustrates the prioritized mission set for heliophysics. The top panel shows the missions recommended for the Solar Terrestrial Probe and Living With a Star programs. The center panel (with years) shows the critical Explorer missions (purple) and the unfunded Flagship missions (green) and Partnership missions (yellow).

With fairly optimistic assumptions about the Heliophysics budget, the anticipated achievements described in this chapter can be accomplished when required. Science return will be multiplied because of mission synergy. The missions in blue have already begun development. Future missions are shown in green.

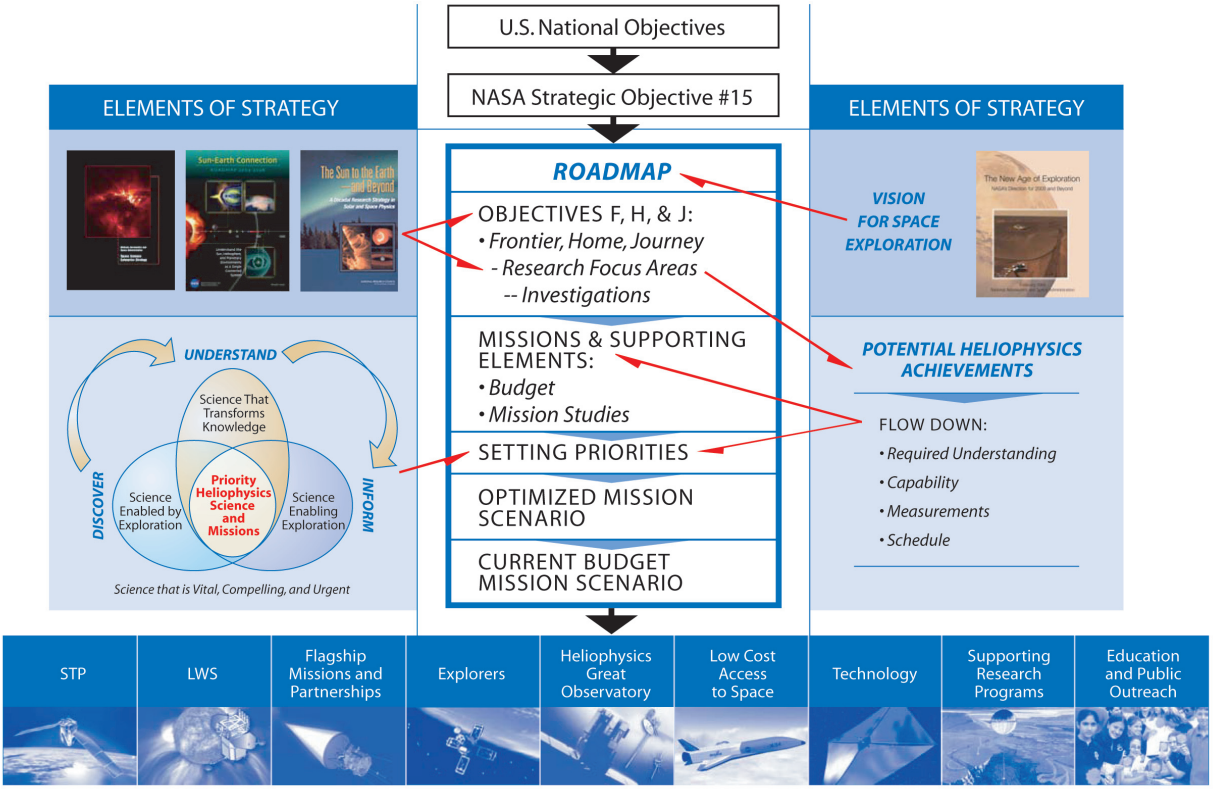
The bottom panel shows the endorsed schedule for the STP and LWS programs assuming the current budget level. This scenario delays many achievements and greatly curtails the ability to simultaneously observe the connected system. Several decision points for future missions are indicated.

Smaller boxes indicate less costly missions. The program elements are discussed in more detail in this chapter. Individual missions are described in the next chapter.

Careful management of the resources available to address these problems points to a three-prong implementation strategy. First, science focused missions must be deployed to solve the fundamental physical problems identified as key impediments in understanding how magnetic and gravitational physical processes operate. Second, these targeted science missions should be strategically ordered to ensure that complementary measurements are taken at a sufficient number of locations. Finally, data from multiple sources must be synthesized through analysis, modeling, and theory to develop scientific understanding and practical knowledge of the system-wide behavior as solar storm erupt. In this way, the science of Heliophysics can be most efficiently addressed with platforms deliberately and strategically distributed throughout the important interaction regions.

In recent years the power of simultaneous observations at multiple vantage points has been clearly demonstrated by what we now call the Heliophysics Great Observatory (page 6). The current Heliophysics Great Observatory is a fleet of widely deployed solar, heliospheric, geospace, and planetary spacecraft that are working together to help understand solar activity and its interaction with geospace and other planetary systems throughout the solar system. Like NOAA's system for observing and predicting terrestrial weather, this observatory utilizes all assets available – remote sensing, *in situ* measurements, theory, data analysis, and models – to provide physical understanding and predictive capability for space weather research. The diverse measurements

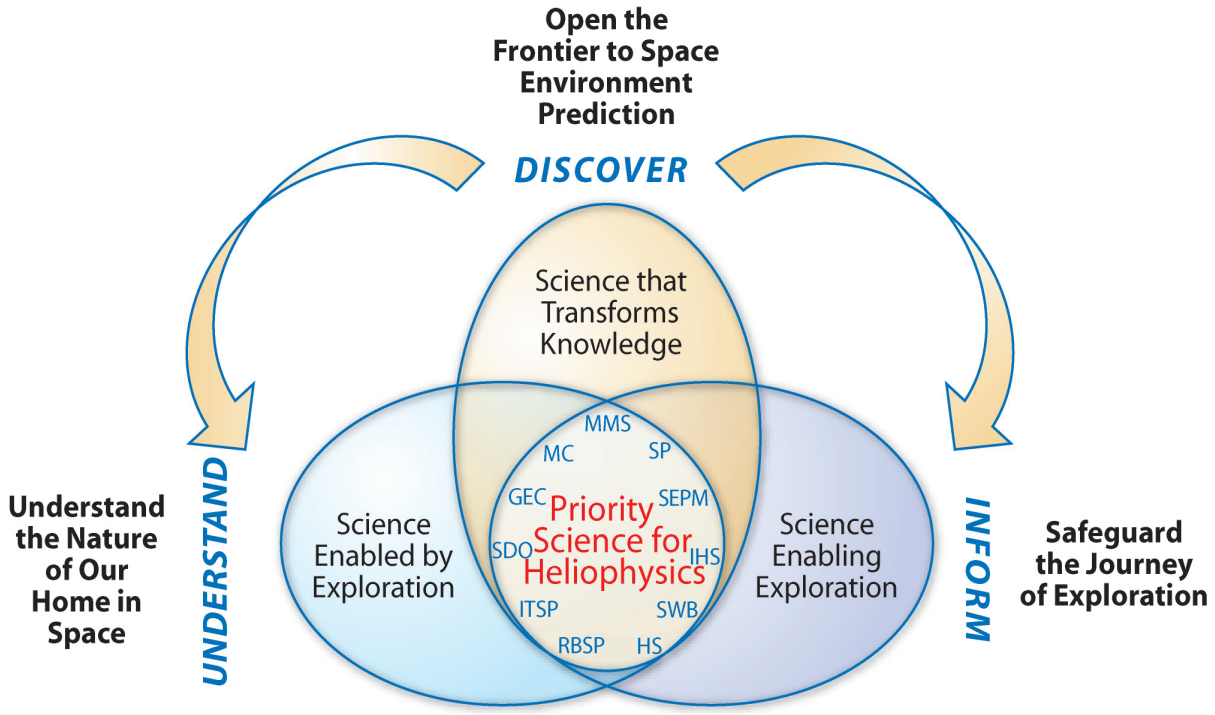
Heliophysics Roadmap Development Framework



The Heliophysics Roadmap derives from the U.S. National Objectives and Vision and draws on earlier strategies developed by NASA and by the National Research Council for the study of the Sun-Earth Connection and Sun-Solar System Connection. These elements of strategy help define the science that is most vital, compelling, and urgent. Plans for achievement in each area depend on scientific technical, and financial resources. The recommended implementation prioritizes the program to provide the necessary capabilities when needed.

across distributed spatial scales are linked by a variety of improving models that serve to fill in the gaps in the observations and provide the knowledge that will lead to predictions of tomorrow's space weather. **The opportunity exists now to deliberately evolve this distributed observatory to meet the needs of the Vision for Space Exploration. This is the Heliophysics community's highest priority.**

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



Science that is Vital, Compelling, and Urgent

The intersecting ovals illustrate the intersection of three categories of science: scientific understanding that is enabled by exploration, science that transforms our knowledge, and science that informs to enable exploration. At the intersection is the 'sweet spot' where the highest priority Heliophysics missions lie. The mission acronyms are explained in Chapter 4.

Prioritized Implementation Strategy

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

Anticipated Heliophysics Science and Exploration Achievements

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

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

Table 3.2. Each anticipated achievement in this table has been developed from the Heliophysics research focus areas. Each targeted outcome requires advances in understanding of physical processes. Measurement capabilities must be available to develop that knowledge. Deployment of missions, development of theoretical understanding, and availability of infrastructure systems are required to provide that measurement capability.

For each outcome in the table the necessary understanding, capabilities, and implementation have been traced. These scientific flow-down charts are available at the Heliophysics 2005 Roadmap web site (http://heliophysics.gsfc.nasa.gov/roadmap.htm) and an example chart will be found in Appendix C. The requirements in the numerous flow-down charts often overlap; so the results have been consolidated. The phasing was determined by the urgency, importance, and cost. Finally a balanced set of missions was chosen to address the most critical science and exploration topics in each phase. The missions have been assigned to program elements and resources identified to implement them. Information gained in earlier missions must be used to decide the selection and ordering of later flight opportunities.

of prediction contributes to developing future operational systems that support the needs of our increasingly technological society and informing of our future exploration endeavors.

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

society and the exploration program.

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

The program relies on several elements: strategically planned missions in the Solar Terrestrial Probes (STP) and Living With a Star (LWS) lines to address widely recognized critical problems; competitively selected Explorers to optimize responsiveness to strategic needs; coordinated operation of new and existing space assets as part of the Heliophysics Great Observatory; support for the low cost access to space program for unique science, community health, and instrument development needs; technology development; supportive, targeted research, theory, and analysis programs; and a strong effort in education and public outreach. Partnerships with other areas of NASA and other agencies, both U.S. and international, are essential. Each of these program elements is described in more detail below.

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

Science by Phase

The Roadmap committees considered three decade-long phases in formulating a plan. The achievements of each phase inform decisions made about implementation in subsequent phases. The phases roughly correspond to development cycles in the Exploration Initiative. Phase 1 ends in 2015 and includes missions launched by that date; Phase 2 ends in 2025 and Phase 3 in 2035. The potential achievements identified in Table 3.2 correspond fairly well to these phases.

In this section the overall program for each decade-long phase is summarized. Subsequent sections provide the rationale for the ordering of each element of the Heliophysics program. The illustration at the beginning of this chapter (Pg. 54) shows the Strategic Mission Roadmap for Heliophysics.

Our Phase 1 program presumes the continued operation of the current missions in the Heliophysics Great Observatory. Because of resource constraints, the “Current Resources” baseline Phase 1 program necessarily includes only those missions that are already in development or formulation (shown in green). These are STEREO, Solar-B, and MMS in the STP program; SDO and RBSP in the LWS program; and the selected Explorers: AIM, THEMIS, and IBEX. The selection of future Explorers will close gaps in the program. Of the partnership missions, the Pluto-Kuiper mission has already been launched and the Jupiter Polar Orbiter (Juno) is in the study phase. A solar sail demonstration mission and the ADAM Mars Scout mission could also occur in Phase 1.

The recommended Phase 1 strategy optimizes the program, moving up the STP mission MMS by two years and launching the missions identified for early in Phase 2 sooner - in time to allow simultaneous observation of related system elements. The multiple synergies and comprehensive views afforded by the Heliophysics Great Observatory now and as it evolves and develops during this interval are a testimonial to the investments and achievements of the past decade in Sun-Earth Connection science at NASA. The first crucial set of questions required to open the frontier to space weather predictions, understand the nature of our home planet, and safeguard our journey of exploration have been largely anticipated in the existing program plan. Heliophysics is clearly poised to make significant progress in the next

10 years on these important objectives.

Solar Probe should be launched in this phase, though data from this flagship mission's first plunge through the solar corona will not be available until Phase 2. This set of investigations provides a very powerful tool for accomplishing the achievements listed in Table 3.2.

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

Missions beyond 2025 in Phase 3 have been identified because we already know many of the scientific questions that will probably remain unanswered. The priorities will be adjusted depending on what is learned and on progress in the Exploration Initiative, but it is clear that constellations of spacecraft will be required in new regions to resolve spatial and temporal changes in the magnetosphere and in interplanetary space where remote global sensing is not possible. Technological development and selection of Explorers may allow some objectives to be achieved earlier.

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

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

Program Elements

The implementation of the Heliophysics Program is currently funded though several sources. Missions come from the Solar-Terrestrial Probes Program, the Living With a Star Program, and the Explorer Program. The fleet of existing missions makes up the Heliophysics Great Observatory that evolves as new missions are launched and new combinations of observations can be made. Larger flagship missions are not part of the baseline funded program and Heliophysics requires additional resources to overcome the roadblocks to scientific progress in these areas. Rockets and balloons provide low-cost rapid access to space. Focused research and analysis programs lead to new understanding and contribute to new investigation requirements. The

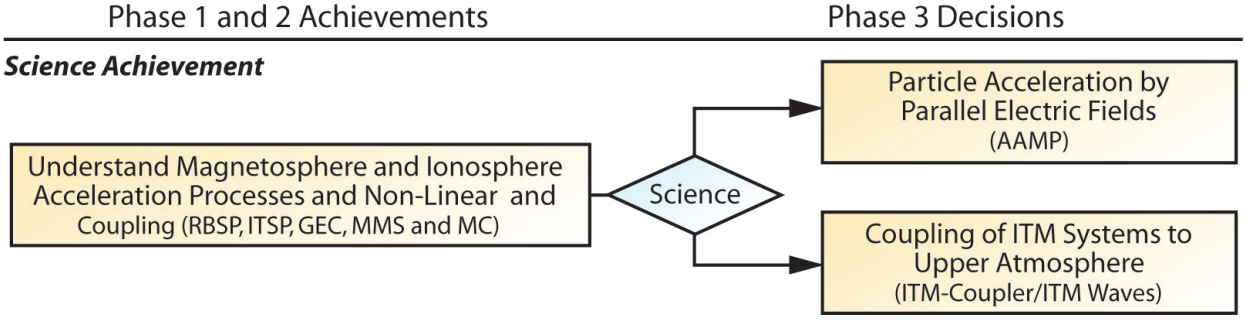
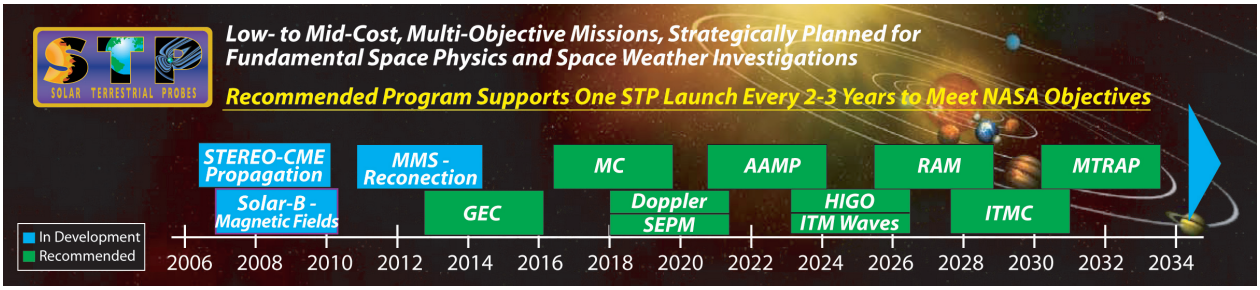


Table 3.3. Schematic illustrating a decision point for selecting a future STP mission.



The figure shows the mission identified for flight through 2035 in our optimized scenario. The improved synergy of STP missions is apparent. Boxes represent anticipated Heliophysics resources in units of medium sized missions. Mission names in blue boxes indicate that resources are committed and development is underway. Green boxes represent new missions assigned here to anticipated resources.

support of data, computing, and community infrastructure ensures that progress will continue to be made. Each of these program elements and the mission strategy for each line is described below. We first describe briefly the mission strategy for each line.

Solar Terrestrial Probes

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

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

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

In order to support the fundamental science necessary to open the frontier for prediction of space weather effects, this Roadmap identifies GEC and MagCon as the next two STP missions. GEC will measure the vitally important yet poorly observed region just below stable satellite orbits to resolve issues of ion-neutral

The figure shows the STP missions identified for flight through 2035 using current budget projections.

coupling and the processes linking the ionosphere and magnetosphere. MagCon, now slated for launch in 2022 in the current budget scenario, provides comprehensive measurements of processes in the magnetosphere with a fleet of spacecraft. These and the other missions we identify are described in more detail in the next chapter.

Coupled with the rest of the program, these missions promise the best assault on the important problems facing Heliophysics. The slowed five-year spacing between launches in the current budget scenario is not ideal, not only because progress is slow, but because synergy between missions is curtailed.

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

Phase 3 STP missions will measure reconnection near the Sun and observe lower latitude disturbances in the ionosphere-thermosphere-mesosphere; a stellar imager (likely a flagship mission) will resolve activity on other stars to enable us to complete our objectives. Even later, more ambitious missions to explore the interactions of external drivers with other worlds in the solar system, specifically Titan,

Measurements of the Solar Wind Up-Stream from Earth

Partnerships and Decision Points for Heliophysics Near L1:

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

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

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

L1 Earth-Sun is a joint Earth-Sun Science partnership mission that includes an in situ solar wind package. The concept mission simultaneously conducts spectral imaging from XUV to IR of both the Earth and the Sun. The scope of this collaboration needs to be worked out more completely.

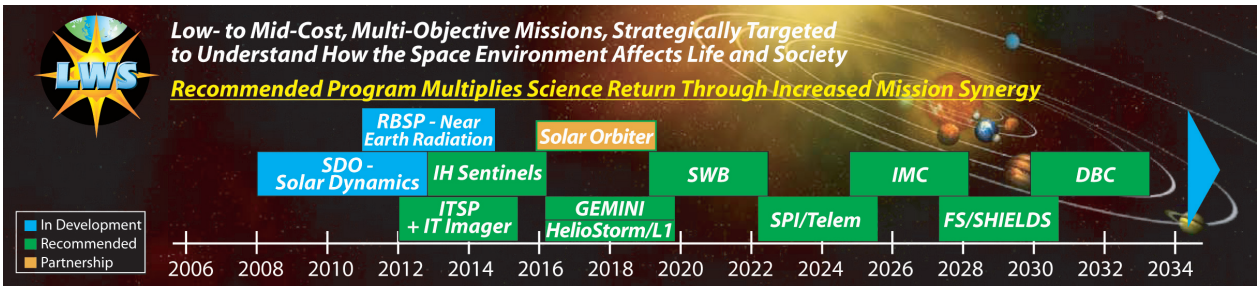
Decision Points and Partnerships:

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

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

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

Venus, and Io, could be accomplished in partnership with others to address questions of habitability and atmospheric evolution. Larger telescopes to remotely probe the solar transition region would complete our understanding of how energy propagates from the Sun outward and remote sensing of other planetary environments would close the path at the receiving end.



This figure shows the missions identified for flight in the LWS program through 2035 in our optimized scenario.

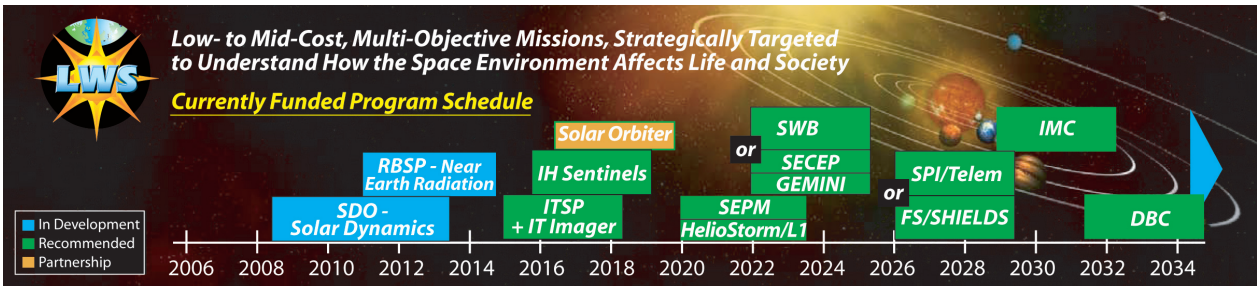
Living With a Star

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

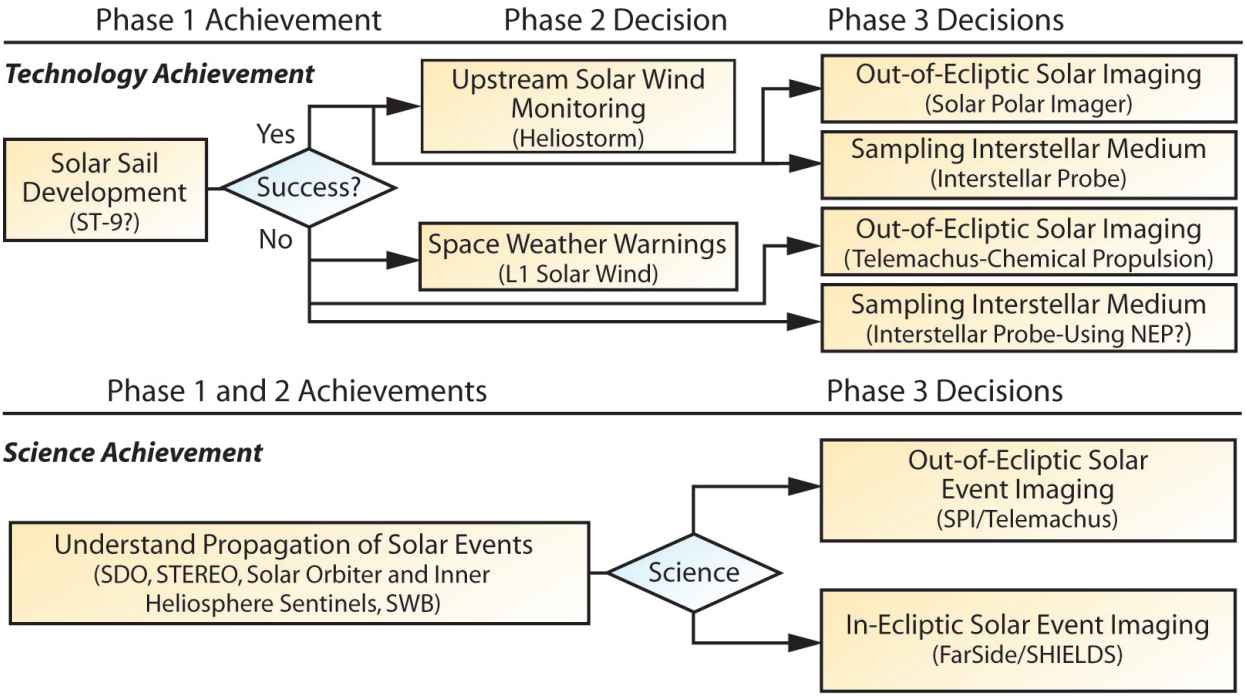
LWS Targeted Research and Technology Program **(TR&T)** uniquely satisfies two critical LWS needs. First, it tackles the major LWS science problems that cross the usual boundaries between scientific disciplines and between research techniques. Second, TR&T develops the specific, comprehensive models required to understand the LWS system, in particular those that can serve as prototypes for operational forecasting and nowcasting.

To achieve the first, some resources are set aside to support new research in a few key areas that are recommended each year by a TR&T steering committee. The LWS program announces the targeted topics and funds science coordinators to help the competitively selected PI teams work together. This innovative approach assures that the best peer-reviewed investigators can combine their individual expertise to address the broad system science required to achieve specific LWS goals.

To meet the second need, LWS invites proposals to develop a particular set of strategic capabilities or technologies, also recommend-



The Recommended LWS mission set assuming the current budget level



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

ed annually by the TR&T steering committee. The strategic capability tools are made available (e.g. at the Community Coordinated Modeling Center, CCMC) for use by the scientific community and for evaluation for potential transition to operations.

Special care must be exercised in selecting the targets for the TR&T program and in determining the fraction of TR&T support set aside for these specific tasks. Continued commitment to selecting the most compelling science investigations addressing the full spectrum of LWS goals serves to keep the program vital, relevant, and responsive.

TR&T also supports post-doctoral fellowships and summer schools intended to build the cross-disciplinary science community necessary for addressing LWS systems science. Even though the first LWS launch still lies several years in the future, TR&T has from its inception delivered new capabilities that advance the goals of the program and provide a sound basis for planning and refining the science requirements of investigations on future missions and using the Heliophysics Great Observatory. TR&T will be indispensable for integrating the science across investigations after they are launched. TR&T is an essential core component of LWS, equivalent in importance to the missions.

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

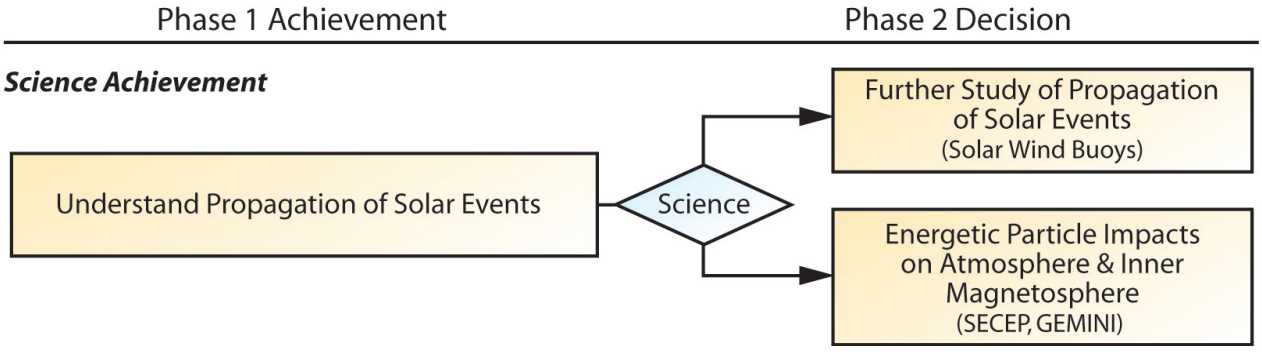
Our Roadmap concurs with earlier recommendations that the next two LWS missions should 1) complete the geospace storm probes by investigating ionospheric disturbances with the Ionosphere-Thermosphere Storm Probes (ITSP) and 2) explore radial evolution of solar wind structures with the Inner Heliosphere Sentinels mission. The priority of the ITSP mission is driven by the very practical need to aid communications and navigation; ITSP will observe the complex interplay of plasma - neutral processes that frequently produce both

unexpectedly large electron density plumes and the subsequent formation of small-scale ionospheric irregularities. ITSP includes a separate imaging instrument. The Exploration Initiative raises the priority of the IH Sentinels mission because hazardous space weather near Earth and in the inner heliosphere, solar energetic particles in particular, cannot be understood without it. In our "current resources" scenario for LWS, these two missions are launched within a year of each other in 2015 and 2016. Our optimized scenario moves the ITSP and IH Sentinels missions ahead three years to provide synergy with RBSP and SDO and to provide earlier information for the design of systems for the return to the Moon later in the decade. Launching in 2012, near solar maximum, could also triple the number of solar energetic particle events (from ~10 to ~30) that would be available for study. We also identify an important partnership opportunity with ESA's Solar Orbiter mission that complements the IH Sentinels *in situ* measurements and will provide solar observations from a different vantage point.

Subsequent LWS missions in Phase 2 address understanding energetic particle production near the Sun with the Solar Energetic Particle Mission (SEPM) and crucial measurements of the solar wind and energetic particle inputs to geospace with Heliostorm or an L1 Heliostorm Mission. These mission candidates can be smaller in cost than typical strategic missions. The choice between Heliostorm and an L1 mission is complex (see box on page 60 and top figure on page 62). Heliostorm would use solar sails to hover twice as far upstream of the L1 point in the solar wind for advanced warning of geospace disturbances. The mission will measure the same solar wind parameters as L1-Heliostorm. Heliostorm is the preferred option. Measurement of incoming solar wind parameters is crucial to many other investigations, so depending on Heliostorm, the status of the Earth Science L1-Earth-Sun mission, the lifetime of existing assets, and partnerships with other agencies, we have reserved some small amount of resources for L1 observations.

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

Later Phase 3 choices in the LWS program



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

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

The Explorer Program

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

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

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

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

The Explorer program also plays a key role in developing and maintaining the scientific and engineering community needed to meet the objectives of the Roadmap, NASA, and the nation. Explorers provide hands-on training of in-

strumentalists, both scientists and engineers, thus enabling Heliophysics strategic missions, and directly contributing to the NASA Mission element "to inspire the next generation of explorers". Managing cost-constrained missions such as Explorers requires specialized expertise.

Flagship and Partnership Missions

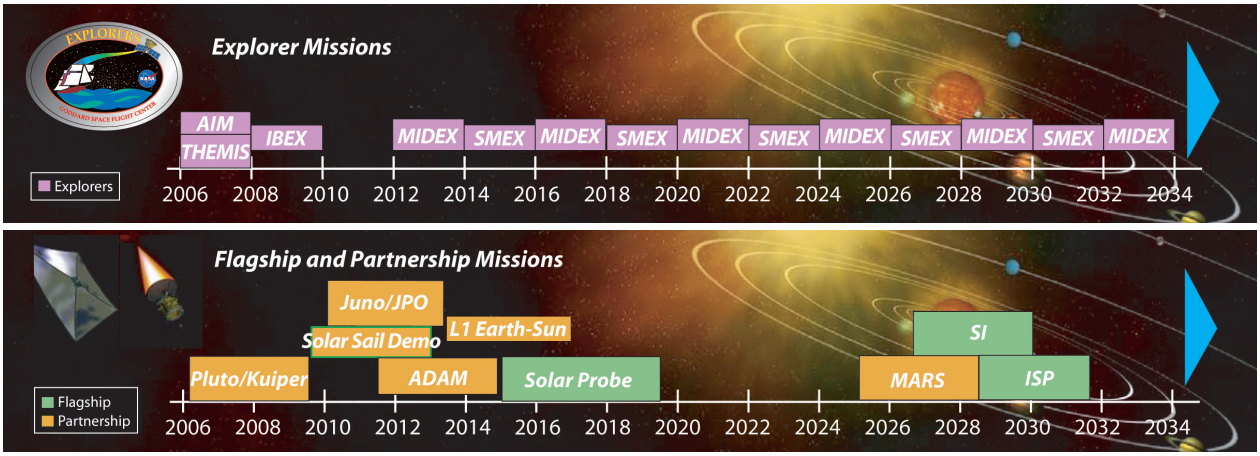
Urgent need for progress across a range of topic areas means that all of the Heliophysics resources cannot be applied to a single problem for an extended interval. Yet some major roadblocks to progress simply cannot be overcome with missions supportable in the strategic lines available to Heliophysics.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

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

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

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

Partnerships provide another method to increase scientific return. Several missions have been identified in our plan that rely on partner-



Explorer missions are an indispensable element of the Heliophysics strategy. Flagship missions overcome roadblocks to scientific progress but require additional funding because of their larger cost. Partnership missions greatly strengthen the Heliophysics Program.

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

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

The Heliophysics Great Observatory – Evolving to Meet the Needs of the Vision for Exploration

The very large "Halloween Solar Superstorms" described on page 6 demonstrates the unique and powerful capability of the Heliophysics Great Observatory to view this system of systems. The effects of the solar storms were observed simultaneously from the Sun, to the Earth, to Mars, and beyond to the edge of the solar system. It would not have been possible to link the consequences of these superstorms at Earth and Mars to the solar drivers that produced them without this collection of satellites and the human and computational resources to interpret the observations. The power of the Great Observatory comes from the combination of multiple operational assets, timely and convenient data access, large-scale models, and associated data analysis. Many of the spacecraft are Heliophysics missions, but additional "observation posts" are provided by spacecraft supported by other programs such as Mars Global Surveyor (MGS), Cassini and the Hubble Space Telescope. For example, from MGS, we learned that the fluxes of solar energetic particle radiation caused by the superstorms were quite different at Mars and Earth. Our Great Observatory will need to evolve and expand to fully understand why space weather effects vary so much at different locations in our solar system.

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

The Heliophysics Great Observatory will continue to evolve as new spacecraft join and older ones retire or change their operating modes. Missions both in their prime phase and in extended phases (supported by the Heliophysics MO&DA program) provide the variety of observation posts needed to study Sun-Solar System connections, as demonstrated by the 2003 Halloween Storms. A great strength

of this fleet is that it is regularly evaluated and reviewed to maximize the return on the agency investments. This Senior Review process determines which spacecraft are most necessary to meet the needs of the Heliophysics program as defined by the community-developed Strategy Roadmap. The criteria for continuation include relevance to the goals of the Heliophysics Division; impact of scientific results as evidenced by citations, press releases, etc.; spacecraft and instrument health; productivity and vitality of the science team (e.g., publishable research, training of younger scientists, education and public outreach); promise of future impact and productivity (due to uniqueness of orbit and location, solar cycle phase, etc.); and broad accessibility and usability of the data. The Heliophysics **Guest Investigator (GI)** program is a critical component of the Heliophysics Great Observatory. The GI program enables the broadest community of Heliophysics researchers in universities and institutions across the country to use Great Observatory data in innovative scientific investigations pursuing the goals of this roadmap. The focus of competitively selected research funded by the program continuously evolves to ensure that the most important current questions are addressed.

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

Low Cost Access to Space

The Low Cost Access to Space (LCAS) program, whose key elements are the sounding rocket and balloon programs, is an essential component of NASA's space physics research program. LCAS investigations make cutting-edge science discoveries using state-of-the-art instruments developed in a rapid turn-around environment. Of course the capabilities of the LCAS program must continue to evolve and improve so investigators can continue to do forefront research. Like Explorer missions, LCAS investigations fill important gaps in the prescribed program, augmenting strategic line missions. These investigations, selected for the best science, serve two additional purposes that cannot be adequately addressed in other flight programs: the training of experimental space physicists and engineers and the development and flight verification of new instrumentation and methods.

A Terrier-Black Brant IX rocket lifts off from Poker Flat Research Range near Fairbanks on its way into an aurora to study high-altitude plasma waves. *Photo courtesy of Chuck Johnson, UAF Geophysical Institute.*

Three examples illustrate the strategic relevance of the LCAS rocket program. One current investigation will use two rockets to simultaneously probe different altitude ranges in the polar cusp, the high-latitude region where Earth's magnetic field maps most directly to

the solar wind. These multipoint observations of ions accelerated in the cusp can only be provided by sounding rockets and will make a significant contribution to investigation F3.3. Recent rocket experiments in the South Pacific are revealing the origin of equatorial plasma turbulence. In this case the ability of rocket experiments to measure multiple vertical profiles of electric fields and electron density in the ionosphere during selected events contributes to investigation F2.4. The understanding of auroral physics gained during another, earlier series of rocket flights demonstrates the three-pronged role the program plays in science discovery, instrument development, and science training. New, higher-altitude rockets made evident the crucial role of microphysics and the need for high time-resolution measurements to elucidate the acceleration processes. The "top-hat" plasma detectors developed for these rockets are now common on space plasma satellite missions. The PI and graduate students went on to develop a successful Explorer mission as PI and instrument leads.

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

An essential ingredient of the Vision for Exploration is a source of well-trained engineers and scientists who understand the demands of building and delivering spaceflight systems and hardware. The LCAS program provides important hands-on training for these human resources. 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; this is something no other flight program can do. The rocket program alone has resulted in more than 350 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.

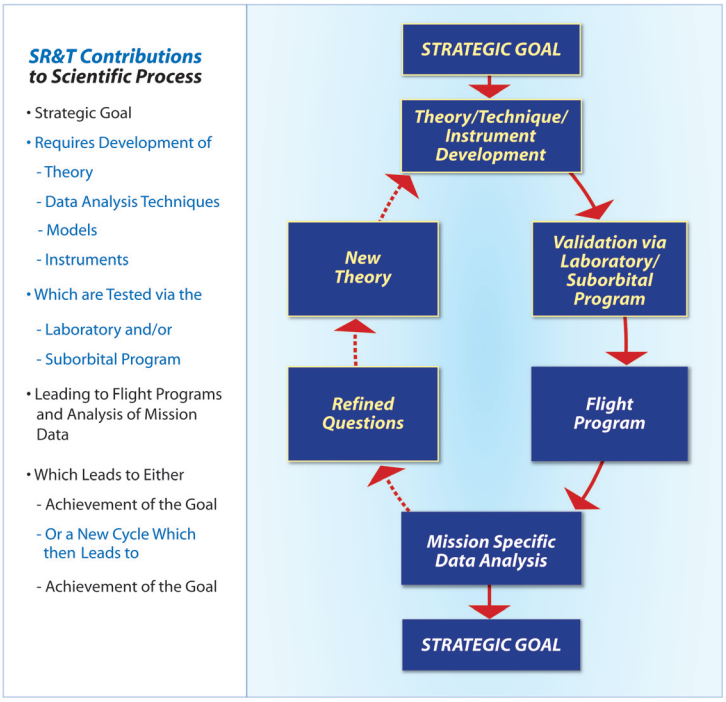
The combination of unique science, advanced instrument development, and training makes LCAS a critical path item for achieving NASA's national space science goals.

Scientific Research and Analysis

Scientific research and analysis are at the heart of Heliophysics Division activity. The bulk of the discussion in this chapter relates to missions and their sequencing, because that aspect of the program is most amenable to long-range planning. Note, however, that the primary purpose of the Roadmap is to lay out a route to achieve the three science and exploration objectives detailed in the previous chapter. Many of the indispensable stepping stones along that path are supplied by the research and analysis programs that include Supporting Research and Technology (SR&T) and the Heliophysics Theory Program, along with three programs discussed previously: the Guest Investigator Program, LCAS, and the LWS TR&T.

SR&T comprises an ever-evolving suite of individual PI-proposed investigations that cover the complete range of science disciplines and techniques essential to achieve the Heliophysics Division objectives. SR&T enables exploration of innovative concepts in sufficient depth to determine whether they have real potential, and because of this, the diversity of the program is one of its critical components. The Theory Program supports larger PI-proposed team efforts that require a critical mass of expertise in order to make significant progress in understanding complex physical processes with broad importance, such as magnetic reconnection or particle acceleration. The SR&T and Theory programs provide not only the foundation on which the rest of the Heliophysics Division research enterprise is built, but much of the superstructure into which the individual mission efforts are integrated. These

Space Science: Process



responsive programs develop the pioneering theories, techniques, and technologies that result in missions and they also capitalize on the new information from the missions to advance our understanding across the whole spectrum of Heliophysics.

SR&T, including the instrument and technology development components, and the Theory Program make vital contributions throughout the mission development cycle. The process begins with a clear definition of an important and attainable science and exploration target and proceeds through mission development, flight, and data analysis. In the end, a new cycle begins in which either new or newly refined questions and/or techniques are employed in follow-on missions. Being able to move from a promising science goal to a practical mission definition requires the availability of the theories, modeling, data analysis techniques, and instrumentation that are developed in these research and analysis programs. The approaches that are suggested on the basis of this groundwork are then tested via SR&T supported laboratory and/or suborbital work. Once a mission has actually flown, its productivity can be multiplied through SR&T investigations; for instance, laboratory measurements may greatly enhance the quality of the information that can be recovered from spacecraft data or unexpected results can be explored. At the same time, the program supports the development of the new theory, data analysis, modeling, observing techniques, technology, and instrumentation that will be needed to address the next generation of questions.

Critical contributions of these programs can be seen, for example, in the first LWS mission, SDO. A primary science thrust of this mission is understanding the solar interior using helioseismology. Another is understanding the dynamic magnetic structure of the solar corona. Many of the techniques and models crucial to these two areas came to fruition in the SR&T and Theory programs. SDO also relies on technology, such as normal-incidence, multi-layer XUV imaging, and laboratory measurements that were enabled by the SR&T program. An upcoming STP mission provides another example. MMS will overcome obstacles to our understanding of magnetic reconnection, especially in the collisionless regimes found in the heliosphere and magnetosphere. Many of the current theories and models for collisionless reconnection have been developed through the Theory Program.

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

Research Infrastructure

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

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

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

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

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

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

Support for a competitive number of research teams and investigators is of paramount importance to a healthy and robust scientific community. There is a real danger that the loss of 'critical mass' of research teams has already begun to impinge on NASA's science and exploration goals. This is especially important for hardware development teams that have a high startup investment and have difficulty retaining technical expertise in uncertain funding cycles. NASA support for low-level hardware development is generally deemed insufficient to support enough truly innovative instrument development. Only the largest teams are per-

ceived as capable of competition for hardware development. Paradoxically, the opposite can be said about modeling support, in that large-scale modeling efforts are not sufficiently funded for the tasks they face. In all cases, there must be a balance between large and small research efforts, as well as between pure and applied science.

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

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

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

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

NASA Heliophysics has traditionally pursued cooperative research and analysis efforts with programs funded by other agencies, such as NSF's ground-based observatory structure; the CEDAR, GEM, and SHINE research programs; and the Center for Integrated Space-Weather Modeling (CISM), an NSF Science and Technology Center. Current and future ground-based observations, will provide understanding of certain fundamental physical processes that cannot be measured from space alone; they provide a context for the space-based Earth-system measurements and enable coordinated studies of events over the entire Sun-Earth system.

For example the MILEURA wide-field array offers another vantage point by which to study inhomogeneities in the solar wind, the Advanced Technology Solar Telescope (ATST) and the Frequency Agile Solar Radiotelescope (FASR) provide coronal magnetic field measurements that Heliophysics does not have the resources to obtain, and chains of magnetometers provide information about the global electromagnetic coupling between the magnetosphere and solar wind. The Advanced Modular Incoherent Scatter Radar (AMISR) is a new ionospheric radar that can be deployed to different locations as science priorities change. An ambitious new program called Distributed Arrays of Small Instruments (DASI) aims to deploy a comprehensive network of remote sensing instruments that will track with unprecedented spatial and temporal resolution the flow of energy through the extended terrestrial atmosphere.

These longstanding partnerships will con-

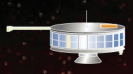
tinue to strengthen our future space-based capabilities and so must continue to be nurtured and supported.

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

Chapter 4.
Heliophysics: The Missions

Evolving Heliophysics Great Observatory

2021



Magnetospheric Constellation
Sensorweb for macroscale dynamics

2020

SOLAR MAX

L1/Heliostorm
Measure space weather inputs to geospace

Solar Energetic Particles Mission
Understand acceleration of solar energetic particles

2019

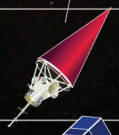
2018

2017

GEC
Multi-point high latitude Magnetosphere - ITM coupling

L1 Earth Sun
Measure Earth's energy budget

2016

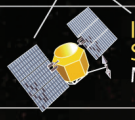


Solar Probe
In situ solar wind acceleration at 4 R$_S$

Solar Orbiter
ESA Partnership to observe Sun from unique vantages

2015

Ionosphere-Thermosphere Storm Probes
Multi-point mid-latitude I-T



Inner Heliosphere Sentinels
Multi-point inner heliosphere

2014

2013

2012

MMS
Multi-point reconnection diffusion region

Strategically Selected Future Explorers

2011

Radiation Belt Storm Probes
Radial multi-point particle acceleration inner magnetosphere dynamics

ADAM
Possible Mars Scout for Aeronomy and Dynamics

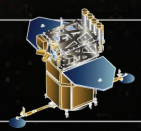
2010

SOLAR MAX

Juno/JPO
Exploring Jupiter's magnetosphere

2009

2008



SDO
High time resolution solar dynamics & spectral irradiance

IBEX
Global heliosphere termination shock imaging

2007

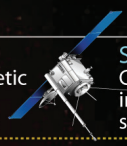
2006

AIM
Mesosphere climate composition polar mesospheric clouds

CINDI
Electrodynamics of low latitude ionosphere

THEMIS
Multi-point geotail dynamics

Solar-B
3D magnetic field evolution

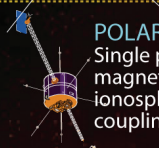


STEREO
CME's and the inner helio-sphere in 3D

TWINS A & B
Stereoscopic 3D magneto-spheric dynamics

Existing Assets

FAST
Single point auroral dynamics



POLAR
Single point magnetosphere-ionosphere coupling

Geotail
Single point tail dynamics

TRACE
Imaging Solar and Coronal Magnetic Structures

Ulysses
Sampling the high latitude heliosphere

Voyager
Exploring the boundary of the heliosphere

STP/ISTP
LWS
Explorers
Partnership
Other

TIMED
ITM energetics & dynamics

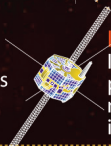


IMAGE
Ionosphere-plasmasphere-magnetosphere imaging

CLUSTER
Reconnection outflow

RHESSI
Localizing Solar High Energy Particle Acceleration

SOHO
Solar interior, irradiance and magnetism; CME's in 1D

ACE, Wind
Multi-point solar wind structure at L1

Low Cost Access to Space (LCAS) Program for Rocket and Balloon Investigations

Chapter 4

Heliophysics: The Missions

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

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

The following brief descriptions answer three key questions:

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

Further details about these and other Heliophysics mission candidates can be found in the Quad Charts in Appendix D of this report.

Candidate Mission Reference List

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

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

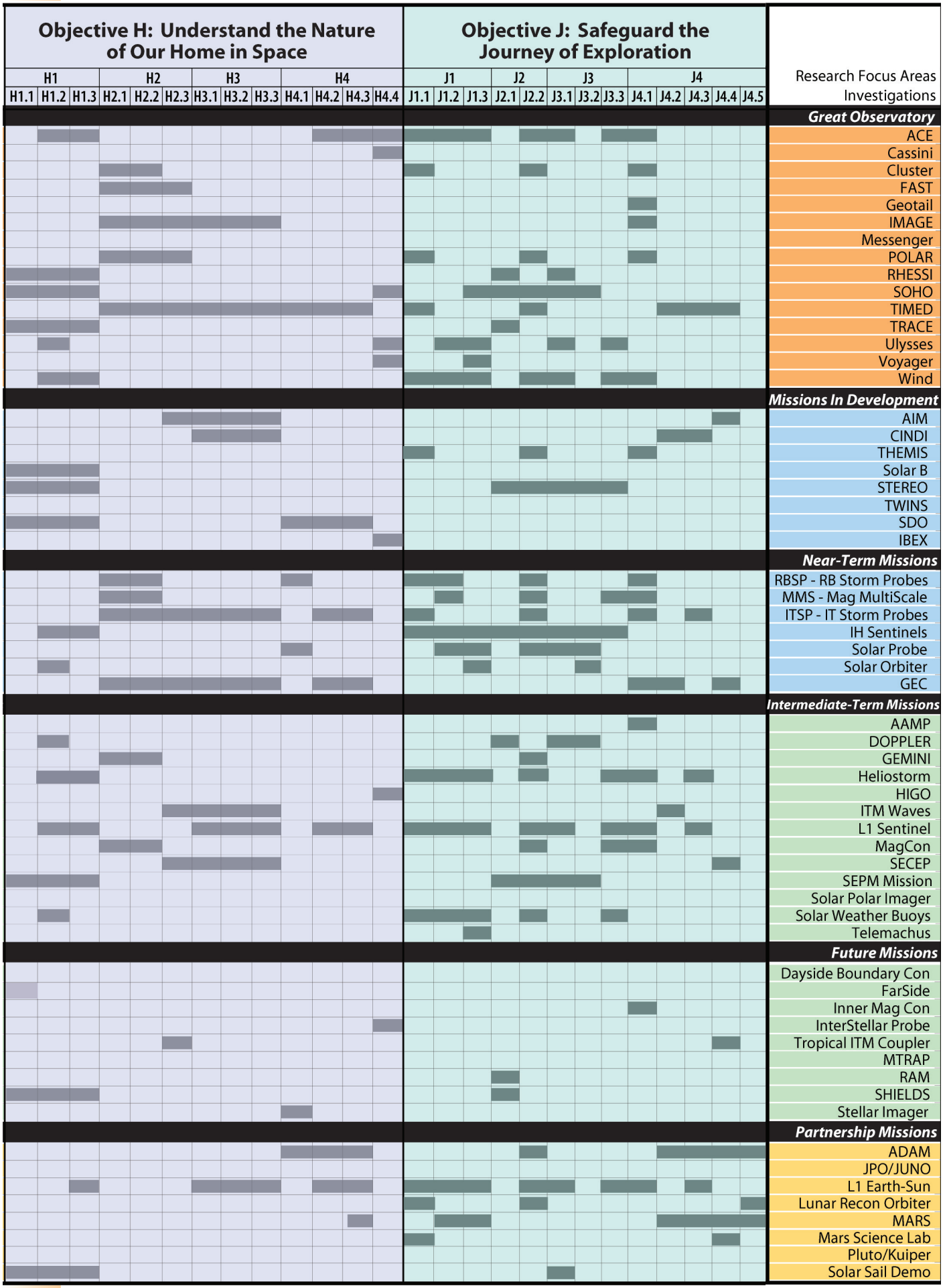
The 13 intermediate-term mission candidates for the following decade include two partnerships and several alternative choices. The intermediate-term missions have either been considered by an STDT or have undergone an intensive, objective conceptual evaluation and costing by the GSFC or JPL mission study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

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

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

Heliophysics utilizes several mission resources. Strategic fundamental science missions are executed as Solar-Terrestrial Probes (STP). The Living With A Star (LWS) mission line is also strategic, dedicated to research on understanding and mitigating effects of space weather. Flagship Missions are grand challenge missions that require separate new starts outside of the STP or LWS programs. Explorer missions are smaller than the others and present opportunities for open competition to address strategic scientific questions that are relevant and timely. MOO's, missions of opportunity, are inexpensive components flown as part of another mission. Partnership missions receive external funding, either from other parts of NASA, other U.S. agencies, or other national entities. The two-page table indicates how missions are related to the Objectives, Research Focus Areas, and investigations developed in Chapter 2. Missions currently in development and near term Heliophysics missions are shown in order of approximate launch date. Later missions are listed alphabetically.

Page No.	Research Focus Areas / Investigations	Objective F: Open the Frontier to Space Environment Prediction														
		F1		F2				F3				F4				
		F1.1	F1.2	F2.1	F2.2	F2.3	F2.4	F3.1	F3.2	F3.3	F3.4	F4.1	F4.2	F4.3	F4.4	F4.5
	Heliophysics Great Observatory															
	ACE			■												■
	Cassini								■							■
	Cluster	■	■	■	■		■					■				
	FAST			■	■		■		■	■						
	Geotail					■										
	IMAGE		■	■	■		■	■		■	■	■				
	Messenger								■							■
	POLAR	■	■	■	■		■			■		■				
	RHESSI			■												
	SOHO				■	■							■	■	■	
	TIMED						■	■	■	■		■				
	TRACE		■	■											■	
	Ulysses														■	
	Voyager										■					
	Wind			■	■	■										■
	Missions In Development															
76	AIM															
76	CINDI							■								
76	THEMIS		■				■									
77	Solar B		■					■					■	■		
77	STEREO		■	■	■	■						■			■	
77	TWINS															
78	SDO		■										■	■		
78	IBEX				■						■					
	Near-Term Heliophysics Missions															
79	RBSP - RB Storm Probes				■					■						
79	MMS - Mag MultiScale	■	■													
80	ITSP - IT Storm Probes				■		■	■	■	■						
80	IH Sentinels			■	■	■									■	
81	Solar Probe					■										
81	Solar Orbiter					■							■	■	■	
82	GEC			■	■			■	■	■						
	Intermediate-Term Heliophysics Missions															
82	AAMP			■	■		■			■	■					
83	DOPPLER		■			■		■								
83	GEMINI															
83	Heliostorm			■		■								■		
84	HIGO				■						■					
84	ITM Waves						■	■	■							
85	L1 Sentinel			■		■										
85	MagCon		■				■									
85	SECEP								■							■
86	SEPM Mission		■	■	■	■										
86	Solar Polar Imager			■	■	■							■	■	■	
87	Solar Weather Buoys			■	■	■									■	
87	Telemachus			■	■								■	■	■	
	Future Heliophysics Missions															
88	Dayside Boundary Con		■				■									
88	FarSide														■	
88	Inner Mag Con						■									
88	InterStellar Probe				■						■					
89	Tropical ITM Coupler						■	■		■						
89	MTRAP	■	■					■								
89	RAM	■	■										■	■		
90	SHIELDS		■			■									■	
90	Stellar Imager													■		
	Partnership Missions															
91	ADAM						■	■	■			■				■
91	JPO/JUNO															
91	L1 Earth-Sun			■		■										
92	Lunar Recon Orbiter															
92	MARS						■	■	■							
92	Mars Science Lab															
93	Pluto/Kuiper					■					■					
93	Solar Sail Demo		■	■	■											


Objective H: Understand the Nature of Our Home in Space
H1
H1.1
H1.2
H1.3
H2
H2.1
H2.2
H2.3
H3
H3.1
H3.2
H3.3
H4
H4.1
H4.2
H4.3
H4.4
Objective J: Safeguard the Journey of Exploration
J1
J1.1
J1.2
J1.3
J2
J2.1
J2.2
J3
J3.1
J3.2
J3.3
J4
J4.1
J4.2
J4.3
J4.4
J4.5
Research Focus Areas
Investigations
Great Observatory
ACE
Cassini
Cluster
FAST
Geotail
IMAGE
Messenger
POLAR
RHESSI
SOHO
TIMED
TRACE
Ulysses
Voyager
Wind
Missions In Development
AIM
CINDI
THEMIS
Solar B
STEREO
TWINS
SDO
IBEX
Near-Term Missions
RBSP - RB Storm Probes
MMS - Mag MultiScale
ITSP - IT Storm Probes
IH Sentinels
Solar Probe
Solar Orbiter
GEC
Intermediate-Term Missions
AAMP
DOPPLER
GEMINI
Heliostorm
HIGO
ITM Waves
L1 Sentinel
MagCon
SECEP
SEPM Mission
Solar Polar Imager
Solar Weather Buoys
Telemachus
Future Missions
Dayside Boundary Con
FarSide
Inner Mag Con
InterStellar Probe
Tropical ITM Coupler
MTRAP
RAM
SHIELDS
Stellar Imager
Partnership Missions
ADAM
JPO/JUNO
L1 Earth-Sun
Lunar Recon Orbiter
MARS
Mars Science Lab
Pluto/Kuiper
Solar Sail Demo

Heliophysics Missions Currently in Development

Aeronomy of Ice in the Mesosphere (AIM)

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

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

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

Coupled Ion-Neutral Dynamics Investigation (CINDI)

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

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

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

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

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

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

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

Solar-B

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

Solar B addresses most of the expected achievements in Phase 1 (now until 2015, page 56): reconnection, the mechanisms of particle acceleration near the Sun, the origins of solar disturbances, understanding of the sources of irradiance variations, causes of the extremes in the local environment, and prediction of space weather. Many Phase 2 topics are also covered.

Solar B complements SDO, STEREO, and SOHO by providing high resolution imaging and understanding of detailed mechanisms of variability. The essential next step in understanding the origins of solar activity requires the high resolution data from Solar B, expected to launch in 2006 .

Solar-Terrestrial Relations Observatory (STEREO)

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

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

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

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

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

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

partially driving its space weather.

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

Solar Dynamics Observatory (SDO)

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

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

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

Interstellar Boundary Explorer (IBEX)

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

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

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

Near-Term Heliophysics Missions

Radiation Belt Storm Probes (RBSP)

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

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

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

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

Magnetospheric Multi-Scale (MMS)

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

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

MMS has recently entered development and its results will be needed as soon as possible as a basis for the predictive models of space

weather needed to undertake heliospheric weather prediction in support of Exploration. Magnetic reconnection is a primary source of energy release and particle acceleration in plasmas. No mission has ever been properly instrumented and configured to measure the small-scale features of reconnection in space. Thus, we know little about this fundamental process that drives much of the activity on the Sun, near Earth, and throughout the Solar System.

Ionosphere-Thermosphere Storm Probes (ITSP)

The ITSP mission is designed to investigate and understand the dynamic changes of the ionosphere-thermosphere system during solar and geospace storms. In particular, the effects of ionospheric irregularities, especially at mid-latitudes, have important societal consequences and are not the subject of any other planned mission. Variations in electron density of the ionosphere and changes in the neutral composition of the thermosphere impact radio propagation for communications, radar, GPS, and increase the drag on low altitude spacecraft.

ITSP combines imaging and in-situ measurements of the I-T system with physics-based models to provide the fundamental understanding required to advance IT models to the level of predictive capability. ITSP will investigate details of ion-neutral interactions, cross-scale coupling of global processes driving mesoscale and microscale variability, circulation, chemistry, and the role of penetration and dynamo electric fields on the behavior and redistribution of the ionospheric plasma.

Two LEO satellites are necessary, slightly separated in local time in order to determine how electric fields, thermospheric winds, and composition interact to redistribute energy and generate changes of electron density in the ionosphere. Daytime thermospheric composition, nighttime electron density, and the global state of the system will be provided by an imager that will fly as a Mission of Opportunity.

The scientific questions addressed by ITSP have direct relevance to the Vision for Space Exploration. Because ITSP will characterize, understand, and predict the I-T processes that degrade augmented GPS performance and produce scintillation of radio signals, similar concerns at Mars may be addressed by applying the knowledge gained at Earth. At Mars, we must be able to land with precision and communicate with assurance. ITSP informs the design of systems for precision navigation and communication without requiring that we build at Mars the equivalent of the Earth's network of ionospheric observatories.

ITSP was designed to overlap with the SDO and RBSP missions in the 2008-2015 timeframe. The ITSP imager will supply context for the RBSP by imaging precipitation boundaries and temporal behavior of magnetospheric populations. The optimal schedule places ITSP at solar maximum and in the declining phase of the solar cycle when the ionosphere is both enhanced and disturbed. This is the most stressing phase of the solar cycle from the standpoint of technical systems and the extreme conditions for the advanced models to be developed. Under current NASA funding guidelines, ITSP cannot be flown until well into the declining phase of the solar cycle. Further, the SDO 5-year mission design life concludes in 2013 so that an extended SDO mission lifetime will be needed to provide the required context observations. These are compromises and risks that could be avoided with a modest acceleration of the program.

The GEC mission may launch in a similar timeframe providing highly desirable scientific synergies that utilize the two orbit configurations and measurement complements. However, because of the urgency of each of these missions, each should fly as early as funding permits, regardless of any loss of overlap with each other or the other LWS missions.

Inner Heliospheric Sentinels (IH Sentinels)

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

Interactions in interplanetary space make the

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

Solar Probe (SP)

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

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

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

Solar Orbiter (SO)

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

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

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

Geospace Electrodynamic Connections (GEC)

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

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

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

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

Intermediate-Term Heliophysics Missions

Auroral Acceleration Multi-Probe (AAMP)

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

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

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

DOPPLER

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

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

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

Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)

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

discover the important feedback and dissipative mechanisms between these regions.

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

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

Heliostorm

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

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

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

Heliospheric Imager and Galactic Observer (HIGO)

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

The spacecraft will use a Venus-Earth gravity assist to attain a final 1 x 4 AU equatorial orbit. A spin-stabilized spacecraft supports imaging the heliopause and the solar wind termination shock, determination of the isotopic and elemental composition of the neutral portion of

the interstellar gas; measurement of the flow direction, speed and temperature of interstellar atoms, and the composition and radial profiles of extended inner source pickup ions. HIGO also will detect time-dependent interactions of large-scale structures with heliospheric interfaces.

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

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

Ionosphere Thermosphere Mesosphere Waves (ITMW)

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

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

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

L1-Sentinel

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

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

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

Magnetospheric Constellation (MC)

MC will employ the first sensor web of ~36 spacecraft in the Earth's magnetosphere that can describe the temporal and spatial structure of complex turbulent plasma processes. These

phenomena occur throughout the vast regions of the Earth's magnetosphere, including much of cislunar space between the Earth and its moon, as well as the important magnetotail. *In situ* plasma, magnetic field, and energetic particle observations will be used to distinguish between nonlinear internal dynamics of the magnetosphere and global responses to varying solar wind conditions. The observations will resolve spatial and temporal scales sufficient to enable close cooperation with state-of-the-art numerical simulations capable of describing magnetic flux, mass transport, energy conversion, and dissipation. By removing the spatial and temporal ambiguities that limit single spacecraft and extending the reach of clustered spacecraft missions to larger scales, MC will be the first to reveal the mesoscale pattern of changes within the magnetosphere. It will quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and the transport of these quantities between regions.

A distributed sensor-web array of spacecraft is the logical successor to the Magnetospheric Multi-Scale Mission (MMS), which is designed to penetrate the microscale physics of reconnection using four closely spaced spacecraft. MC will establish the first true meteorological facility for the mesoscale study of storm development in space weather. Understanding the mass and energy flow in the magnetotail and throughout the rest of the magnetosphere is an unresolved issue of fundamental importance for understanding this environment. With the flight of the New Millennium ST-5 mission, all of the technological obstacles to this mission have been addressed. MC could be the next STP mission after GEC, which puts it in the Phase 2 mission queue.

Sun-Earth Coupling by Energetic Particles (SECEP)

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

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

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

Solar Energetic Particle Mission (SEPM)

SEPM will determine how, when, and where solar energetic particles (SEPs) are accelerated and help determine how the solar wind is accelerated. A large aperture UV coronagraph-spectrometer and a large aperture visible light coronagraph-polarimeter will observe the corona from 1.15 to 10 solar radii. SEPM instrumentation will be about 100 times more sensitive than current coronagraphs. New diagnostics will determine velocity distributions for electrons and minor ions and derive magnetic field strengths in coronal streamers and coronal mass ejections (CMEs). SEPM will

measure critical plasma parameters in pre- and post-shock CME plasmas including suprathermal seed particle populations and it will characterize upstream turbulence which is believed to play a critical role in particle acceleration.

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

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

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

Solar Polar Imager (SPI)

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

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

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

Solar Weather Buoys (SWB)

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

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

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

our outward journey (J.2) to the surfaces of the Moon and Mars.

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

Telemachus

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

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

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

Future Heliophysics Missions

Dayside Boundary Constellation (DBC)

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

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

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

Farside Sentinel (FS)

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

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

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

Inner Magnetospheric Constellation (IMC)

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

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

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

Interstellar Probe (ISP)

Interstellar Probe is the first mission that will leave our heliosphere and directly sample and analyze the interstellar medium. It is a single

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

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

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

Tropical ITM Coupler (ITMC)

ITMC will explore how neutral and plasma interactions distribute energy within and between Earth's low-latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

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

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

Magnetic TRAnsition region Probe (MTRAP)

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

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

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

Reconnection and Microscale Probe (RAM)

The Reconnection and Microscale mission is a next generation, high resolution solar mission focused on understanding the basic small-scale processes in hot magnetized plasmas that are ubiquitous throughout the universe. In hot magnetized plasmas the physical processes governing the dynamics take place on remarkably small spatial and temporal scales. RAM addresses several fundamental questions, such as what are the mechanisms and

magnetic topology that lead to reconnection, what micro-scale instabilities lead to global effects and how do magnetic stresses form and release in the solar corona? RAM includes a 0.02 arcsec/pixel EUV imaging telescope, a 0.1 arcsec/pixel UV/EUV imaging spectrograph, and a small x-ray calorimeter to perform simultaneous high resolution imaging and imaging spectroscopy to understand the small scale dynamic processes and mechanisms of reconnection on the Sun.

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

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

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

SHIELDS is a new mission concept developed specifically in response to the Vision for Exploration to help ensure the safety and productivity of human and robotic explorers.

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

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

Stellar Imager (SI)

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

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

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

Partnership Missions

Aeronomy and Dynamics at Mars (ADAM)

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

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

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

Jupiter Polar Orbiter/Juno

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

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

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

L1-Earth-Sun

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

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

By observing simultaneously the Earth, the Sun, and the solar wind, the L1-Earth-Sun mission will enable the first detailed exploration of the couplings within the Earth-Sun system. It fulfills a fundamental and critical need in the Heliophysics strategic plan with cross-cutting synergistic objectives relevant to understanding fundamental processes which influence Earth's climate as well as strong relevance to

the Vision for Exploration by improving our understanding necessary for solar activity prediction and its impact on the Earth.

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

Lunar Reconnaissance Orbiter (LRO)

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

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

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

Mars Atmospheric Reconnaissance Survey (MARS)

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

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

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

Mars Science Laboratory (MSL)

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

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

New Horizons – the Pluto / Kuiper Belt Mission

The Pluto/Kuiper Belt Mission will help us understand worlds at the edge of our solar system by making the first reconnaissance of Pluto and Charon - a "double planet" - and the last of the nine planets in our solar system to

be visited by spacecraft.

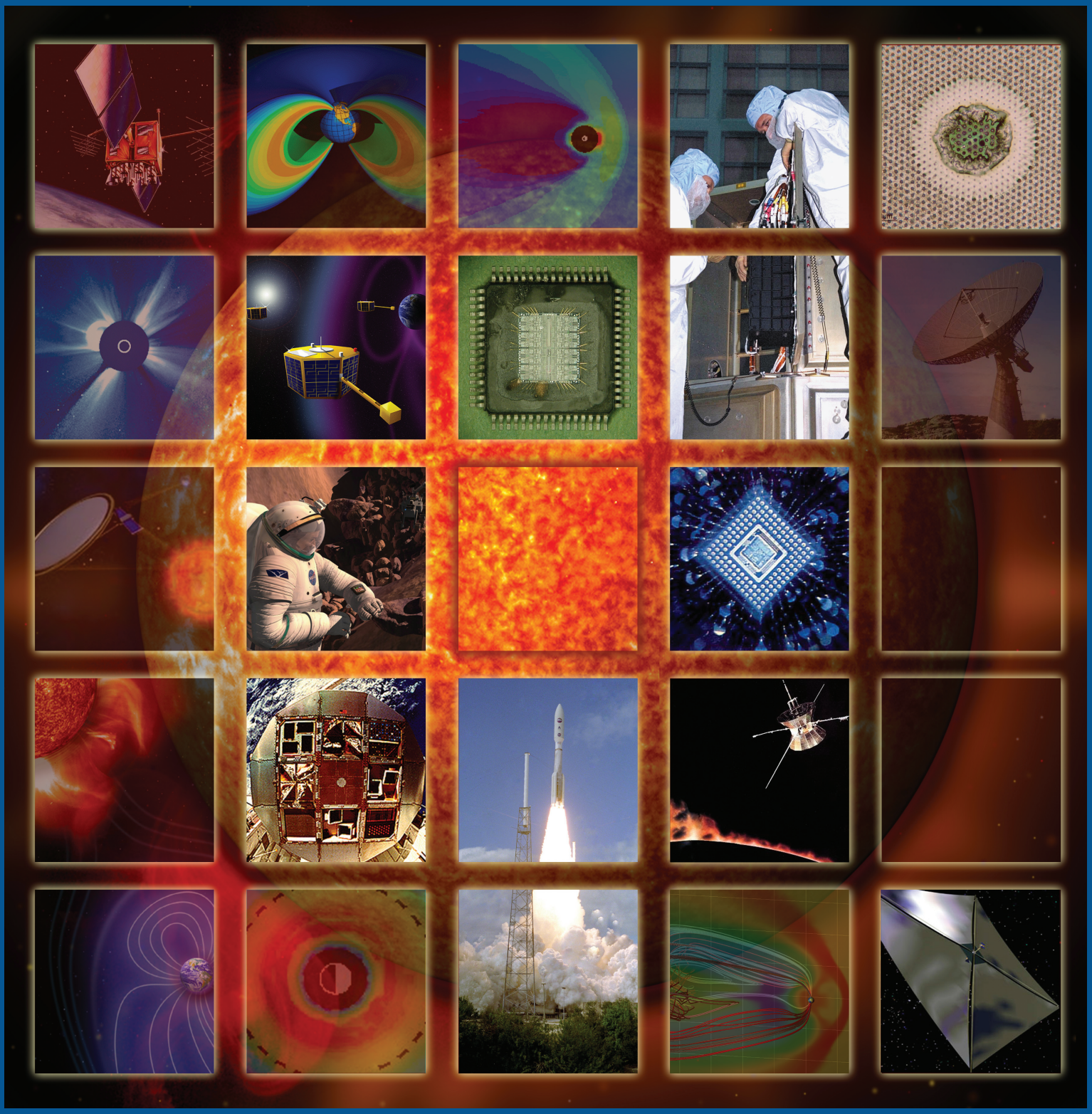
Launched in January 2006, Pluto/Kuiper will swing past Jupiter for a gravity boost and scientific studies in early 2007 and ultimately reach Pluto and its moon, Charon, in July 2015. Then, as part of an extended mission, the spacecraft will head deeper into the Kuiper Belt to study one or more of the icy mini-worlds in that vast region at least a billion miles beyond Neptune's orbit. The mission will help answer basic questions about the surface properties, geology, interior makeup, and atmospheres on these bodies.

Heliophysics will use this opportunity to obtain in situ measurements of the solar wind interaction with Pluto. Ionization of Pluto's escaping atmosphere suggests the interaction with the solar wind will be similar to that of a comet. However, in contrast to cometary interactions that have been measured relatively close to the Sun, the weak magnetic field and tenuous density of the solar wind in the outer heliosphere imply that the interaction with Pluto's atmosphere will include significant kinetic effects and be highly asymmetric. Understanding these interactions will expand our knowledge of the astrophysical processes affecting these bodies and that part of the solar system. The SWAP instrument will make measurements of the solar wind deceleration and deflection due to the interaction with Pluto. The PEPPSI instrument will measure energetic particles produced in the interaction region. SWAP will also measure solar wind conditions at large distances from the Sun and measure the effects of pickup protons from the interstellar medium in the distant heliosphere.

Solar Sail Demo (SSD)

Because of the impossibility of fully validating Solar Sail technology on the ground, the application of solar sails to a strategic science mission absolutely requires a prior successful flight validation. Following a Solar Sail Demonstration mission with, say, 40m edge length and 25 g/m^2 sails, the technology could be readily scaled to meet the needs of the Heliostorm mission (100m edge length and 14 g/m^2 sails). Once a mission in the class of Heliostorm has flown, further scale-up could be accomplished for Solar Polar Imager (160-m edge length, 12 g/m^2). A third generation solar sail would be required for a visionary mission such as Interstellar Probe.

The flight of a Solar Sail Demo must precede the first strategic launch by 5-6 years. A Solar Sail Demo mission in mid-2010 would permit the flight of Heliostorm in 2016 or thereafter. Approximately 5 years would then be needed after Heliostorm to enable the scale-up to Solar Polar Imager.



Chapter 5. Heliophysics: Technology Investments

Chapter 5

Heliophysics: Technology Investments

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

Innovation is the engine that drives scientific progress, through the development of new theories, the invention of new technologies that lead to improved measurements , and ultimately the emergence of entirely new capabilities. To pursue a rigorous study of the Heliophysical system we will pursue the development, infusion, and study of new technology, both for its stimulating effect on science and to enable and enhance new missions of exploration. Continuing progress in the characterization, modeling, and prediction of this system will also require technological development in a number of key areas.

Heliophysics Capability Requirements

- Simultaneous sampling of space plasmas at multiple points with cost-effective means and measuring phenomena with higher resolution and better coverage to answer specific science questions and enable system science;
- Achieving unique vantage points such as upstream of the Earth-Sun L1, polar orbit around the Sun, or even beyond the heliosphere;
- Developing the next generation of capable, affordable instrumentation;
- Enabling the return of vast new data sets from anywhere in the solar system;
- Synthesizing understanding from system-wide measurements using new data analysis and visualization techniques.

The highest priority Heliophysics technology needs follow these key focus areas

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

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

Table 4.1. Enabling and Enhancing Technologies for Heliophysics Missions

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

Technology	Enabling	E
	Enhancing	+
Programs	Solar Terrestrial Probes	
	Living With a Star	
	Flagship Missions	
	Partnerships	

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

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

1. Developing compact, low-cost spacecraft and launch systems. Because of the complexity and large scale of solar system plasmas, progress requires clusters or constellations of spacecraft making simultaneous multi-point measurements (e.g., MMS, the LWS Storm Probes, Magnetosphere Constellation, GEC, Solar Weather Buoys, and the Inner Heliosphere Sentinels). These missions require the development of low mass, power, and volume instrumentation as well as low mass, economical spacecraft. Smaller, well integrated, spaceflight systems allow these missions to be accommodated on a single, and sometimes less expensive, launch platform. Good fiscal management also requires that we reduce the single unit cost of these multi-spacecraft systems; this will require efforts on multiple fronts. One important area of technology is the development of low-power electronics (LPE) for the instruments and spacecraft bus. One example is the CULPRIT Reed-Solomon Encoder on ST-5, scheduled for flight validation on ST-5 in 2006. LPE technology, if available system-wide on a satellite system, can reduce power consumption by up to 70%. Power dissipation at the component level can be reduced by factors of 50-100 over conventional technology. Other areas of high priority technology development include the development of "assembly-line" test and integration methods for the constellation-level missions and autonomous operation methods to reduce ground operations and to enable reconfiguration of mission elements based on internal or external cues. Support for further development efforts will be provided by the existing Instrument and Technology Development Research Opportunities and through the New Millennium Program.

2. Achieving high ΔV propulsion (solar sails). Progress in key areas of Heliophysics science requires access to unique vantage points and in some cases, non-Keplerian orbits. For example, imaging of the Sun's polar regions requires a high-inclination, heliocentric orbit. Conventional technology would require either 5 years of solar electric propulsion and multiple Venus flybys just to reach a 38° inclina-

tion in the inner heliosphere (as for ESA's Solar Orbiter) or a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (as for our future Telemachus mission). Neither means is as efficient or cost-effective as solar sail technology.

The solar sail will use the Sun's continuous supply of photons to propel spacecraft in the inner solar system to very high velocities ($\Delta v > 50$ km/s). They can also provide low-thrust propulsion to maintain missions in non-Keplerian orbits not feasible by other means. Solar sails will enable three important Heliophysics missions:

- Heliostorm, to provide earlier warnings of energetic particles accelerated by CMEs via measurements upstream of the Earth-Sun L1 point;
- Solar Polar Imager, to provide remote sensing of solar poles from an optimal vantage point – a circular, 0.5-AU, 75° inclination heliocentric orbit;
- Interstellar Probe, to sample interstellar space.

The In-Space Propulsion Technologies Project has advanced sail technology considerably in recent years. In 2004, two 10-m systems were tested in vacuum on the ground, followed by two 20-m systems in 2005. This has moved the solar sail from the realm of science fiction to science fact. The next steps for validation and engineering maturation are to deploy and fly a hundred-meter-class solar sail. A sail technology demo mission will demonstrate deployment feasibility, that a solar sail provides measurable acceleration, and that it can be steered. The technology flight experiment will test and validate the models and processes for solar sail design, fabrication, deployment, and flight. Such models and processes can then be used with confidence to design, fabricate, and operate the solar sails needed for strategic science missions. A sail demo is a candidate concept for the New Millennium Program's ST9 mission scheduled for 2010. Scale-up of the technology to 100-m lengths needed by Heliostorm could occur 5-6 years after a successful sail demo. Scale-up to still larger sails, such as for Solar Polar Imager (~160-m edge length), are imaginable from there. Three decades hence, the deployment of a larger, high-temperature sail required by a mission like Interstellar Probe (200-m radius) could be facilitated by human crews operating near libration points.

A solar sail of 20-meter edge length was successfully deployed in vacuum at the Space Power Facility at Plum Brook Station at the Glenn Research Center.

3. Designing, building, testing, and validating the next generation of Heliophysics instrumentation. In order to continue to lead the world in space science research, NASA must not only support the design and validation of space-quality instruments, but also develop and maintain unique instrument development and test facilities. Heliophysics missions carry a wide range of instrumentation, some designed to make *in situ* measurements of diverse space plasmas and others that make remote sensing measurements of plasma processes. The development of new instruments and instrument concepts is driven by the need to refine and improve instruments, reduce their mass and power consumption, and enable new measurement techniques. Progress in instrument technology development is needed at all technology readiness levels (TRLs), from basic concepts for new detectors (e.g. MEMS-based (micro-electro-mechanical systems) plasma detectors that could be used on MC) to system level demonstrations of improved instruments (e.g. compact Doppler/magnetographs for missions such as Doppler).

Specific component technologies that would benefit Heliophysics missions include: large

area, deep well CCDs, active pixel sensors, low-noise micro-channel plates, foil technology for ENA imagers, high performance EUV mirrors, UV blind ENA imagers, low-mass high-voltage power supplies, advanced X-ray optics and detectors, thin solid-state energetic particle detectors, compact accurate magnetic sensors, and small dead-layer solid state detectors. At the system level, many payloads on future Heliophysics missions will be severely mass and power constrained (MC and Solar Weather Buoys, for example). Technologies that reduce sensor and electronics mass and power would be particularly useful. In addition it is thought that the incredible shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter structural materials and more power efficient ionization sources.

The development of these instruments will proceed from formulation of new ideas and designs (perhaps based on technologies developed in other fields), basic proof of concept, fabrication of test models, laboratory testing, and finally flight validation. One important avenue for assessing the effects of the variable space environment on potential fight instruments and other technologies is the LWS Space Environment Testbed (SET) Program. It is important to maintain a balanced program that supports all levels of development, particularly the final time-consuming development stages that enable instruments to be used in-flight.

For some applications, NASA's low-cost access to space (LCAS) program provides an ideal avenue for testing and validation. A prime example of this paradigm is the development of top-hat style plasma detectors. These were first conceived for studies of the Earth's auroral regions and were first flown on sounding rockets. The sounding rocket successes led directly to advanced concept instrumentation being flown on highly successful magnetospheric missions.

4. Returning and assimilating large data sets from across the solar system. As our exploration of the heliophysical system proceeds, spaceflight missions will place an increasing demand on NASA's communication resources. Missions that image the Sun and Earth require high bandwidth communication to provide high cadence, high resolution imaging in multiple spectral channels. As remote sensing missions are deployed beyond Earth orbit, these requirements become more difficult to meet: missions such as SHIELDS or the Farside Sentinel will study the Sun from as far as 2 AU from the Earth.

Multi-spacecraft missions, both near and far from Earth, will also stretch the capabilities and operating cultures of the current communications infrastructure. Improvements to our communications technologies have begun and will enable new science discoveries. Planned enhancements to the Deep Space Network (DSN), replacing outdated 70m and 34m antenna with arrays of smaller antenna working at Ka-band, will increase the available bandwidth substantially, while also providing the flexibility to communicate with multiple spacecraft simultaneously. Using 200 such antennas, for example, would enable kilobit per second communications from an Interstellar Probe at 100 AU.

Optical communication technologies would also provide a substantial increase in communication bandwidth and potentially provide the capability for high-bandwidth point-to-point communication for missions monitoring the interplanetary radiation environment. The next generation DSN will eventually provide both enhanced RF and optical communications. Arrays of small antennas plus the RF improvements (transmitters, inflatable antennas, transponders, for example) together with optical communication would provide orders of magnitude increase in science data rates. RF arrays would also enable a significant increase in the number of spacecraft that can be supported, particularly in closely spaced clusters.

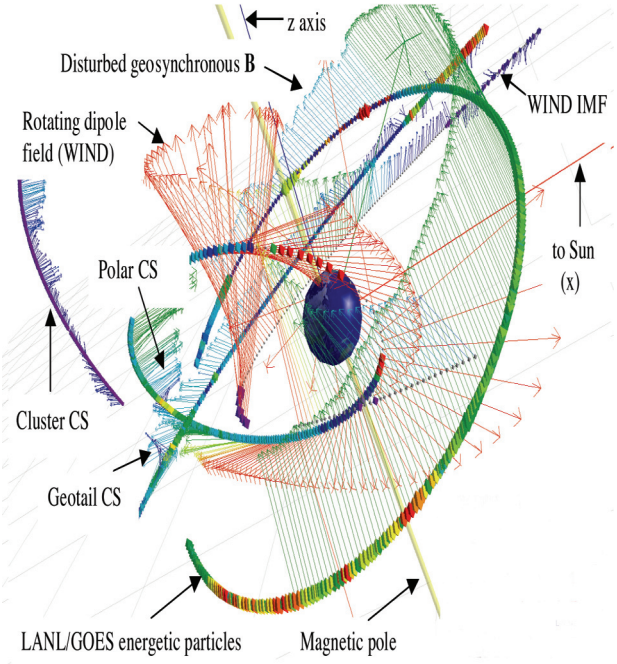
5. Enabling analysis, data synthesis, modeling, and visualization of plasma and neutral space environments throughout the solar system. To effectively model the physical processes controlling our planetary and interplanetary environment, information from the single spacecraft vantage point is being replaced by multi-spacecraft distributed-observatory methods, and adaptive mission archi-

tectures termed "Sensor Webs." These require computationally intensive analysis methods and data ingestion and assimilation techniques appropriate to an incredibly sparsely sampled system. Remote space weather predictive capabilities for explorers far from Earth will need real-time data assimilative technologies. In many missions (e.g. the Inner Heliosphere Sentinels, MagCon, or SEPM) modeling will be an integral element of the mission data products. Other modeling efforts will assimilate data collected by multiple missions into coherent visualizations of broader physical systems. Critical to supporting this future mission operations approach is the development of the computing infrastructure that makes such synergism possible. Well managed archives, virtual observatory systems, and the vigorous application of knowledge support tools are central to many of the major Heliophysics science goals to be achieved 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 Virtual Observatory programs, which will provide pattern and feature recognition to allow large datasets to be mined for events, particularly those detected by multiple platforms; the Columbia supercomputer, which uses 10,240 Intel Itanium-2 processors and provides an order of magnitude increase in NASA's computing capability; and the VisBARD project, in which space science data is displayed three-dimensionally along spacecraft orbits allowing rapid determination of vector configurations, correlations between measurements at multiple points, and global relationships.

Organizations such as NASA's Coordinated Community Modeling Center (CCMC), the NSF-funded Center for Integrated Space Weather Modeling (CISM) and the Center for Space Environment Modeling (CSEM) at the University of Michigan are producing integrated models, transitioning research tools into operational infrastructures, and building software frameworks that link models. These efforts are by definition cross-disciplinary, requiring expertise in numerical analysis, high-performance computational science, and solar, interplanetary, magnetospheric, ionospheric and atmospheric physics.

Effective future progress will require a carefully designed 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. In the late 20th century, a major revolution in chaotic systems and nonlinear dynamics arose because of a new coupling



A ViSBARD view of slightly less than a day of magnetospheric data including about 40 time series along the orbits of nine Heliophysics Great Observatory spacecraft. The magnetic field vectors and numerous other scalar quantities can be retrieved directly from the internet. The software allows pan, zoom, rotation, symbol scaling, and time selection and scrolling. This view provides a global picture of events that is not possible with large numbers of line graphs.

Labels have been added (CS=current sheet, IMF=interplanetary magnetic field). Energetic particle data from the geosynchronous spacecraft are overlapping; to see each set individually, a smaller time interval must be chosen, in which case the time resolution of the glyphs will also increase up to the limit of the data. *Image courtesy of D.A. Roberts.*

of models and high-performance computing. Similarly, we expect that the emerging linkage of rich data sets, high-performance computing, models and sensors will lead to even greater scientific understanding of how our solar system operates and how we can best operate within it. It is within this context that the appropriate relationships and investments in planning, data access and preservation, and analysis and research are best coordinated to provide the research-supported space weather capability at the core of this roadmap.

6. Enabling Space Weather Prediction. The Earth Sciences and particularly tropospheric meteorology have long been engaged in the process of understanding and simulating our atmosphere and oceans in sufficient scope and detail to support the prediction of weather. Not only can we characterize the long-term statistics of atmospheric weather, we can also "nowcast" current conditions and foretell their short-term development. Moreover, we can make forecasts of how the weather will evolve over the midterm of several days to a few weeks, albeit with accuracy that decreases with time in the future. We can even simulate and forecast how the climate will respond to changes such as the level of anthropogenic compounds, volcanic eruptions, or bolide impacts.

To support NASA's exploration goals, we must adopt the space environment across the inner solar system as our enlarged domain for study, simulation, and prediction. Even though a host of new phenomena present themselves as challenges for space weather forecasting, the basic techniques of data assimilation into global circulation models is an element common to all atmospheric sciences. In one sense, we have simply expanded the definition of "global" and necessarily added the plasma state of matter. This process is already well underway in the case of geospace weather. NOAA, DoE and DoD, along with NASA, have been active in this area for decades in the characterization, nowcasting, and increasingly, forecasting of geospace weather. NASA must now expand this purview to the Moon and Mars.

The regions to be explored include first the Moon and cislunar space, then later Mars and cismartian space, and eventually the asteroid belt. This requires better knowledge of Earth's upper atmosphere, because returning explorers will rely on aerocapture for successful landing. Also needed is an improved predictive knowledge of the radiation belts, which have proven to be more variable and volatile than was expected from early reconnaissance. When astronauts travel beyond the Earth's ionosphere, knowledge of solar energetic particles becomes of paramount importance, as indicated by the vulnerability of the Apollo astronauts, who narrowly avoided devastating space storms in 1972.

Among the seldom-appreciated features of the lunar landscape are the dust fountains that exist at the solar terminators. Lunar dust is extremely abrasive and problematic for operation of human-tended systems. At Mars, dust and Martian meteorology present even more obvious concerns for arriving astronauts. Efforts to use aerobraking and aerocapture at Mars have been complicated by strong variability of the atmosphere, indicating the need for better predictive models of that medium as well. In all these areas, human exploration must be informed by science to maximize productivity and minimize risks.

Understanding space weather throughout the inner solar system becomes more important as astronauts and critical spacecraft systems spend more time away from the sheltering Earth. It will be incumbent upon NASA to support the operational resources required. The activities described here form a sound research foundation for space weather support. We will need greater rigor in the verification and validation of predictive models, observations will be required from remote sites, and greater computer power must be brought to bear on the continuous operation of modeling tools. This all depends upon many infrastructural developments that go beyond what is in place today. What must ultimately emerge is a research supported operational capability directed toward Inner Solar System Environment Services, one that is highly analogous to the National Weather Service for tropospheric weather or the NOAA Space Environment Center for geospace weather.

Chapter 6. Heliophysics: Sun-Solar System Connection Impacts

- Education and Public Outreach
- Links with Other NASA Activities
- Advancing U.S. Scientific, Security, & Economic Interests
- External Drivers of the NASA Heliophysics Program

Sun-Earth Day

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

2001 - Having a Solar Blast
2002 - Celebrating the Spring Equinox
2003 - Live from the Aurora
2004 - Venus Transit
2005 - Ancient Observatories: Timeless Knowledge
2006 – Eclipse In a Different Light

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

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

Wijiji, Chaco Canyon: This photo was taken from inside the northwestern corner of the Wijiji Great House. It is believed that this site may have been used as a calendar station for the winter solstice. On December 4-5 the rising sun appears in the leftmost region of the deepest notch on the horizon. Over the next 16-17 days the rising sun appears further and further to the right until finally reaching the rightmost region of the notch on the winter solstice. *Photo Credit: Troy Cline*

Education and Public Outreach

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

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

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

These messages are of high interest and relevance to the public and they span the range of scientific activity engaged in by the Heliophysics community. The traceability to the Heliophysics science and exploration objectives is clear. Chart 6.1 below shows the logical flow-down outlining how the Heliophysics scientific objectives and associated research focus areas lead to the five E/PO themes. The themes then inform the implementation of programs of formal and informal education and public outreach.

The anticipated scientific achievements articulated in Chapter 3 for each of the next three decades that relate most clearly to these themes are shown in Table 6.2A. The themes and achievements are color coded to show the most direct links. Table 6.2B also identifies the missions that are most closely associated with the achievements and themes.

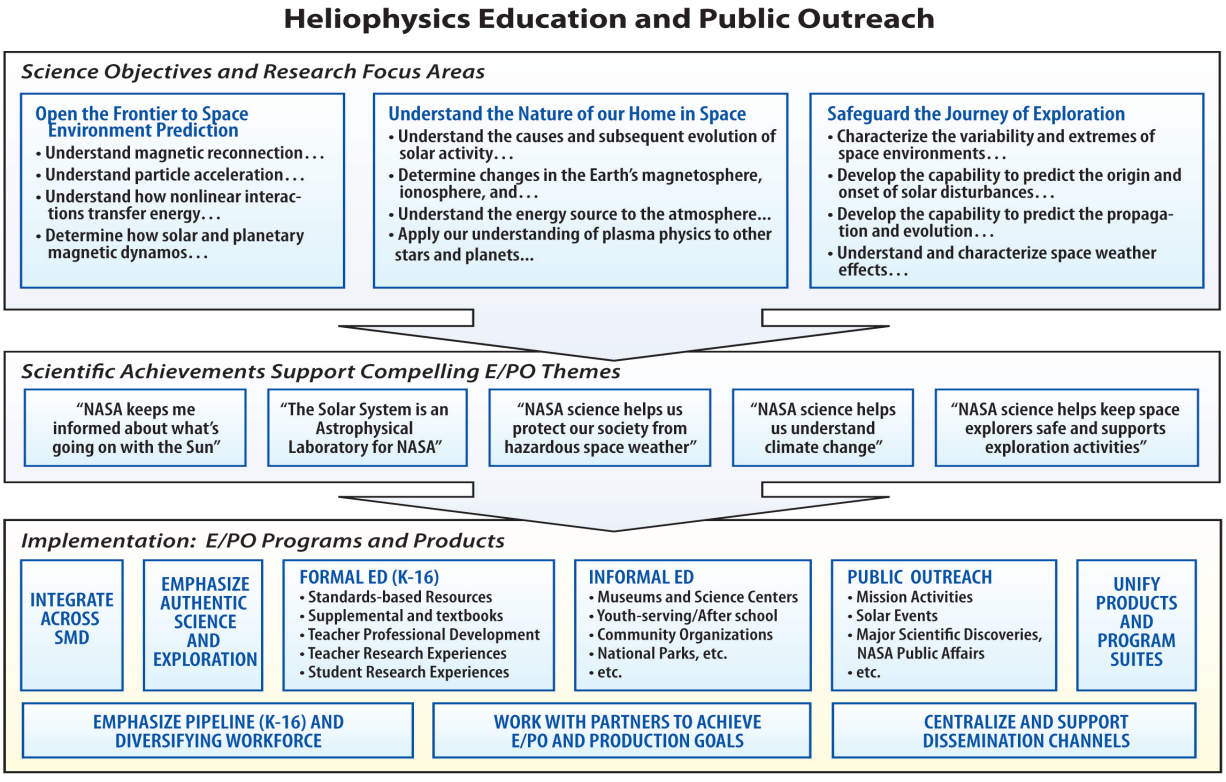


Chart 6.1. Logical Flow from Heliophysical Science to E/PO Themes and Implementation

Table 6.2A. Science Achievements from the Roadmap support Heliophysics E/PO Themes

Science Achievements Support Heliophysics E/PO Themes

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

Scientific progress requires new knowledge systems and innovative use of new technology
"Measure and Characterize...Develop Physical Models...Learn to Predict...From Sounding Rockets to Solar Sails"

Expanded and invigorated education and public outreach are essential to the achievement of the Vision for Space Exploration (VSE). NASA's Strategic Objective for Education and Public Outreach is to "Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation." The Heliophysics community emphasizes the connection between achievement of this strategic objective and the Vision for Space Exploration. The development of the workforce needed to achieve NASA's objectives requires that E/PO activities engage young people and capture their interest and passion. We need to increase the capacity of our nation's education systems, both in school (Formal: K-16) and out of school (Informal), to prepare students for scientific and engineering careers.

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

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

An exciting example of E/PO targeted at un-

Table 6.2B. Heliophysics recommended missions identified with Heliophysics E/PO Themes

Missions Key to Science Achievements Identified with Heliophysics E/PO Themes

Heliophysics Science Objectives	Heliophysics E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-Beyond
Objective F: Open the Frontier to Space Environment Prediction	"NASA keeps me informed about what's going on with the Sun" "The Solar System is an Astrophysical Laboratory for NASA"	Cluster, TRACE, Polar MMS, Solar Reconnection, RBSP, SDO, Solar-B, STEREO, THEMIS Auroral Imaging, L1-Earth-Sun Cluster, L1-Monitor ITSP, IBEX, MMS, SDO, STEREO, L1-Earth-Sun	IBEX, ITImager, MMS, RBSP, SDO, Solar-B, STEREO, THEMIS Magnetospheric Constellation, IH Sentinels, Solar Probe, GEC, ITSP, Solar Orbiter, L1-Earth-Sun	SHIELDS, SPI, Farside, SWB, SPI , RAM, MTRAP, Magnetospheric Constellation, IMC,DBC,Stellar Imager Assumes: ITSP, L1-Earth-Sun, SEPM, Auroral Imagers, IH Sentinels, MTRAP, IMC, Magnetospheric Constellation, DBC, AAMP
Objective H: Understand the Nature of our Home in Space	"NASA science helps us protect our society from hazardous space weather" "NASA science helps us understand climate change"	ACE, Cluster, IMAGE, FAST, Polar, TIMED, GEC, MMS STEREO, ITSP, ITImager, RBSP, SDO, Rocket Campaigns IMAGE, TIMED, AIM, CNOFS ITSP, ITImaging, GEC, SDO, Rocket Campaigns	MSL, Spitzer New: MAD, TE, Lunar Solar Wind History Experiment Europa Mission SDO, ITSP, RBSP, SP, DOPPLER, SEPM, RAM, SIRA, SHIELDS, Solar Orbiter SECEP, ITMWaves , L1/L2 cont. global obs. Rocket Campaigns	Existing: Magnetospheric Constellation, AMS, ITM-Waves, GEMINI, Dayside Boundary Con. New: Rocket Campaigns/LCAS, IMC, ITC New: Solar Polar Imager, ITMC, L1-Earth-Sun (irradiance, particles),SECEP, SHIELDS
Objective J: Safeguard the Journey of Exploration	"NASA science helps keep space explorers safe and supports exploration activities"	TIMED, Soho, ACE, Cassini, Cluster, SDO RBSP, ITSP, IH Sentinels, L1-Earth-Sun, MMS, MSL, Rocket Campaigns	IH Sentinels, SWB, Heliostorm/L1-Earth-Sun, Magnetospheric Constellation, IMC, GEC, GEMINI , DOPPLER, SHIELDS, SEPM, MTO, MAD, SPI	Interstellar Probe, HIGO, Telemachus, Outer heliosphere radio Assumes, results from robotic surveys of Mars and MAD, results from solar-interplanetary and Geospace missions (SDO, DP, HIS, RBSP, ITSP, LRO, Lunar experience) SCOPE, Telemachus

Scientific progress requires new knowledge systems and innovative use of new technology
"Measure and Characterize...Develop Physical Models...Learn to Predict...From Sounding Rockets to Solar Sails"

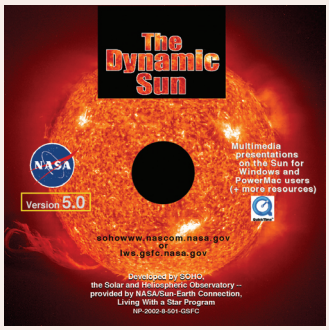
derrepresented communities is NASA's Sun-Earth Connection Education Forum's (SECEF) Sun-Earth Day programming for 2005: Ancient Observatories: Timeless Knowledge (see box). This broad program allowed NASA and Native American astrophysicists to share their research into the efforts of ancient cultures to understand the Sun and its affects on their lives, highlighting the importance of the Sun across the ages. Through programs such as these, Heliophysics scientists convey NASA's mission and research program activities to diverse audiences. Both English and Spanish language materials have been disseminated.

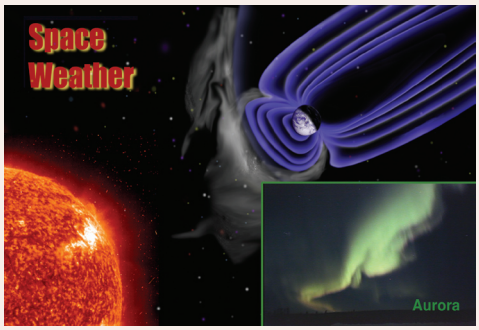
Examples of Strong Mission E/PO Programs: SOHO & IMAGE

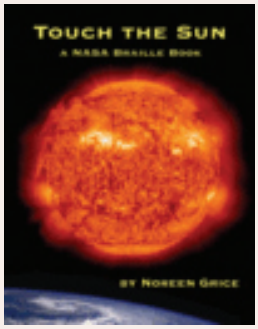
SOHO, the Solar and Heliospheric Observatory mission, runs a vigorous program to disseminate images to informal audiences and to the media, regularly distributing images of the Sun from the LASCO, EIT, and MDI instruments in near real time on the Web, and weekly to the American Museum of Natural History's AstroBulletin, and to a variety of media publishers, including National Geographic. Sun and space weather 3-D/motion postcards (lenticulars) are a very popular tool for engaging students and the general public. Over 200,000 lenticulars have been distributed.

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

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



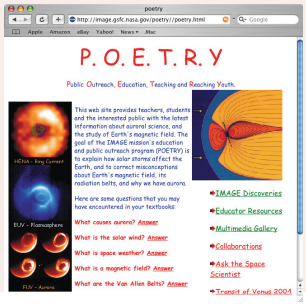




IMAGE, the Imager for Magnetosphere-to-Aurora Global Exploration mission, has been at the forefront of providing teachers with math and space science classroom activities. The IMAGE team works hard to improve public awareness of space weather impacts and to improve student math skills. Its annual space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

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

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



E/PO Challenges and Recommendations

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 via the press and other communication outlets. Table 6.3 presents a summary of challenges to effective E/PO. The remainder of this section presents a series of recommendations to expand and enhance NASA's E/PO activities.

Table 6.3. Challenges and recommendations to effective E/PO

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

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

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

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

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

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

nership with professional organizations such as the National Science Teachers Association has proven effective for NASA, and should be expanded.

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

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

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

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

Extend focus to higher education in order to ensure adequate numbers of trained scientists and engineers for the Heliophysics community and the rest of NASA to achieve the VSE. Solar and space physics needs a national effort that relates the exciting applications in our field to specific curricular needs of introductory physics and astronomy – classes

with substantial enrollments at just about every college in the nation. The excitement of space science can entrain and encourage more undergraduates through physics, math and engineering programs at the university level. This will compliment current programs geared towards providing early research experience (such as NSF's REU program) that are very important for attracting non-traditional students into the workforce. Attention needs to be paid to how the space physics workforce is developed – where do students come from and why – in order to ensure sufficient numbers for a healthy scientific community able to achieve NASA's goals.

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

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

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

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

Focus on innovative external partnerships to create programs that reach a broad range of the public. Through leveraging partnerships with informal science learning centers (museums, planetaria, science centers), national parks, community groups (Girl Scouts), publishers, and the media, Heliophysics science can be more widely disseminated by taking advantage of existing channels. For example, NASA has connected very effectively with the National Parks to provide content on the aurora and noctilucent clouds for summer pro-

grams in Alaska and information about the Sun in support of educational programs at parks in the southwest. Such programs provide amplified impact by enhancing the capacity of established channels to engage, excite and educate the public with science and engineering content. New avenues should also be explored, for example, products developed with the gaming industry could engage the public, young and old, in the Vision for Space Exploration.

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

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

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

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

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

For smaller efforts NASA should continue to offer supplements for which individual PIs can apply to support E/PO activities that stem from their scientific research and mission activities. New E/PO activities should map to one of the

five themes articulated above. Themes will be modified and replaced as part of future Heliophysics strategic planning activities. However, rather than expect each investigator to invent a new set of E/PO activities, we recommend that the allocation of E/PO funds ordinarily be linked to efforts consonant with a broad portfolio of approved, adaptable E/PO programs and product templates from which the PI may select. Further, NASA should require that dissemination ordinarily be through one or more of NASA's approved and maintained channels.

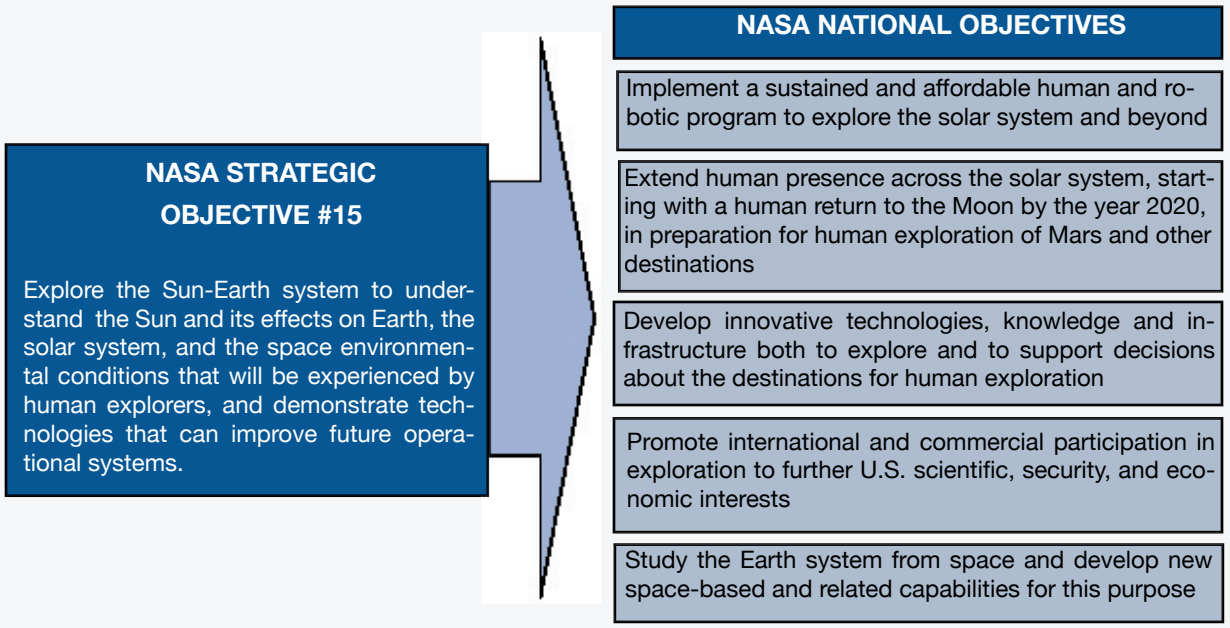
The portfolio of approved E/PO product and program suites should be developed using existing successful E/PO efforts as models, as well as taking advantage of best practices in formal and informal education. It is very important that these be developed through collaboration between the Science Directorate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

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

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

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

Links Between Heliophysics and Other NASA Activities



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

Links Between the Heliophysics Strategic Roadmap and other NASA Strategic Roadmaps

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

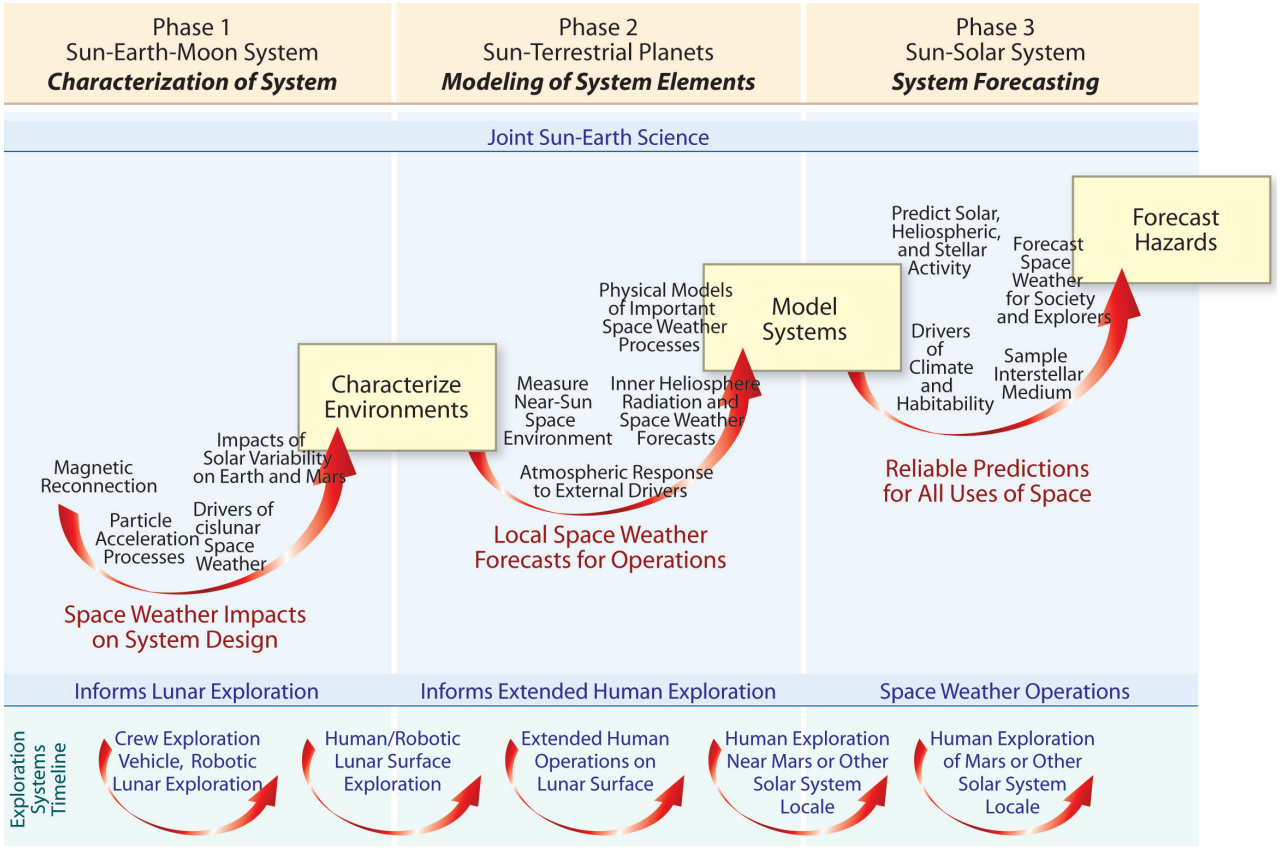
To the degree that the space environment matters to people or their technological systems, whether on Earth or in space, Heliophysics has application to human activities. Penetrating energetic particles and photons produced by acceleration and radiation processes in space plasmas profoundly and adversely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

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

sential enabling activities for space exploration operations. Therefore, we recognize strategic linkages between the Heliophysics Roadmap and all three Exploration Roadmaps (Lunar exploration, Mars exploration, and the development of the Crew Exploration Vehicle).

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

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



Links Between the Heliophysics Strategic Roadmap and NASA Capability Roadmaps

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

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

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

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

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

Instrumentation: Many future Heliophysics missions will require development of new scientific instrumentation, including large focal plane arrays, large-scale adaptive optics, and solar-blind energetic particle and photon detectors. The development of hyperspectral and three-dimensional detectors are needed for solar and geospace remote sensing. Miniaturization of high voltage power supplies will relieve mass and volume resource constraints. Increased quantum efficiency of UV and EUV detectors will enable significant savings in mass as small but sensitive instruments can be developed. The shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and power efficient ionization sources. Conductive polymers and other exotic materials and coatings may lead to development of solar blind detectors, new and better dust analyzers, and miniature mass spectrometers. It is important to develop and maintain ground test

facilities for simulating particle and radiation environments in space. Radiation test facilities will be particularly important as technological innovations and the push to develop more power efficient instruments results in smaller electronic instrumentation. Ground testing is extremely valuable, but NASA's low-cost access to space (LCAS) program is required for complete testing and full validation of advanced instrumentation. Imaging is an area of instrumentation where we should place significant development effort. Remote imaging provides more information than any practical number of single-point measurements. Imaging is crucial to understanding the complex interacting set of systems that control the Sun-Solar System connection well enough to develop the properly constrained and accurate predictive models that are critical to support exploration, including a sustained human presence in space. The three primary imaging tools include Energetic Neutral Atom (ENA), Radio Tomography, and Photon Imaging, Photon imaging includes x-ray, extreme ultraviolet (EUV), far ultraviolet (FUV), visible (VIS) and infrared (IR).

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

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

U.S. External Partnerships and Relationships

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious. The nation's efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, geospace, and other planetary environments as a single connected system. External constituencies requesting and making use of new knowledge and data from NASA's efforts in this area include the Federal Aviation Administration (FAA), the Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA), the power industry, and the industry of satellite manufacturers and operators (See Table 6.5).

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

International Cooperation

The **International Heliophysical Year** (ihy2007.org): The U.S. House of Representatives Science Committee approved House Con. Resolution 189: Celebrating the 50th anniversary of the International Geophysical Year (IGY) and supporting an International Geophysical Year-2 (IGY-2) in 2007-08. The resolution calls for a worldwide program of activities to commemorate the 50th anniversary of the most successful global scientific endeavor in human history - the International Geophysical Year (IGY) of 1957-58. The resolution also calls for an "IGY-2" that would be even more extensive in its global reach and more comprehensive in its research and applications.

International Living with a Star: In January 2002, the Interagency Consultative Group (IACG) established the International Living With a Star (ILWS) program. The IACG consists of the heads of the space science programs of the European Space Agency (ESA), the Japan Aerospace Exploration Agency

	Real-time Space Weather Data	Space Environment Specification	Satellite Anomaly Diagnosis	Navigation, Radar, Communication, Transmission Media Error Corrections	Spacecraft Subsystem Technology Transfer	Models of Space Processes for Use in Nowcasting and Forecasting
NASA CONSTITUENCIES						
Satellite Operations Center	○		○			
Space Operations Directorate	○	○				○
Exploration Systems Directorate		○				○
DSN/TDRSS/Other Communications	○			○		○
EXTERNAL CONSTITUENCIES						
NOAA/NWS	○	○				○
FAA	○			○		
DoD	○	○	○	○		○
Commercial Satellite Operators	○	○	○		○	
Power Industry	○					○
Communication Industry	○			○		○

Table 6.5. NASA and external constituencies requesting and making practical use of new knowledge and data from NASA's Heliophysics program.

(JAXA), the National Aeronautics and Space Administration (NASA), and the Russian Aviation and Space Agency (RASA). 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 20 contributing organizations are listed at http://ilws.gsfc.nasa.gov.

Currently Operating Heliophysics Missions with significant International participation:

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

Heliophysics Missions in Development with significant International participation:

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

Near-term Mission Concepts:

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

External Drivers of the NASA Heliophysics Program

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

Space Launch Cost in the Free Market

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

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

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

Public Trust and Risk Tolerance

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

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

NASA missions are growing in size, cost, and complexity. Growing complexity drives a compounding of levels of risk management, including detailed process control, frequent reviews, and greater requirements on project management. Risk management seeks to minimize avoidable failures, which imposes delay and

unplanned costs on all missions because they share common technologies independent of their science focus. As with other complex aspects of our society, the cost of risk management is an increasing fraction of the total.

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

National Security

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

Yet, foreign contributions, such as the Huygens lander on the Cassini mission or the joint development of the SOHO mission, have immeasurably improved the quality of many science missions. Solar Probe and ESA's Solar Orbiter may provide similar opportunities as part of the International Living With a Star program. Strengthening the technical teamwork between the U.S. and our partners permits activities that could not be achieved separately.

NASA and External Factors

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

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

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

Appendices

Appendix A. 2005 Heliophysics Roadmap Teams

Chairs and Coordinators

J. Todd Hoeksema - *Stanford University*
Thomas Moore - *NASA Goddard Space Flight Center*
Al Diaz - *NASA Headquarters*
Timothy Killeen - *National Center for Atmospheric Research*
Franco Einaudi - *NASA Goddard Space Flight Center*
Barbara Giles - NASA Headquarters
Azita Valinia - *NASA Goddard Space Flight Center*

Committee Members

Markus Aschwanden - *Lockheed-Martin*
Scott Bailey - *University of Alaska*
Thomas Bogdan - *National Center for Atmospheric Research*
Cynthia Cattell - *University of Minnesota*
Scott Denning - *Colorado State University*
Gregory Earle - *University of Texas at Dallas*
Joseph Fennell - *Aerospace Corporation*
Jeffrey Forbes - *University of Colorado*
Stephen Fuselier - *Lockheed-Martin*
Glynn Germany - *University of Alabama, Huntsville*
William Gibson - *Southwest Research Institute*
Nat Gopalswamy - *NASA Goddard Space Flight Center*
Don Hassler - *Southwest Research Institute*
Rosamond Kinzler - *American Museum of Natural History*
Craig Kletzing - *University of Iowa*
Barry LaBonte - *JHU Applied Physics Lab*
Michael Liemohn - University of Michigan
Paulett Liewer - NASA Jet Propulsion Lab
Edward Lu - NASA Johnson Space Center
Neil Murphy - NASA Jet Propulsion Lab
Victor Pizzo - National Oceanic and Atmospheric Administration
Edmond Roelof - JHU Applied Physics Lab
James Russell - Hampton University
James Slavin - NASA Goddard Space Flight Center
Leonard Strachan - Smithsonian Astro-physical Observatory
Michelle Thomsen - Los Alamos National Lab

Ex Officio Members

Donald Anderson - NASA Headquarters
Richard Fisher - NASA Headquarters
Mark Weyland - NASA Johnson Space Center
Michael Wargo - NASA Headquarters
Al Shafer - Office of the Secretary of Defense

Mission Study Engineers and Science Support

Juan Ayon - NASA Jet Propulsion Lab
John Azzolini - NASA Goddard Space Flight Center
Michael Calabrese - NASA Goddard Space Flight Center
Mary DiJoseph - NASA Goddard Space Flight Center
Parminder Ghuman - NASA Goddard Space Flight Center
Craig Pollock - NASA Headquarters
Jennifer Rumburg - NASA Goddard Space Flight Center
James Spann - NASA Marshall Space Flight Center
Chris St. Cyr - NASA Goddard Space Flight Center
J. Timothy Van Sant - NASA Goddard Space Flight Center

The Heliophysics community mourns the death of our colleague, Dr. Barry LaBonte. He contributed in many ways to this Roadmap for our nation's future - as a team member, as a long-time leader of Sun-Earth Connection science, and as an innovative solar observer. Barry's wisdom helped us see more clearly, think more deeply, and communicate more effectively. His incisive humor and global views brought us together. His intellectual integrity and intolerance for fuzzy thinking helped us remain true. Barry's enthusiasm for science, education, and exploration was infectious and his dedication to plain speaking was inspiring. We will miss Barry LaBonte.

Appendix B. Bibliography of Key Agency and NRC Documents

Key Agency Documents

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

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

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

The Columbia Accident Investigation Board Report, 2003 (the CAIB report)

Space Science Enterprise Strategy, October 1, 2003.

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

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

NRC Bibliography (Past 5 Years)

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Plasma Physics of the Local Cosmos, Committee on Solar and Space Physics, National Research Council, 2004, ISBN 0-309-09215-9

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

Steps to Facilitate Principal-Investigator-Led Earth Science Missions, Committee on Earth Studies, National Research Council, 2004, ISBN 0-309-09185-3.

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

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

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

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

Assessment of Mars Science and Mission Priorities, Committee on Planetary and Lunar Exploration, 2003, ISBN 0-309-08917-4.

The Sun to the Earth -- and Beyond: A Decadal Research Strategy in Solar and Space Physics, Solar and Space Physics Survey Committee, National Research Council, ISBN 0-309-08509-8

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

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

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

NRC Bibliography (Past 5 Years) - *continued*

Interim Assessment of Research and Data Analysis in NASA's Office of Space Science: Letter Report, Committee on Solar and Space Physics, Committee on Planetary and Lunar Exploration, Committee on Astronomy and Astrophysics, Space Studies Board National Research Council, Letter report, 2000.

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

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

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

Appendix C.
Reconciling the Roadmap and Decadal Survey Approaches & Results

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

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

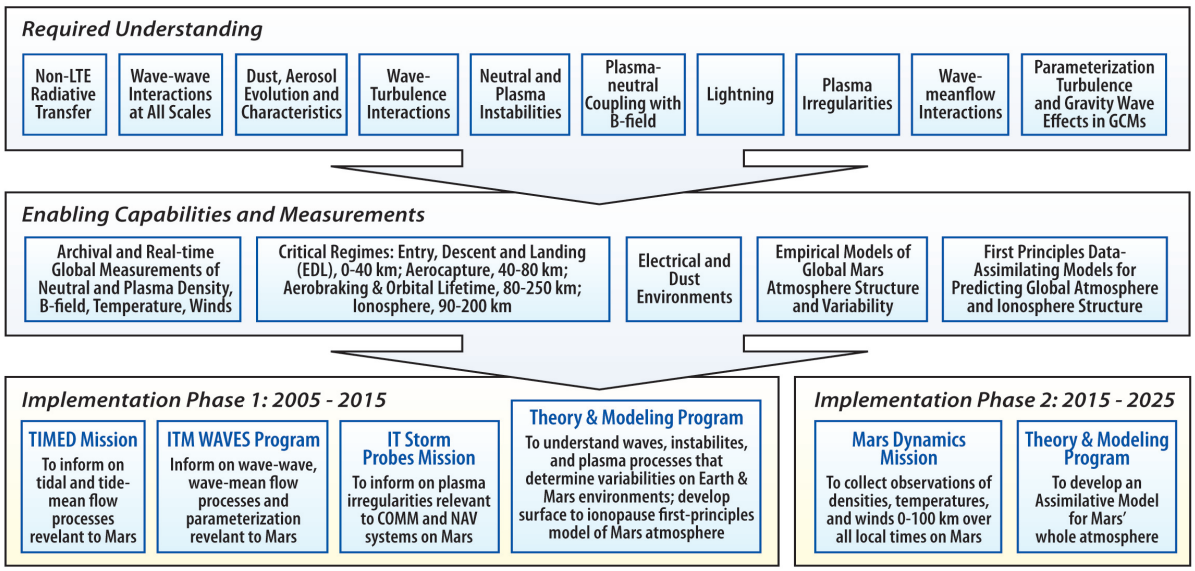
The investigations present the more familiar scientific approach to organizing the efforts, one that lays out a logical progression toward addressing the broad topics outlined in the research focus areas. The investigations are enumerated in Chapter 2 with the descriptions of the research focus areas for each objective. With each investigation it was relatively straightforward to identify missions and supporting elements of the program required to make real progress. Setting priorities was more difficult.

The targeted outcomes shown in Chapter 3 provide an alternate basis for constructing a program; one that the Roadmap Committees found helpful for assigning priority to various components of the program. We identified for each research focus area the achievements that should be completed during each of the next three decades. The achievements are shown in Table 3.2 (Pg. 58) of Chapter 3. Each achievement was developed and expanded in a flow-down chart listing first the required understanding, then the enabling capabilities and measurements, and finally the implementation linked to missions and other supporting pro-

Table C.1

Detailed Requirements Flowdown

TARGETED OUTCOME: Phase 2, Safeguarding the Journey
Determine Mars Atmospheric Variability Relevant to Exploration Activities



gram elements. One sample chart is shown in the accompanying figure.

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

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

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

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

The NRC and roadmap committees ended up in remarkably similar places. The science and exploration objectives, the research focus areas, investigations, and achievements match very well. There is a somewhat broader scope in this roadmap because of the connections with Earth science, the new emphasis on the journey of exploration, and the longer time period considered. The missions proposed include all the top priorities of the 2002 NRC Report: The Sun to the Earth - and Beyond for NASA. Together with the completion of STEREO, Solar-B, and SDO and the continued operation of the Heliophysics Great Observatory, these include Solar Probe, MMS, RBSP & ITSP, JPO/Juno, IH Sentinels, GEC, LCAS, MMS, L1/Heliostorm, GEMINI, L1 Monitor, Solar Orbiter, Explorers, and all of the relevant recommendations for vitality as well. (A few mission names have changed). Table C.2 gives a detailed comparison between the 2002 Decadal Survey Science Challenges and the Research Focus Areas described in Chapter 2.

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

There are some important changes to the intermediate and long term program. The importance of the inner heliosphere through which disturbances propagate has increased. New missions to understand energetic particles

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

Table C.2

Comparison of the 2005 Heliophysics Strategic Roadmap Primary Science Objectives Research Focus Areas and the 2002 Decadal Survey Science Challenge

2002 SOLAR AND SPACE PHYSICS DECADAL SURVEY SCIENCE CHALLENGES

2005 HELIOPHYSICS STRATEGIC ROADMAP PRIMARY SCIENCE				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.	2 Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.	3 Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.	4 Understanding the basic physical principles manifest to processes observed in solar and space plasmas.	5 Developing near-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in the Earth's magnetosphere.
Objective F	**Research Focus Areas**							
Open the Frontier to Space Environment Prediction: Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium	RFA F1	Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms	F1	○		○	○	
	RFA F2	Understand the plasma processes that accelerate and transport particles	F2	○			○	
	RFA F3	Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system	F3	○	○	○	○	
	RFA F4	Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments	F4	○	○		○	
Objective H	**Research Focus Areas**			1	2	3	4	5
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	RFA H1	Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment	H1	○		○	○	○
	RFA H2	Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects	H2			○	○	○
	RFA H3	Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving change	H3	○				○
	RFA H4	Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability	H4	○	○	○	○	
Objective J	**Research Focus Areas**			1	2	3	4	5
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	RFA J1	Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers	J1			○		○
	RFA J2	Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events	J2	○				○
	RFA J3	Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers	J3		○			○
	RFA J4	Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities	J4		○	○		○

D. Heliophysics Mission Studies

Numerous missions of significant interest to the Heliophysics community have been proposed during the course of the Roadmap process. Each one is presented briefly in this Appendix in a half-page Quad Chart. Each Quad Chart covers the four main elements of a mission: it lists the major scientific objectives, describes the mission concept, outlines the measurement strategy, and identifies technology enablers and enhancers; a signature graphic is usually included as well. The charts are presented for informational purposes and have been only lightly edited.

This appendix includes the top priority strategic missions identified in the 2005 Roadmap. Additional missions are also included in order to document current community ideas along with missions identified in previous roadmaps that were actively discussed, but not included in the 2005 Roadmap narrative.

The level of study maturity varies, as detailed on page 140. Some missions exist only as a quad chart concept and description. Others have undergone some level of engineering concept or Vision Mission study or been proposed as Explorers. Some missions are already in pre-formulation or have been the subject of extensive science definition team effort. This Appendix includes the Heliophysics Explorer, STP, and LWS missions currently in formulation and implementation in order to connect the existing program's science objectives and achievements with the missions described in this Roadmap.

The evolution of mission priorities derived from the NASA Strategic Planning and Budget process drives the direction and pace of additional studies for selected missions to raise their study maturity level in support of this process.

Alphabetical Listing of Quad Chart Summaries

- **Auroral Acceleration Multi-Probes (AAMP)**
- **Aeronomy of Ice in the Mesosphere (AIM)**
- **Aeronomy and Dynamics at Mars (ADAM)**
- Bepi-Colombo (BC)
- **Coupled Ion-Neutral Dynamics Investigation (CINDI)**
- **Dayside Boundary Constellation (DBC)**
- **Doppler**
- **Farside Sentinel (FS)**
- **Geospace Electrodynamic Connections (GEC)**
- **Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)**
- Geospace System Response Imager (GSRI)
- **Heliospheric Imager and Galactic Observer (HIGO)**
- **Heliostorm**
- **Interstellar Boundary Explorer (IBEX)**
- **Inner Heliospheric Sentinels (IH Sentinels)**
- **Inner Magnetospheric Constellation (IMC)**
- **Interstellar Probe (ISP)**
- Io Electrodynamics
- **Ionosphere Thermosphere Mesosphere (ITM) Waves**
- **Ionosphere-Thermosphere Storm Probes (ITSP)**
- Janus
- **Jupiter Polar Orbiter/Juno**
- L1 Diamond
- **L1 Earth-Sun**
- L1 Mars

- **L1-Sentinel**
- L1 Solar-Climate Connection Explorer
- **Lunar Reconnaissance Orbiter (LRO)**
- Lunar Imaging Radio Array (LIRA)
- **Magnetic TRAnsition region Probe (MTRAP)**
- **Mars Atmospheric Reconnaissance Survey (MARS)**
- **Mars Science Laboratory (MSL)**
- Magnetosphere-Ionosphere Observatory (MIO)
- **Magnetospheric Constellation (MC or MagCon)**
- **Magnetospheric Multiscale (MMS)**
- Mars Dynamics
- Mars GOES
- Near Earth Solar Coronal Explorer (NESCE)
- Neptune Orbiter
- **New Horizons - Pluto Kuiper Belt Mission**
- **Radiation Belt Storm Probes (RBSP)**
- **Reconnection and Microscale Probe (RAM)**
- **Solar-B**
- Solar Connection Observatory for Planetary Environments (SCOPE)
- **Solar Dynamics Observatory (SDO)**
- **Solar Energetic Particle Mission (SEPM)**
- **Solar Heliospheric & Interplanetary Environment Lookout for Deep Space (SHIELDS)**
- Solar Imaging Radio Array (SIRA)
- **Solar Orbiter (SO)**
- **Solar Polar Imager (SPI)**
- **Solar Probe (SP)**
- **Solar Sail Demo (SSD)**
- **Solar-TERrestrial RElations Observatory (STEREO)**
- **Solar Weather Buoys (SWB)**
- Space Environment Testbeds (SET)
- Space Physics Package and Interface
- ST-5 Microsat Technology Constellation Validation
- **Stellar Imager (SI)**
- **Sun-Earth Coupling by Energetic Particles (SECEP)**
- Sun-Earth Energy Connector (SEEC)
- **Telemachus**
- **Time History of Events and Macroscale Interactions During Substorms (THEMIS)**
- Titan
- **Two Wide-Angle Imaging Neutral-Atom Spectrometeres (TWINS)**
- **Tropical ITM Coupler (ITMC)**
- Venus Aeronomy Probe
- Whole Sun Sentinels

Heliophysics Mission Study Status 12/15/05

	Mission	Mission Study Status	Concept Maturity	2000 RM Study	2003 RM Study	2005 RM Study	2002-5 IRM	Vision Mission	2005-8 IRM	SDT	Pre-Form	Formulate	Implement	Comments	Planned Launch
LONG-TERM/MARS (2017-2029+)	***STP Missions***														
	STEREO	Solar-TERrestrial Relations Observatory	H		Q	Q							STP		2006
	Solar-B	Solar-B	H		Q	Q							STP		2006
	MMS	Magnetospheric Multiscale	H		Q	Q						STP		AO Selection 2005	2013
	GEC	Geospace Electrodynamics Connections	M-H		Q	Q				STP				SDT Report 2004	
	MC	Magnetospheric Constellation	M-H		Q	Q				STP				Updated SDT Report 2004	
	ITMC	Tropical ITM Coupler	L	RM	RM	Q									
	ITMwaves	Ionosphere Thermosphere Mesophere Waves	L	RM	RM	RM									
	HIGO	Heliospheric Imager and Galactic Observer	L-M	RM	RM	Q	IRM							Report 7/04	
	LWS Missions														
	SDO	Solar Dynamics Observatory	H		Q	Q							LWS		2008
	ITSP	Ionosphere Thermosphere Storm Probes	H		Q	Q					LWS			AO Prepared	
	RBSP	Radiation Belt Storm Probes	H		Q	Q					LWS			AO Release 8/05	2010
	IHS	Inner Heliosphere Sentinels	M-H	RM	RM	Q				LWS				SDT Report Due 12/05	2012
	WSS	Whole Sun Sentinels	Q			Q									
	Farside	Farside Sentinel	Q			Q									
	IMC	Inner Magnetospheric Constellation	L-M	RM	RM	Q	IRM							Report 6/03	
	SET	Space Environment Testbed	H			Q							LWS		
	TLM	Telemachus	L-M		RM	Q	IRM							Report 10/03	
	SP	Solar Probe	M-H		Q	Q				LWS				SDT Report 08/05	
	Explorers														
	CINDI	Coupled Ion Neutral Dynamics Investigation	H										EXP		2006
	TWINS	Two Wide-angle Imaging Neutral-atom Spectrometers	H			Q							EXP		2006
	AIM	Aeronomy of Ice in the Mesosphere	H			Q							EXP		2006
	THEMIS	Time History of Events and Macroscale Interactions during Substorm	H			Q							EXP		2006
	IBEX	Interstellar Boundary Explorer	H			Q					EXP			Mission Selection 1/05	2008
	SSE/Heliophysics Missions														
	NH	New Horizons (Pluto/Kuiper)	H										NF		2006
	JPO	Jupiter Polar Orbiter/JUNO	M	RM	RM	Q						NF		New Frontiers Step 2- JUNO	
	Other Missions														
	BC	Bepi-Colombo	H			Q				SDT		ESA		ESA AO Issued 4/04	
	SO	Solar Orbiter	H		Q	Q	IRM			SDT	ESA			ESA Mission Report Fall 2004	
	SPP	Space Physics Package	L			RM									
	ST-5	Microsat Technology Constellation Validation	H			Q							NMP		2006
	SSD	Solar Sail Demonstration	LM			Q					NMP				2010
NEAR-INTERMEDIATE/PRE LUNAR (2005-2016)	***STP Missions***														
	DBC	Dayside Boundary Layer Constellation	L	RM	Q	Q									
	MIO	Magnetosphere-Ionosphere Observatory	L		RM	Q									
	PAS	Particle Acceleration Solar Orbiter	L	RM	RM	Q									
	AAMP	Auroral Acceleration Multi-Probes	L		RM	RM									
	GSRI	Geospace System Response Imager	L	RM	RM	Q									
	SCOPE	Solar Connection Observatory for Planetary Environments	Q		Q	Q									
	RAM	Reconnection and Microscale	L-M	RM	RM	Q	IRM							Report 10/03	
	MTRAP	Magnetic TRAnsition Region Probe	L-M		RM	Q	IRM							Report 3/05	
	SPI	Solar Polar Imager	M	RM	RM	Q		VM						Report 2003	
	Doppler	Doppler	L			RM									
	L1EarthSun	L1 Earth Sun	Q		Q	Q									
	SEPM	Solar Energetic Particle Mission	L		Q	RM									
	SI	Stellar Imager	M	Q	Q	Q		VM							
	LWS Missions														
	L1D	L1-Diamond	L-M		Q	Q	IRM							Report 10/04	
	L1 SCE	L1 Solar Climate Connection Explorer	Q		Q	Q									
	SWB	Solar Weather Buoys	L			RM									
	SECEP	Sun-Earth Coupling by Energetic Particles	L			RM									
	SIRA	Solar Imaging Radio Array	L		Q	RM									
	LIRA	Lunar Imaging Radio Array	Q			Q									
	SEEC	Sun-Earth Energy Connector	L	RM		Q									
	SHECon	Sun-Heliosphere-Earth Constellation	Q		Q	Q									
	HS	Heliostorm	L			RM									
	SHIELDS	Solar Heliospheric & Interplanetary Environment Lookout in Deep Space	L			RM									
	GEMINI	Geospace Magnetospheric and Ionospheric Neutral Imager	L			RM								GSRI Lite	
	SSE/Heliophysics Missions														
	IE	Io Electrodynamics	L	RM	Q	Q									
	TE	Titan Explorer	M					VM						Planetary with Mag. Comp.	
	NO	Neptune Orbiter	M	Q	Q	Q		VM(2)						Planetary with Mag. Comp.	
	MA	Mars Aeronomy	L	RM	Q	RM								Variants studies at JPL	
	VAP	Venus Aeronomy Probe	L	RM		Q								Variants studies at JPL	
	MD	Mars Dynamics	L			RM									
	ADAM	Aeronomy and Dynamics at Mars	Q			Q								Mars Aeronomy + Mars Dynamics	
	Other Missions														
	IsP	Interstellar Probe	M	RM	RM	Q		VM(2)						2001-2 Reports	

Notes:
Q = Mission Quad Sheet Level of Study
RM = Roadmap Mission Engineering Team Study
IRM = HQ Selected Inter-Roadmap Mission Studies w/IMDC/Team X
VM = Vision Mission Under Study
SDT = Science Definition Team Mission Studies
STP = Present Status in STP Program
LWS = Present Status in LWS Program
EXP = Present Status in Explorer Program
Concept Maturity = (Q- Very Low @ Quad Level)
(L-Low @ RM Study Level)
(LM- Low Medium @ IRM Study Level)
(M - Medium @ Projected Vision Mission Study Level)
(MH - Medium-High at SDT Study Level)
(H - High at Pre-Formulation Study Level and above)

Aeronomy of Ice in the Mesosphere (AIM)

Science Objectives:

Resolve why Polar Mesospheric Clouds (PMCs) form and why they vary

Determine the mesospheric response to solar energy deposition and coupling among atmospheric regions

Mission Description:

Small Explorer, Launch September, 2006, 2-year baseline mission; CDR completed; In phase C; 3-axis stable platform, 210 kg, Sun synch orbit at 600 km, noon/midnight local time, 2 Gbits data per day, 3 instruments

Strategy:

- **Solar Occultation: PMCs and environment in which they form: Temperature, H_2O, CO_2, CH_4, O_3, NO**
- **Panoramic UV nadir imaging: PMCs, their spatial and temporal morphology, particle sizes, ice content**
- **In-situ dust detection: cosmic dust influx, mesospheric cloud nucleation sites**
- **State-of-the-art modeling: relating solar forcings to observed response in mesosphere and thermosphere**

Technology:

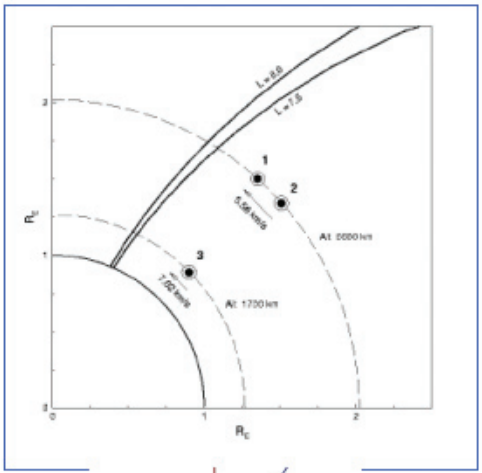
Unprecedented precision in specification of upper atmosphere environment through application of differential absorption radiometry; first panoramic, high resolution, stereographic, PMC images from space

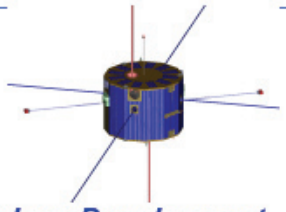
Key Result to come from AIM:

AIM will provide understanding of PMC microphysics and the role of temperature, chemistry and dynamics in PMC formation; will establish the basis for the study of long-term solar and anthropogenic induced variability in the Earth's upper atmosphere and climate

1

Auroral Acceleration Multi-Probe (AAMP)





Technology Development

- Low Mass/Power Instrumentation

Science Objectives

•**To understand the electrodynamic connection between Earth's ionosphere and magnetosphere**

- What structures accomplish the connection?
- What is the electrical impedance and how is it established?
- What is the role of ionospheric feedback?
- How does magnetospheric dynamics affect the coupling?

Mission Description

- **Example Mission Design**
  - Delta II Launch of 3 spacecraft into a 600 km x 6000 km, 90 deg. inclination.
  - Separate spacecraft in true anomaly.
  - 2 year mission lifetime
- **Flight System Concept**
  - Spinning solar powered spacecraft
  - Payload: Fields and Particles + Imaging (71 kg/43 W)

Measurement Strategy

•Measure j: B & precision attitude (0.02° maximum error)
Measure ϕ: DC E-field, particle distribution, || B necessary
Distinguish waves, static structures: ~10 μsec timing
Identify kinetic processes via established signatures

2

AERONOMY AND DYNAMICS AT MARS (ADAM)

Science Objectives

- Characterize the temperature, neutral and ionized densities, and wind structures of Mars' upper atmosphere vs. latitude, longitude, local time and season.
- Understand how the solar wind interacts with the upper atmosphere, ionosphere, and magnetic field structures of Mars
- Understand the sources of variability of Mars' aerocapture and aerobraking environments
- Identify & characterize planetary escape processes at Mars
- Clarify priorities for Future Mars Atmosphere Missions

Flight System Concept

- Solar array powered, 3-axis stabilized, 1352 m/s ΔV
- Payload: 123 kg, 175 W,68 kbps data rate
- 36 arcsec control, 3.6 arc-sec knowledge

Required Measurements

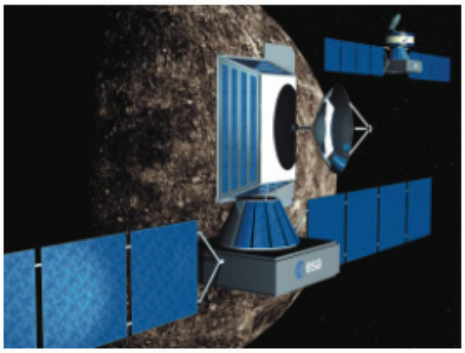
- Neutral temperature, winds, densities, 40-200 km
- Ion and neutral composition, > 100 km
- Thermal plasmas (ions and electrons), pick-up ions, energetic particles and magnetic and electric fields
- UV spectra for remote sensing of escaping atoms
- Neutral species escape rates, isotopic ratios

Example Mission Design

- Delta II Launch vehicle (C_3=8.5 km^2/s^2, Type 1 chemical MOI of 1 km/s; 1,080 kg launch injection mass)
- Initial MOI orbit: 250 x 57,000 km @ 60-80 deg
- Aerobrake to Phase 1 orbit: 150 km X 6000 km @ 60-80 deg Phase 1 = 1 Mars year
- Aerobrake to Phase 2 orbit: 550 x 550 km @ 60-80 deg; Phase 2 = 1 Mars year

3

Bepi-Colombo



Technology

Solar Electric Propulsion will be demonstrated on ESA's technology mission, SMART-1 (2003)
High Temperature (HT) MLI, HT coatings
HT, high intensity GaAs solar cells
HT, 2-axis large amplitude antenna articulation mechanism
HT X/Ka high gain antenna reflector and feeds
Miniaturized integrated electronics for HT environments
Mercury Horizon Sensor, HT Sun Sensors
Lander

Science Objectives

Measure the composition, state and distribution of mass within Mercury's interior.
Map Mercury's intrinsic magnetic field and determine the nature of its interaction with the solar wind.
Measure the composition, density, and dynamic variations in the charged particles that populate Mercury's magnetosphere.
Image the entire surface of mercury at a resolution <100 m and determine its composition.
Determine if water ice exists in deep craters in Mercury's polar regions.
Measure the composition and density of Mercury's tenuous exosphere.

Mission Description

2-3 ESA/ISAS spacecraft using SEP and gravity assist (Moon, Venus, Mercury) to orbit Mercury
- (MPO) Mercury Polar Orbiter (ESA) (3AS)
- (MMO) Magnetospheric Orbiter (ISAS) (Spinner)
- (MSE) Mercury Surface Element (ESA if approved)

Option 1: 2 spacecraft on 2 separate Soyuz-Fregat Launchers as much as 1 year apart
Option 2: 3 spacecraft on 1-Ariane V

Launch 2012

Measurement Strategy

Planetary orbiter (MPO):
- 3-axis stabilized
- Visible/near IR camera, photon spectrometers (IR, UV, X-ray, gamma-ray), neutron spectrometer, accelerometer, K-band transponder

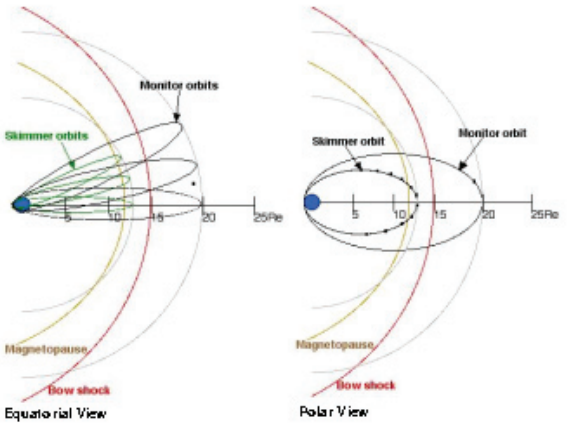
Magnetospheric orbiter (MMO):
- Spin-stabilized
- Magnetometer, ion spectrometer, ion/electron analyser, cold plasma detector, energetic particle detector

Surface element (MSE):
- Physical properties and geochemistry package, camera, seismometer

MPO remote sensing

4

Dayside Boundary Constellation



Science Objectives

Measure highly asymmetric and dynamic bow shock and magnetopause structures which regulate the solar wind's impact on the magnetosphere.
Establish the casual relationship(s) between these boundary phenomena and corresponding solar wind, foreshock, and magnetosheath drivers.

Mission Concept

Orbits: 3 orbit planes near equator with 30 deg separation
- Active precession to keep apogee on earth sun line
- 11 "skimmers" per plane with 11 to 12 Re apogee
- 1 "monitor" per plane with ~ 20 Re apogee

"Skimmer" separations range from 1 to 5 Re near apogees in phase with those of "monitors"

Measurement Strategy

Minimum measurement compliment to
- Identify boundary layer, magnetopause and shock crossings
- Determine timing over ~Re separations: $\Delta t \sim 60$ seconds between SC
- Measure solar wind & IMF (monitors)

Vector magnetic field
- ~0.5 nT accuracy, ~0.1 nT resolution
- 0.1 sec resolution (required to despin)

Plasma
- Ions: density, flow, temperature. ~5 sec resolution
- Electrons: 50 eV to 1 keV. ~5 sec resolution.

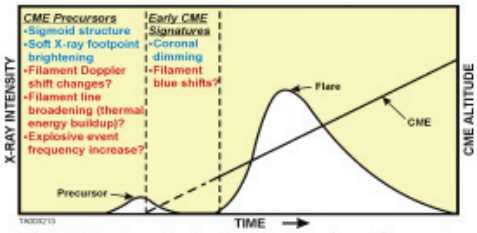
Minimum New Technology

No "enabling" technology required
Low level long duration thrust needed for orbit precession – small solar sail potential

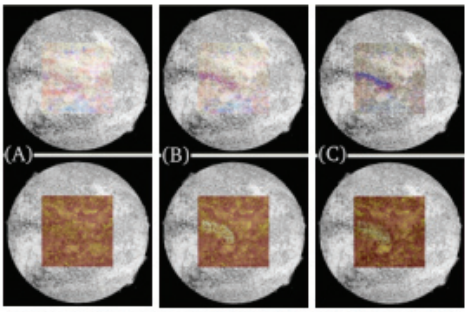
5

DOPPLER

A Space Weather Doppler Imager Mission Concept



DOPPLER will enable the identification of new flare and CME, and SPE precursors, which could greatly improve space weather nowcasting and forecasting.



Simulation of the observational signature of a filament/CME eruption. TOP: Doppler velocity image; BOTTOM: line width image. (A) Quiet Sun with quiescent prominence; (B) 30-60 min. prior to liftoff, draining motions and reconnection yield Doppler and line-width signatures; (C) 15-30 min. after liftoff, DOPPLER captures acceleration and turbulent-motion profiles.

Exploration Science Objectives

- *What are the most relevant observational signatures of flare, CME and Solar Particle Event (SPE) eruption?*
- *Are there identifiable precursor signatures which can be used to forecast flare, CME and Solar Particle Event (SPE) eruption?*
- *What do we need to improve our ability to nowcast and forecast space weather and Solar Particle Events to ensure safe human exploration?*

S3C Science Objectives

- *What are the physical mechanisms of mass flow and energy release in the solar atmosphere?*
- *What is the interaction and connectivity of structures throughout the solar atmosphere?*

Measurement Strategy

- *UV/EUV Imaging Spectrograph for flow velocities and energy release signatures*
- *Filter Magnetograph for surface magnetic field measurements*
- *Chromospheric/Coronal EUV imagers for morphology and dynamics*
- *Energetic particles (SEP) measurements for event characterization*

Mission Description

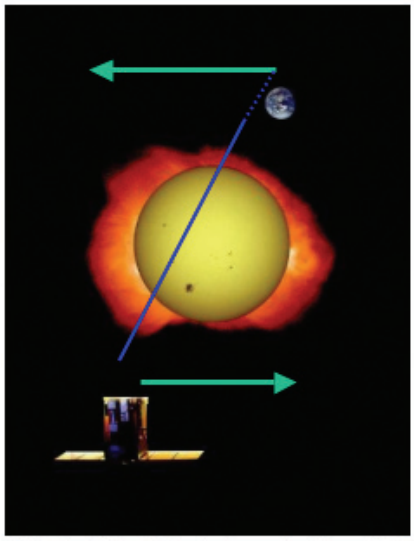
- *3_axis stabilized platform with arcsecond pointing capability*
- *S/C in 98°, 600 km sun-synchronous orbit for continuous solar viewing*

Technology Development

- *High cadence imaging spectrograph development*
- *Low mass/power instrumentation and advanced communication/DSN for future deployment to Sentinel or Mars orbit locations*

6

Farside Sentinel



The Farside Sentinel will observe the full evolution of solar phenomena by tracing their activity on the far side of the Sun.

Fundamental Question:
What is the 3-D structure of the Sun's magnetic field in its interior and in the entire atmosphere?

Science Objectives:
- Probe 3-D structures deep inside the Sun
- Measure the Sun's global magnetic field
- Follow the evolution of active regions
- Determine coronal magnetic fields
- Study coronal mass ejection origin and development
- Understand spatial characteristics of interplanetary events

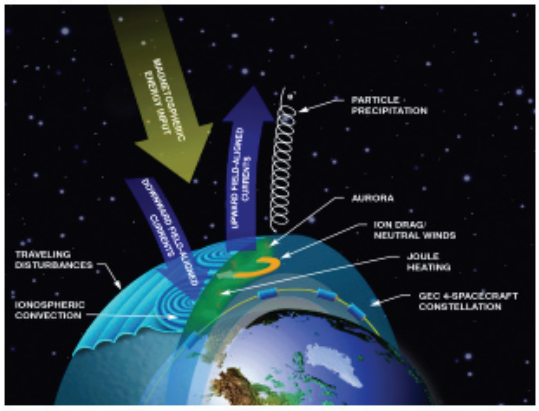
Mission Description:
- Inclined orbit at 1 AU on the far side of the Sun
- Venus gravity assist for orbit insertion

Measurement Strategy:
- Full-disk magnetic and velocity field observations
- X and Ka band Faraday rotation to sound the corona
- EUV images of coronal structures
- In situ particles and fields

Technology Requirements:
- High-data-rate interplanetary communication
- Low-mass advanced propulsion

7

Geospace Electrodynamic Connections (GEC)



Science Objectives

- **Understand the response of the Ionosphere-Thermosphere system to Magnetosphere forcing**
- **Resolve the dynamic coupling of the Ionosphere-Thermosphere system to the Magnetosphere**

Mission Description

- **A constellation of four spacecraft flying in formation (Pearls-On-A-String) each carrying identical sets of nine instruments.**
- **185 X 2,000 km; 83 degree inclination parking orbit**
- **Orbital maneuvers, at select times, to lower perigee to an altitude of ~ 130 km, lasting up to one week**

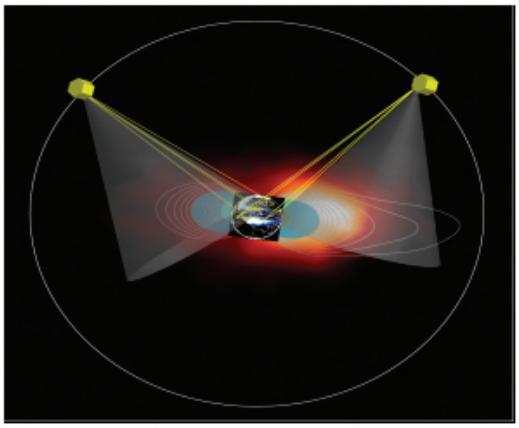
Measurement Strategy

- **Measure in-situ all relevant plasma-neutral coupling parameters**
- **Spacecraft cross important high latitude magnetosphere-ionosphere coupling regions**
- **Unequal, variable spacecraft spacings to resolve different scales**
- **Low dips to altitude where atmosphere begins to dominate the plasma dynamics.**

Key Mission Enhancing Technologies

- **Aerodynamic Structures & Materials**
- **Low Magnetic & Electric Field Emissions**
- **Body Mounted Solar Arrays (ESC) with Lightweight / Rigid Booms**
- **Precise formation flying**

GEospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)



Science Objectives

- Determine dynamic coupling between ionosphere and Magnetosphere
- Determine how magnetospheric energy is dissipated in the Ionosphere-Thermosphere (I-T) system
- Determine the important feedback mechanisms from the I-T system to the magnetosphere
- Determine global magnetospheric dynamics

Mission Description *(Near/Intermediate/Far Term)*

- **Mission Design**
  - 2 high altitude spacecraft in $8R_e$ circular near-polar orbit
  - Ground-based radar network covers 30° to 90° north and south latitudes
  - 2 year mission life
- **Flight System Concept**
  - 2 separate Pegasus –class launches
  - 3-axis stabilized platforms
  - xx m/s ΔV
  - 0.01° (control), 0.02° (knowledge)
- **Payload**
  - Payload: 79 kg, 48 W, 110 kbps (avg.)
  - 3 FUV, 1 EUV, 1 ENA Imaging instruments per S/C, nadir pointing with yaw about nadir
  - ~ 10 ground radar installations with 2 antennas each

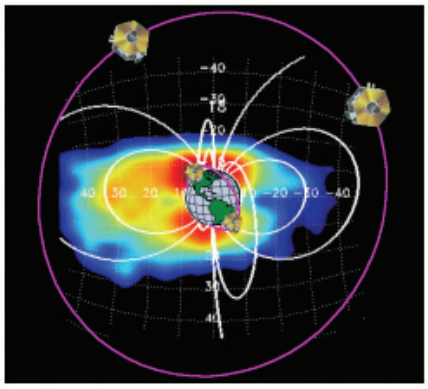
Enabling Technology Development

- No "enabling" technology required

Measurement Strategy

- Two high altitude spacecraft with global ENA and EUV imaging of the magnetosphere, and high resolution global spectroscopic FUV imaging of the I-T system
- Ground radar measurements coordinated with space-based sensors

Geospace System Response Imager (GSRI)



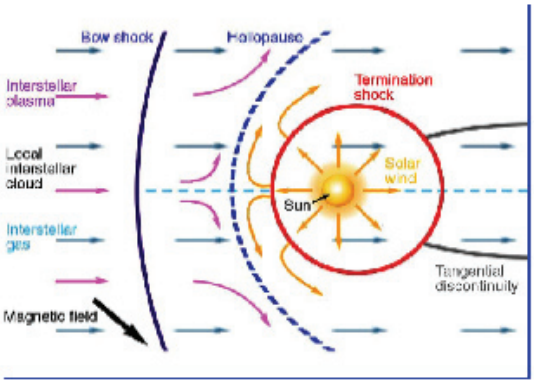
Minimum Technology Design was Baselined
- No "enabling" technology required
- New enhancing technologys should reduce spacecraft cost by 10%

Science Objectives
- Determine dynamic coupling between ionosphere and magnetosphere
- Determine how magnetospheric energy is dissipated in the Ionosphere-Thermosphere (I-T) system
- Determine the important feedback mechanisms from the I-T system to the magnetosphere
- Determine global magnetospheric dynamics
- Determine causes and consequences of magnetospheric storms and sub-storms

Mission Description
- Mission Design
  - 2 Low Altitude Spacecraft (LAS) in 500-km sun-synchronous (97.4-degree inclination)
  - 2 High Altitude Spacecraft (HAS) in 8Re circular orbit also at 97.4-degree inclination
  - Ground-based radar network covers 30 to 90 deg north and south latitudes
  - 2 year life
- Payload
  - LAS F-P Interferometer plus in-situ ions and Mag field instruments nadir and RAM oriented
  - HAS 8 Imaging instruments nadir pointing with roll about nadir
  - 10 ground radar installations with 2 antennas each

Measurement Strategy
- Two high altitude spacecraft with global ENA and EUV imaging magnetosphere, and high high resolution global spectroscopic FUV and x-ray imaging of the I-T system –all data available real-time
- Two low altitude spacecraft with Fabrey-Perot interferometers and in-situ field and particle measurements
- Ground radar measurements coordinated with space-based sensors

Heliospheric Imager and Galactic Observer



Science Objectives

- Image the global interaction between the interstellar medium and the solar wind that forms the global heliosphere and its boundaries
- Determine the Nucleosynthetic Status of a Present-Day Sample of the Galaxy and Explore the Implications of this Knowledge for Big Bang Cosmology, Galactic Evolution, Stellar Nucleosynthesis, and the Birthplace of the Sun
- Map the Location and Establish the Characteristics of the Extended Inner Source of Neutrals in the Heliosphere, and Set Limits on the Dust Density in the Heliosphere
- Search for molecules and the building blocks of life liberated by sublimation of small comets, asteroids and grains (detectable through measurement of pickup particles)

Mission Description

- **Example Mission Design**
  - Delta II 2925 Launch, 735 kg @ C_3 = 27.17 km²/s² (26.1 min)
  - ΔV-EGA (2-) Trajectory
    - 2 year cruise, 2.9 year orbital science operations
    - 1 x 4 AU Equatorial Final Orbit
- **Flight System Concept**
  - Spin-Stabilized Platform
  - Solar Array Design
  - Payload: 82 kg, 60 W, 1 kbps @ > 2 AU
  - 554 m/s ΔV
  - 900 arcsec (control), 360 arcsec (knowledge)

Measurement Strategy

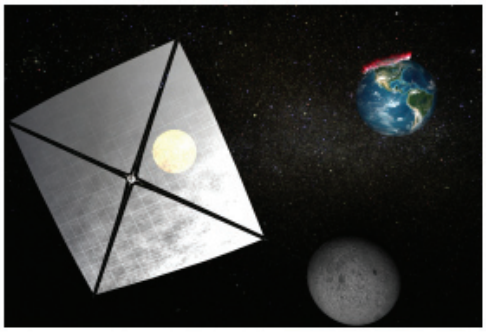
- Image the Heliopause using Global Sky Maps of 83.4 O+
- Image the Heliosheath using Energetic Hydrogen Atoms
- Determine the isotopic and elemental composition of the neutral portion of the interstellar gas from measurements of pickup ions and of the main neutral species
- Determine the Flow Direction, Speed and Temperature of Interstellar Atoms
- Determine Composition and Radial Profiles of Extended Inner Source Pickup Ions
- Determine Time-dependent Interactions of Large-Scale Structures and Shocks in the Heliosphere through Radio Detection

Enabling Technology Development

- High resolution diffuse EUV Spectrometer
- Advancing anti-coincidence noise suppression technique
- Negative Ion Conversion Surface

11

Heliostorm



Science Objectives

- Understand the Sun-to-Earth evolution of CMEs, shocks and particle radiation from solar eruptions
- Remote- and local sense Earth-impacting solar disturbances
- Determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes
- Provide warning time to protect lunar and Earth-orbiting and ground assets
- Provide a demonstration platform for Exploration and a pathfinder for the L1-Diamond science mission

Mission Description

- **Example Mission Design**
  - Delta II Launch Vehicle
  - Trajectory: ballistic transfer from Earth to L1 Halo (~90 days), solar sail transition (a_c = 0.21 mm/s²) from L1 to ~120 R_E Sunward of L1 OPS station
  - Continuous Solar Viewing: 2 years In Final Orbit
- **Flight System Concept**
  - Solar-array powered S/C with solar sail
  - Payload: Fields and Particles+ Imaging (33 kg/24 W)

Technology Development

- Solar Sail: 100m edge @ 14.3 g/m²
- Solar Sail Navigation Tools
  - ISP Development Funding
- Autonomous Solar Sail Thrust Vector Control
- "Multi-Chip Module" (MCM) Electronics
  - Radiation Tolerant μ-packaged MCMs on 2- 6U cPCI cards

Measurement Strategy

- Optical: CME imaging with radio for early warning of shocks
- Radio: triangulate the location of interplanetary shocks
- Energetic particles provide environmental data for lunar missions and strength and distance of approaching shocks
- Plasma/Magnetic Field provide warning and environmental data for lunar missions and for Earth
- Optical system provides diagnostics during sail deployment and check-out

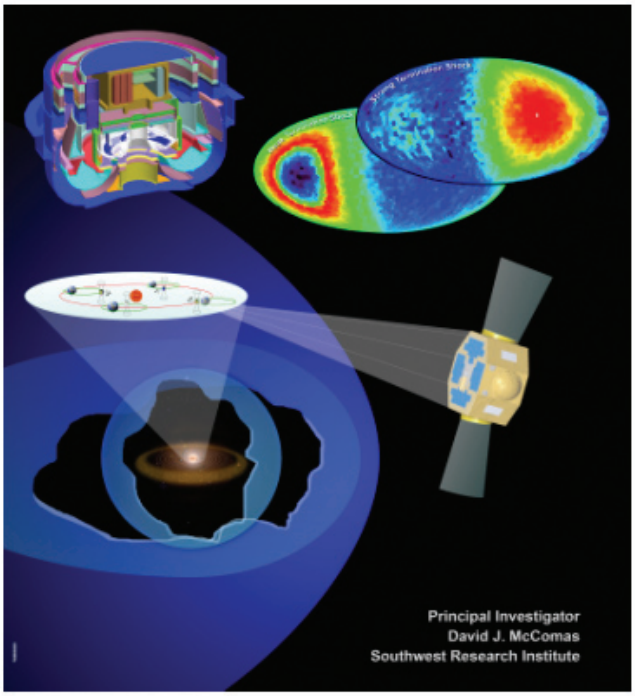
12

Interstellar Boundary Explorer

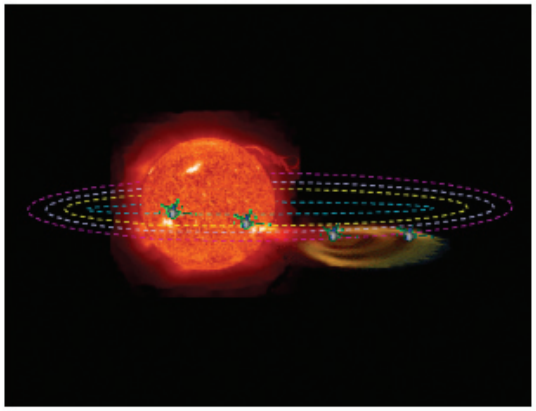
Imaging the edge of our solar system and beyond-

Discovering the global interaction between the solar wind and the interstellar medium

- **Objective: Determine the global interaction between the solar wind and the interstellar medium:**
  - –Global structure of the termination shock
  - –Energetic proton acceleration by the termination shock
  - –Global properties of the solar wind flow beyond the termination shock and in the heliotail
  - –Interstellar flow interaction with the heliosphere beyond the heliopause
- **Spacecraft and Mission:**
  - –Sun-pointed spinning S/C in high altitude (~35 R_E) highly elliptical orbit provides viewing beyond Earth's magnetosphere
  - – Explorer scheduled for launch in 2008
- **Measurement Strategy:**
  - –Hi and Lo energy single pixel energetic neutral atom cameras
  - –Sun-pointed spinner with cameras orthogonal to spin-axis. Each spin maps out a great circle of the global image. A full-sky map of energetic neutral atoms is made in 6-months as the sun-pointing of the spin-axis is maintained while the Earth (and S/C orbit) move about the Sun



Inner Heliospheric Sentinels



Fundamental Question:

- Discover, understand and model the solar-heliospheric connections that govern solar-particle radiation storms and geospace disturbances.

Technological Requirements:

- No new technologies are required.
- Miniaturization of electronics desired.

Science Objectives

- Determine the physical conditions and mechanisms that govern solar particle production and transport in the inner heliosphere.
- Determine the radial, longitudinal, and temporal variations of energetic particle distributions.
- Determine the ambient structure of the inner heliosphere and the coupling of solar and heliospheric magnetic fields and plasma required to reliably model the inner heliosphere
- Determine how geo-effective solar wind structures propagate and evolve in the inner heliosphere.
- Develop reliable predictive global heliospheric models

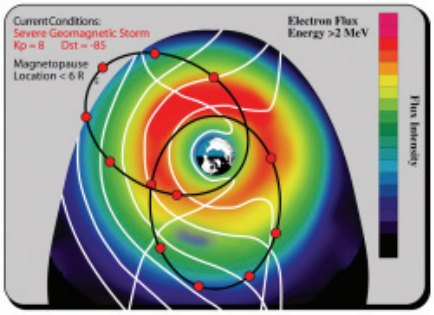
Measurement Strategy

- Magnetic field, solar wind, energetic particle, and radio and plasma-wave measurements.
- X-ray, gamma-ray and neutron detection.
- Observations in the inner heliosphere, the site of SEP energization and rapid transient evolution.
- Longitudinally and radially distributed observations

Possible Mission Scenario

- Four identical spinning spacecraft in ecliptic orbits (0.25 – 0.35 x 0.72 AU).
- Identical particles, fields, and energetic photon instrumentation on all four s/c.
- Single medium class ELV launch with Venus gravity assist.
- Telemetry requires infrequent, bi-weekly DSN contact.
- Solar remote sensing and out of ecliptic solar wind measurements provided by the ESA Solar Orbiter

Inner Magnetospheric Constellation (IMC)



Science Objectives

- Create time-dependent maps of the inner magnetosphere (1.5-12 RE)
- Fully specify and understand the space environment where spacecraft and astronauts work.
- Discover the origin and dynamics of magnetospheric particle populations
- Derive the global, time-dependent magnetic and electric fields.
- Determine the development and evolution of magnetic storms.

Mission Description

- 2 "petal" low inclination orbits that maintain uniform coverage independent of precession.
- 3 satellites per orbit, 6 total.
- Instruments: 3-axis Magnetometer, Electron Analyzer, Energetic Particles, 2-axis Electric Fields

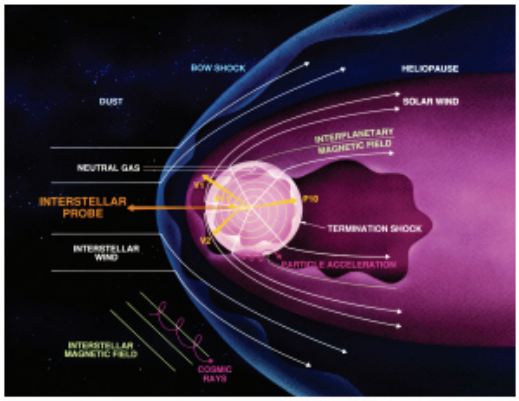
Measurement Strategy

- The large-scale equatorial electric & magnetic fields are directly measured.
- An independent measurement of the fields - integrated along particle drift paths - is obtained from the energetic particle phase space density contours.
- Different energies have different drift paths and highly constrain the construction of global synoptic "weather maps" of the inner magnetospheric response to geomagnetic disturbances originating on the Sun..
- Direct measurement of the origin and dynamics of global particle structures such as the ring current, the relativistic electron radiation belts, the plasmasphere and detached/extruded plasmaspheric populations.

Minimum Technology Design was Baselined

- No "enabling" technology required
- New enhancing technologys should reduce spacecraft cost by 10%

Interstellar Probe
Heliophysics Flagship Mission



Science Objectives

- Explore the interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust
- Determine the structure and dynamics of the heliosphere, as an example of the interaction of a star with its environment
- Study, in situ, the structure of the solar wind termination shock, and the acceleration of pickup ions and other species
- Investigate the origin and distribution of solar-system matter beyond the orbit of Neptune

Mission Description

Example Mission Design*
- Delta II 7425 Launch (719 kg Cap., C_3 = 0 km²/s²)
- Flight System Launch Mass: 564 kg
- Solar Sail Trajectory Targeted for Nose of Heliosphere
  - 0.25 AU Solar Pass, 200 AU in 15 yrs.

Flight System Concept

- "Flying Antenna" Design Implementation (191 kg)
- Sized for 30 year Operations
- Payload: Fields & Particles + Imaging

Measurement Strategy

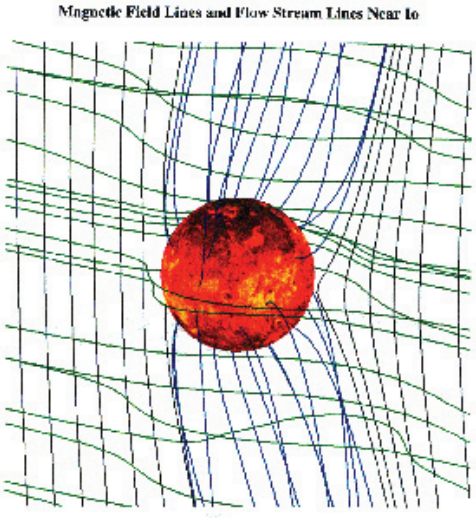
- Measure, in situ, the properties and composition of interstellar plasma and neutrals, low energy cosmic rays, and interstellar dust
- Determine the structure and dynamics of the heliosphere with in situ measurements and global imaging
- Map the infrared emission of the zodiacal dust cloud, measure in situ the distribution of interplanetary dust, and determine the radial distribution of small Kuiper Belt objects

Technology

- Solar Sail: < 1 g/m², 200 m radius
- DSN 70m Subnet w/ Ka-band Uplink
- Next Generation ARPS
- Next Generation System On A Chip
- Ka-band S/C Components and Phased Array
- Hot-Gas Propulsion
- Micro-S/C Technology
- Low Mass/Power Instrumentation

* Nuclear Electric Propulsion (NEP) may be a future implementation, developments within the Nuclear Systems Initiative will be closely followed and utilized to their fullest advantage

Io Electrodynamics



Science Objectives

- Investigate the Energy Conversion Processes in a Magnetized Plasma
- Understand Mass Transport in a Rapidly Rotating Magnetosphere
- Determine How Intense Parallel Electric Fields are Generated in a Magnetized Plasma
- Determine How Momentum is Transferred Through Field-Aligned Current Systems
- Determine the Role of Io on Radio Wave Generation at Jupiter

Mission Description

- Example Mission Design
  - Delta III Launch: Direct Trajectory
  - Elliptical Io-Resonant Equatorial Orbit
    - 5.9 R_J x 71 R_J, ~ 1 mo. Orbital Period
    - 2-Year Flight Time, 3-Year OPS
- Flight System Concept
  - Rad-Hard Spin-Stabilized Platform
  - Chem/Bi-Prop w/ ARPS Implementation
  - Payload:
    - Fields & Particles Instrumentation (Plasma, Energetic Particle, Magnetic & Electric Fields)
    - UV Imager

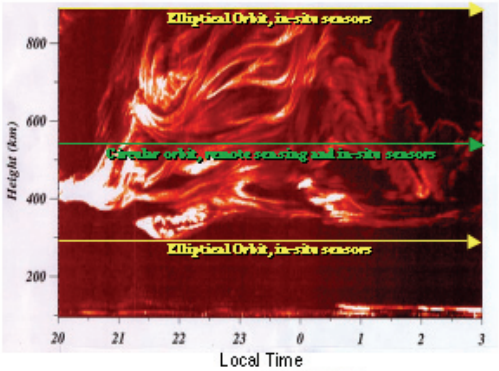
Enabling Technology Development

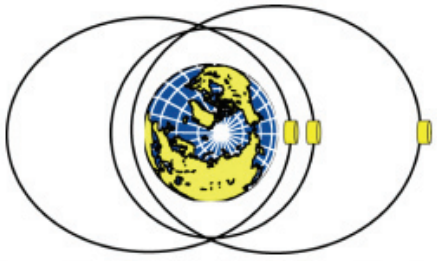
- Rad-Hard Electronics/ACS Sensors
- Advanced Radioisotope Power

Measurement Strategy

- Multiple Flybys of Io
- Different Science Emphasis for Each Encounter/Flyby
- High Resolution Flyby Data Stored in Mass Memory for Playback Over Post-Encounter Trajectory (Apojove)
- Image Jupiter aurora to track magnetic footprint of Io

Ionosphere Thermosphere Mesosphere Coupler (ITMC)





Science Objectives

- Measurement of neutral and plasma electro-dynamics at different altitudes simultaneously.
- Determine the coupling between the Earth's low latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

Mission Description

- 3 satellites with identical orbit periods and the same low inclination (<20°)
  - 2 with elliptical orbits (250 x 1500 km)
    - Apogees: 180 degrees apart
    - Dipping to 150 km perigee
  - 1 with a circular orbit of 600 km
- Payload (ram and nadir pointing)
  - 8 in-situ instruments on all 3
  - 4 remote sensing on circular spacecraft

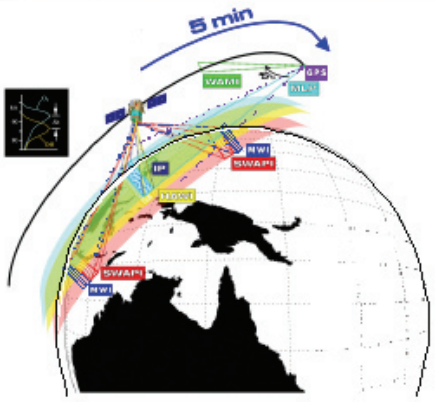
Measurement Strategy

- Remote sensing: gravity waves, airglow, neutral winds, plasma density profiles;
- In-situ: electric, magnetic fields, thermal, energetic plasma, neutral properties, winds, lightning;
- Coverage (continuous in each orbit):
  - Conjunctions of the two elliptical satellites with each other and the circular satellite provide investigations of vertical coupling

Minimum Technology Design was Baselined

- No "enabling" technology required
- New enhancing technology should reduce spacecraft cost by 10%

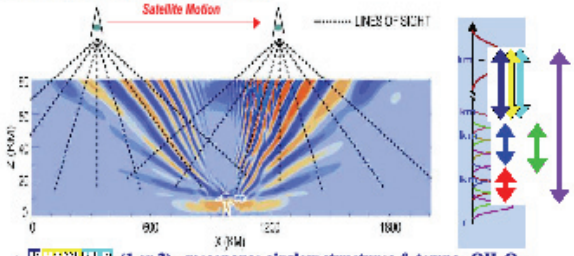
Ionospheric-Thermospheric-Mesospheric Waves (ITMW)



Mission Description

- Mission Design
  - One satellite provides a tomographic-like view of the Earth's Ionosphere, Thermosphere and Mesosphere
  - Launched in 2012 on a Delta II
  - Orbit altitude is circular 500 km, 70° Inclination
- Flight System Concept
  - Single-string design with a few selected redundant components to achieve four year mission life
  - Instrument Payload: 160 kg, 210 W, 93 kbps (8 Gb/day)
  - Attitude (arc seconds): control of 72, knowledge of 72

Measurement Strategy



- IP (1 or 2) - mesopause airglow structures & temps., OH, O_2, limb & nadir. Lower Thermosphere Waves Imager 6300Å and/or 1356Å.
- GPS occultation measurements for ionospheric wave structures.
- WINDII interferometer, winds (UARS/WINDII heritage)
- NWI CO_2 sub-limb mesospheric temperatures (TIMED/Saber heritage)
- SWAPI CO_2 sub-limb stratospheric temperatures

Science Objectives

Provide critically needed understanding of small-scale gravity waves (GWs) and their roles in energy and momentum transports relevant to atmospheric modeling and prediction.

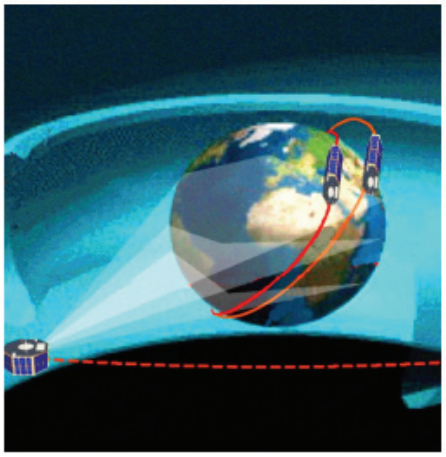
1. Earth Science: Quantify geographic, meteorological, and seasonal GW sources, characteristics and propagation, and influences on mean circulation and variability
2. Earth Science: Parameterize these effects for numerical weather prediction, climate studies, and global change
3. Space Science: Quantify interactions with large-scale motions, tides and planetary waves, their effects on the mesosphere, thermosphere, and ionosphere, and their roles in plasma dynamics and Space Weather
4. Mars Exploration: Develop understanding of GW interactions, instability, and momentum transport, relevant to parameterizations for general circulation modeling of other planetary atmospheres where GWs have huge influences

Enabling Technology Development

- All instruments are at a Technology Readiness Level of 7 or higher

Ionosphere-Thermosphere Storm Probes (ITSP)

Living With a Star Program - Geospace Storm Probes



Science Objectives

- Identify and quantify the causes for global (and especially mid-latitude) ionospheric-thermospheric variations, including:
  - -the response to solar extreme ultraviolet radiation
  - -the response to geomagnetic storms
  - -sources and characteristics of ionospheric irregularities

Mission Description

- Two spacecraft in 60° inclination circular orbits at nominal altitudes of 400 - 450 km and 10-15° azimuthal separations.
- An ionosphere-thermosphere imager on a mission of opportunity (not necessarily concurrent with I-TSP) maximizes scientific return.

Measurement Strategy

- In situ measurements of parameters relevant to the plasma-neutral coupling, in particular neutral winds and composition.
- Spacecraft inclinations provide good sampling of longitudinal variations at middle latitudes
- Azimuthal separation provides good sampling of gradients.
- Imager observations of neutral composition and ionosphere provide a global view of I-T structural evolutions.
- An integral part of LWS Program:
  - Solar Dynamics Observatory provides EUV data
  - Radiation Belt Storm Probes provide magnetospheric input.
- Correlative studies with other ground based and spacecraft assets

Enabling and Enhancing Technologies

- Low Magnetic & Electric Field Disturbances

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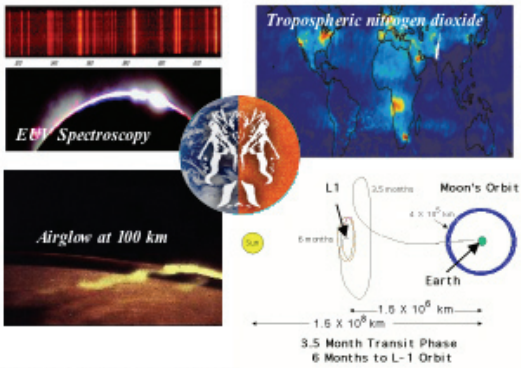
Janus – An Earth-Sun Mission at L1



Science Objectives

- Understand the structure of Earth's atmosphere from the surface to the thermosphere-ionosphere for a range of seasons, solar radiation and energetic particle inputs.
- High-resolution synoptic mapping of environmentally important species, tracking of pollution plumes, and ozone layer dynamics.
- Explore the dynamical and chemical linkages between the upper and lower atmosphere, including the effect of solar forcing.

Mission Description

- Delta launch vehicle to L1 Halo orbit
- 3.5 month transit, 6 months to orbit
- 3 year lifetime, 5 year goal
- Daily science telemetry, and real-time, low-rate broadcast mode

Technology Development

- None required

Measurement Strategy

- Continuous Earth and Sun viewing, and continuous upstream particle monitoring
- Sun (EUV) and Earth (EUV, FUV, VIS, IR) spectroscopy to provide new physical understanding
- Coronagraph and solar wind and energetic particle measurements provide continuous space weather information

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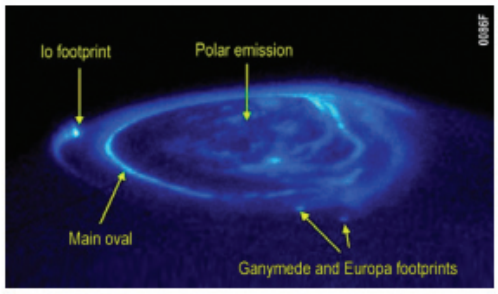
Jupiter Polar Orbiter (Juno)



- Measurement Strategy
  - Measure Particles and Fields In-Situ in the Auroral Acceleration Region
  - Image Aurora in the UV
  - Precisely measure the Magnitude and Configuration of the Near-Planet Magnetic Field
  - Map the 3-D Structure of the Radiation Belts
  - Microwave radiometry of both planetary atmosphere and synchrotron zone
  - Precise Doppler measurements of gravitational field

- Magnetospheric Science Objectives
  - The Relative Contributions of Planetary Rotation and of the Interaction with the Interplanetary Medium to Jovian Magnetospheric Dynamics
  - How Global Electric and Magnetic Fields Regulate the Processes that Produce the Radiation Belts, Plasma Sheet, and the Aurora
  - How momentum is transferred between Jupiter's ionosphere and magnetosphere
  - Identify the Particles Responsible for the Generation of the Jovian Aurora and Determine their Magnetospheric Source Regions
- Other Science Objectives
  - Determine internal structure by gravity & magnetic field mapping
  - Determine O/H ratio with microwave radiometry

- Mission Description
- New Frontiers Mission
- Mission Design
  - Atlas V 551 Launch , 2914 kg (3635 kg capacity) @ C_3 = 31 km^2/s^2
  - Elliptical Polar Orbit
    - 1.06 R_J x 39 R_J, 90° inclination
    - 5.2 Year cruise, 1-Year OPS
- Flight System Concept
  - Spin-Stabilized Platform
  - Solar Array Implementation
  - Payload: Magnetic Field & Particles, Imagery, Radiometry, Gravity

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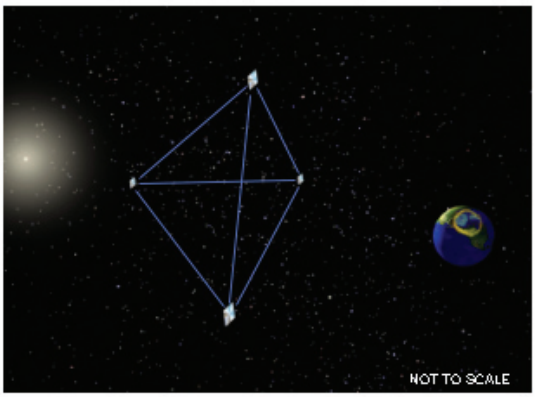
L1 Diamond



Science Objectives

- Measure the properties of solar-wind turbulence (as seen in density, velocity vector and magnetic field) as a function of separation in space and time, ranging from the dissipation scales of perhaps hundreds of kilometers to the outer scale of millions-of-kilometers
- Direct measurements of the possible spatial symmetries of the turbulence
- Discover associations of the turbulence with suprathermal and energetic particles
- Measure the spatial variation in convected and propagating waves, shocks and other disturbances in the solar wind

Mission Description

- **Example Mission Design**
  - Delta IV Launch Vehicle
  - Trajectory: ballistic transfer from Earth to L1 Halo (~90 days), solar sail transition from L1 to constellation stations,
    - 3 s/c in triangle formation, centroid 280 - 500 Re sunward of Earth on Sun-Earth line, 4th s/c above the ecliptic
    - Variable constellation baseline (for 3-D structure)
  - Continuous Solar Viewing: 2 years In Final Orbit
- **Flight System Concept**
  - 4 solar-array powered S/C with solar sails
  - Payload: Fields and Particles (16 kg/15 W)

Enabling Technology Development

- Solar Sail
- Solar Sail Navigation Tools
- Autonomous Thrust Vector Control
- "Multi-Chip Module" (MCM) Electronics

Measurement Strategy

- 4-s/c constellation with varying separations to study the full range of turbulence structures in both space and time
- High time resolution with time delays providing valuable correlations between the observed quantities

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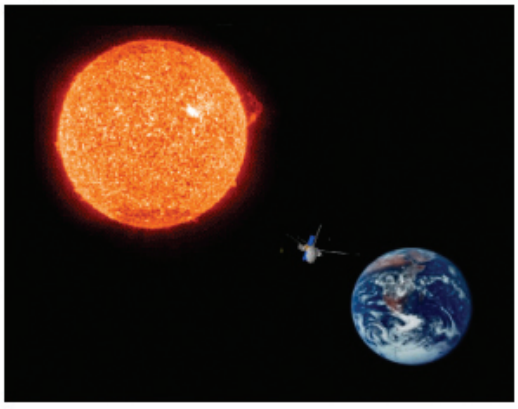
L1 Earth-Sun



Science Objective

•Include solar activity forecasts and the Earth's response into climate forecasts

Science Goals

•Understand feedback processes in the Earth's atmosphere consistent with observed time scales of solar variability of total and spectral irradiance.
•Determine if the patterns of solar surface temperature are in agreement with convective theory.
•Understand the varying spectrum of radiation emitted by magnetic regions of the Sun.

•Additional Objective

•Provide an inter-calibration standard for Earth observing sensors.
•Deliver continuous space weather observations from L1.

Mission Description

• L1 orbit. Duration: One Solar cycle (11 years). 6 year minimum to observe Max to Min.

Measurement Strategy

- **Spatial imaging of bolometric flux of solar photosphere**
- **Rapid (~1 min) global imaging spectroscopy of solar UV, EUV and soft X-rays at moderate resolution**
- **Imaging solar magnetograph**
- **Synoptic scale imaging of terrestrial fluxes**
- **Synoptic, high temporal and spatial resolution spectral imaging of the sunlit Earth over the entire ultraviolet (UV), visible, and infrared (IR) spectrum**
- **Synoptic measurements of environmentally important chemical species and tracers in Earth's atmosphere**
- **Synoptic measurements of greenhouse gases, aerosols, upper-atmosphere dynamics and cloud height/phase with a resolution of at least 10km**
- **Observations of backside of the Moon (approx. monthly) to check/calibrate instruments. Integrate calibrations with LEO and GEO.**
- **Solar Coronagraph and Space Environment Instruments provide continuous upstream measurements of energetic particles at L1**

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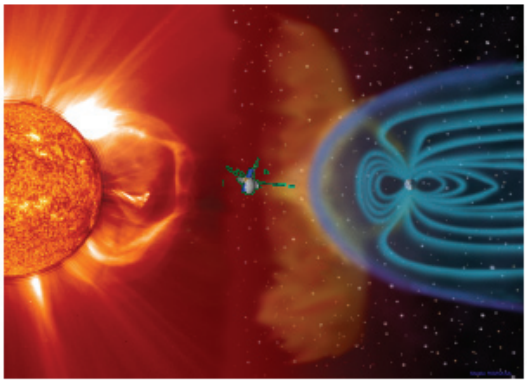
L1 Solar-Climate Connection Explorer (L1SCE)



Science Objectives

- **Examine the mechanisms that potentially link solar variability to changes in the Earth's climate**
- Relate changes in spatially resolved Earth albedo to variations in solar irradiance
- Examine the role of energetic particle fluxes in mechanisms that affect climate
- Identify the atmospheric processes and their coupling that are affected by the variation of solar irradiance and how they drive climate change

Observation Strategy

- Measure the spatial, spectral and temporal variation in the Earth's albedo, while making simultaneous measurements the solar photon and energetic particle input to the Earth's atmosphere

Technology Development

- No enabling technology development needed

Mission Description

- **Example Mission Design**
  - Trajectory: ballistic transfer from Earth to L1 Halo
  - Continuous Earth & Solar Viewing: >3 years In Final Orbit
- **Flight System Concept**
  - Spacecraft at L1 monitoring both the Sun and the Earth
  - Payload: Multi-wavelength imaging spectro-radiometer, Multi-wavelength solar Irradiance, In-situ Plasma, Magnetic field and Energetic particle instruments

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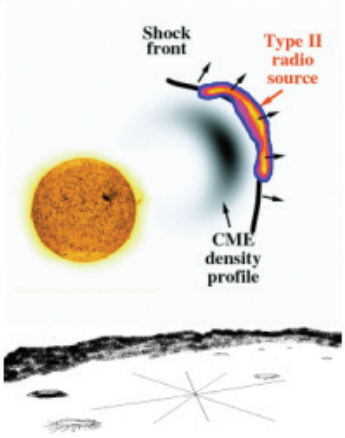
Lunar Imaging Radio Array (LIRA)



Lunar radio observatory images CME-driven shock and density enhancement with high angular and high time resolution.

Measurement Strategy:

- Lunar-based radio interferometer with dipole array; aperture synthesis imaging
- Full bandwidth (30 kHz-60 MHz) acquired for maximum sensitivity
- Autonomous observatory operations
- Correlations & snap-shot images calculated on-site for rapid prediction delivery
- First lunar radio observatory to be located on Earth-facing hemisphere of moon

Science Objectives:

- Image radio waves from CMEs/shocks as they propagate from the Sun to 1 AU; track events for CME/solar wind analysis and space weather prediction
- Identify solar energetic particle (SEP) onsets & trajectories with radio imaging; enhance space weather prediction of SEP arrival and maximum flux
- Image and understand response of Earth's magnetosphere to CMEs & other space-weather events from an external perspective with high angular & time resolution
- Image the low-frequency (< 60 MHz) radio universe at high angular resolution and catalog and understand the sources observed, including newly-discovered sources

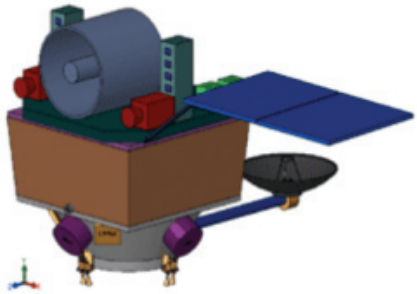
Mission Description:

- Lunar-based observatory to perform high resolution aperture synthesis radio imaging
- Dipole array laid out in spokes emanating up to 5 km from central hub where receivers, computing capability, and communication antenna(s) are located
- ~10,000 crossed dipole antennas and leads are deposited on polyimide sheeting (Kapton, CP1, …) of ~1 m width and ~1 mil thickness
- Polyimide sheeting is unrolled with rover assistance, after which rovers are available for lunar surface or other investigations
- Correlations and snap-shot images computed on moon at LIRA hub
- Mission life greater than 10 years

Enabling and Enhancing Technology Development:

- Develop technology/materials for thin sheet deposited antennas and leads
- Design/implement deployment rover
- Integrate Prometheus/other power sources for computation and downlink
- Design hardware/software for lunar-based correlation and image processing
- Implement high-data-rate downlink to Earth

Lunar Reconnaissance Orbiter (LRO)



Science Objectives

•LRO will obtain measurements necessary to characterize future robotic and human landing sites
•It also will identify potential lunar resources and document aspects of the lunar radiation environment relevant to human biological responses

Mission Description

•The LRO mission will be launched from the NASA KSC/ETR on an intermediate-class (e.g., Delta II) launch vehicle as early as October 2008
•After achieving the final mapping orbit, the LRO baseline mission is nominally 1 Earth year at 30-50 km circular, polar orbit.
•This may be followed by an extended mission of up to 5 years in a low maintenance orbit that allows continued observations and possibly the use of LRO as a communication relay satellite.
•The LRO spacecraft will be a 3-axis stabilized platform with both stored data and real-time downlink capabilities.
•The current estimate for the downlink data rate is 100 Mbps with delivery of up to 900Gb/day of observation data to earth.

Measurement Investigations

•Lunar Orbiter Laser Altimeter
•Lunar Reconnaissance Orbiter Camera
•Lunar Exploration Neutron Detector
•Diviner Lunar Radiation Experiment
•Lyman-Alpha Mapping Project
•Cosmic Ray Telescope for the Effects of Radiation

Measurement Strategy

*Characterization of deep space radiation environment in Lunar orbit
*Geodetic global topography
*High spatial resolution hydrogen mapping
*Temperature mapping in polar shadowed regions
*Imaging of surface in permanently shadowed regions
*Identification of putative deposits of appreciable near-surface water ice in polar cold traps
*Assessment of meter and smaller scale features for landing sites
*Characterization of polar region lighting environment

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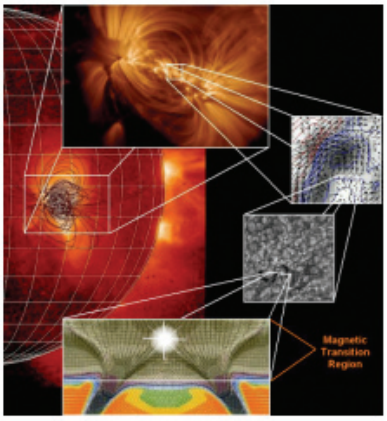
Magnetic Transition Region Probe



Science Objectives

- Discover, measure, and understand the 3D structure and dynamics of the magnetic transition region between the photosphere and upper chromosphere.
- Connect the structure and events in the magnetic transition region with their photospheric roots and the magnetic stressing and heating of the chromosphere and corona.
- Resolve and measure the appearance, transport, and destruction of magnetic field on the fundamental intergranular scales in the photosphere.

Mission Description

- Example Mission Design
  - Delta IV Launch Vehicle (due to shroud requirement)
  - Geo-synchronous, Earth-orbiting satellite
    - 3 years In Orbit
- Flight System Concept
  - 3-Axis Stabilized Solar Inertial Observatory Platform
  - Solar Arrays
  - 751 Mbps link to Ground Terminal
  - Payload: 570 kg, 330 W (peak), 750 Mbps
  - 36-as control (payload implements 10-as with 1-as knowledge)

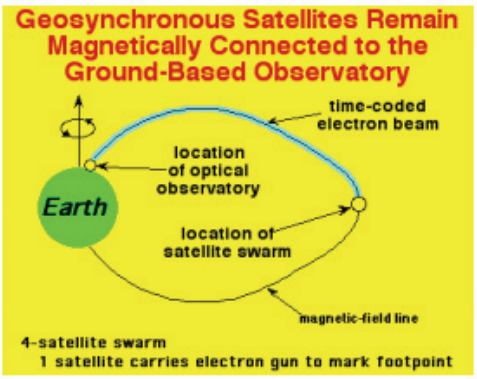
Measurement Strategy

- Visible/infrared maps/images of vector magnetic field, intensity, and velocity in the magnetic transition region and the photosphere, with large FOV (> 100,000 km), high resolution (< 100 km), and high sensitivity (< 30 G, transverse).
- UV maps/images of line-of-sight magnetic field, intensity, and velocity in upper chromosphere/lower transition region.
- EUV images and spectra of coronal structures in and around the FOV of the magnetic transition region observations and with comparable resolution.

Enabling Technology Development

- Large, light weight, reflecting optics for use in visible near IR and vacuum ultraviolet
- Extendable optical bench
- Large format (up to 16K x 16K pixels), low power, high QE at 150 nm, multiport CCDs.
- Image motion compensation/stabilization for large apertures and EUV
- Variable Emissivity Surfaces
- High Data Volume Ground Processing
- Instrument Auto-Boresighting System
- High Stability Platform
- Compact PCI Cards
- Ka-band Transponder/TWTA/Switches

Magnetosphere-Ionosphere Observatory



Science Objectives

- Determine what causes the aurora
- Determine how 10's-100's of gigawatts of energy are extracted from the magnetotail
- Probe magnetosphere-ionosphere coupling

Mission Description

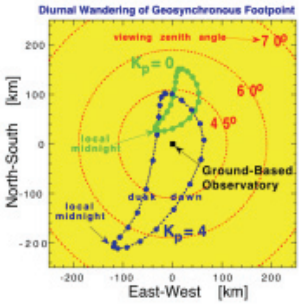
- Main spacecraft contains a high-power electron gun
- 3 satellite spacecraft in close cluster with main spacecraft
- Geosynchronous satellites remain magnetically connected full-time to ionospheric observatory
- All spacecraft carry critical measurement instruments
- Observatory locates the beamspot within the auroral ionosphere

Measurement Strategy

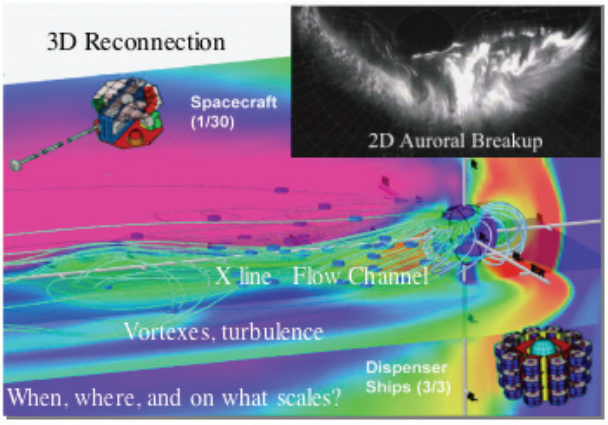
- Find the magnetospheric end of auroral arcs
- Verify position from electron-beam connection
- Measure plasma, flow, and field gradients in aurora using multiple spacecraft
- Discriminate among auroral arc theories

Minimum Technology Design was Baselined

- Exploits technologies developed by NASA's program in active space experiments.
- New enhancing technology should reduce spacecraft cost by 10%



Magnetospheric Constellation (MC) Mission



More info:
http://stp.gsfc.nasa.gov/missions/mc/mc.htm

Enabling Technology Development

- None

Technology Requirements

- ST-5 design-experience base
- Fabrication, assembly and testing techniques from Iridium, GPS, other commercial, DoD constellations

Science Objectives

- Determine how the magnetosphere stores, processes, and releases energy from the solar wind interaction:
  - How does the magnetotail behave?
  - How are particles injected to form the radiation belts?
  - How does the magnetopause respond to the solar wind?

Mission Description

- Constellation of 30-36 ST-5 class s/c
- 15˚ inclination, nested orbits
- Apogees from 7-27 R_E, _V = 814 m/s
- Per s/c: 20 kg, 15 W, 1 kbps, 1˚ pointing

Measurement Strategy

- Synoptic vector measurements of magnetic field, plasma flow & energetic particles
- Mean spacecraft separation: 2 R_E
- Time resolution: 10 sec
- Mission targets are plasma sheet and low latitude magnetopause

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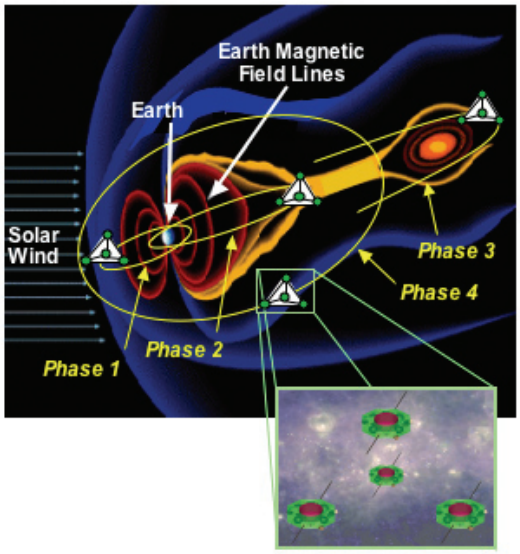
Magnetospheric Multiscale (MMS)



Science Objectives

- Understand the fundamental plasma physics processes of reconnection, particle acceleration, and turbulence on the microscale and mesoscale in the Earth's magnetosphere.

Mission Description

- 4 spin-stabilized spacecraft in a tetrahedron constellation (2 year mission)
- Inter-spacecraft ranging system
- 4 orbital phases:
  - Phase 1: 1.2 R_E by 12 R_E, 10° incl. (9 months)
  - Phase 2: 1.2 R_E by 30 R_E, 10° incl. (3 months)
  - Phase 3: 8 R_E by 100-120 R_E lunar assist maneuver to achieve ~90° orbit plane change
  - Phase 4: 10 R_E by 40 R_E, 90° incl. (11 months)

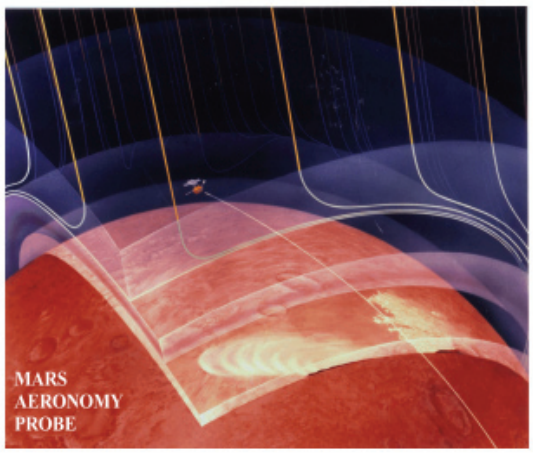
Measurement Strategy and Coverage

- 4 suites of identical instruments: electric field, energetic particles, hot plasma & magnetometer
- Measurements taken during 4 phases include:
  - Phase 1: Dayside Magnetopause: reconnection acceleration, turbulence, solar wind entry
  - Phase 2: Nightside Substorm: reconnection, plasma sheet boundry, accel., current disruption
  - Phase 3: Magnetotail: reconnection structures and dynamics, plasma escape/motion across boundary
  - Phase 4: Post-Cusp Magnetopause: northward re-connection, reverse convection, pointing flux entry

Minimum Technology Design was Baselined

- No "enabling" technology is required

Mars Aeronomy



Technology Development

- Low Mass/Power Instrumentation
- Micro-Spacecraft Components and S/S

Science Objectives

- Determine the altitude and solar zenith angle variation in the composition, density and temperature of the neutral and ionized components of the upper atmosphere
- Determine the intrinsic magnetic field at Mars and how the solar wind interacts with the upper atmosphere and ionosphere
- Determine the major features of the circulation of the atmosphere at all levels, in particular the middle and upper regions
- Investigate the oxidation of CO and organics and the corresponding dearth of free oxygen and ozone

Mission Description

- **Example Mission Design**
  - Delta IV 4040-12 (2205 kg Capability at C_3=8.5 km^2/s^2)
  - Initial MOI orbit: 150 km x 2 Sol Orbit, i= 102°
  - Aerobraking orbit: 150 x 2 Sol to 6,000 km @ 102°
  - Phase 1 Sci Orbit: 150 x 6,000 km, i= 102° (MOI+174^d)
  - Propulsive Inc. change into "frozen" orbit (MOI+440^d)
  - Phase 2 Sci Orbit: 150 x 6000 km, i= 63.4°
  - 2 year mission duration (includes 6 months for aerobraking)
- **Flight System Concept**
  - Solar-array powered, 3-axis stabilized, 2330 m/s ΔV
  - Payload: 37 kg, 44 W (avg), 11.5 kbps (avg data rate)
  - Control: 0.1 deg, Knowledge: 0.05 deg, Stability: 1.8 arcsec/sec

Measurement Strategy

- Neutral Species Escape Rates, Isotopic Ratios, Densities, Temperatures, Winds and Composition
- Thermal Plasmas (Ions and Electrons), Pick-up Ions, Energetic Particles and Magnetic and Electric Fields
- Integrated Theory and Data Analysis Program
- UV spectra for remote sensing of escaping atoms

Mars Dynamics

Science Objectives

- Characterize the temperature, density and wind structures of Mars' upper atmosphere (UA), 25-200 km
- Understand the sources of variability of Mars UA
- Understand how wave-wave interactions, wave-mean flow interactions, and wave dissipation contribute to the mean state and variability of Mars' and Earth's UA
- Define the aerobraking and aerocapture environments for Mars exploration spacecraft
- Provide the data required to constrain GCMs and to develop atmospheric models that support the manned exploration effort

Mission Description

- **Example Mission Design**
  - Launch Date: 5/2018 (C_3=8.5 km^2/s^2, Type 1 with chemical MOI of 1 km/s)
  - Delta II 2925-9.5 (1,080 kg launch injection mass)
  - Initial MOI orbit: 250 x 57,000 km @ 80 deg
  - Aerobraking orbit: 100 x 550 to 57,000 km @ 80 deg
  - Final science orbit: 550 x 550 km @ 80 deg
  - 2 year mission duration (includes 6 months for aerobraking)
- **Flight System Concept**
  - Solar array powered, 3-axis stabilized, 1352 m/s ΔV
  - Payload: 123 kg, 175 W, 11.1 kbps data rate
  - Control: 36 arcsec, Knowledge: 3.6 arcsec

Measurement Strategy

- F-P Interferometer: temperature, winds, airglow emissions
- Radiometer: temp, density, pressure, CO_2 density and emissions; constituents
- Solid State Laser: Raleigh temperatures in atmosphere
- Neutral Mass Spectrometer:
- Accelerometer: atmospheric density

Enabling Technology Development

- Low mass/power instrumentation
- The LIDAR solid state transmitter needs to be assembled in a lab environment to demonstrate the power and pulse characteristics.

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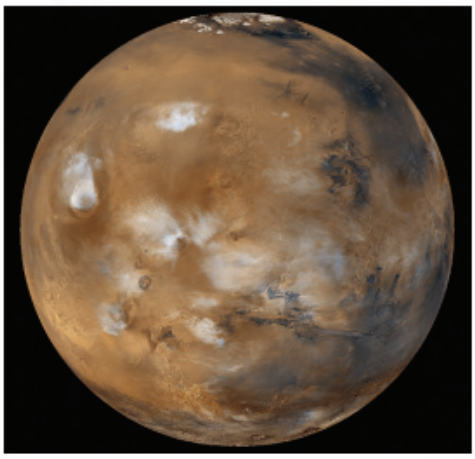
Mars GOES



Mars GOES ("Geo"stationary Operational Environmental Satellite) is the Mars analog to the Earth-orbiting GOES satellite. Its primary objective is to provide timely global Mars Weather and Space Weather information necessary to support future human exploration of Mars.

Mission Objective

- Astronauts on future Mars missions will require their own, independent weather and space weather prediction, forecasting and nowcasting because statistically more than _ of the time Mars is on the far side of the Sun, and therefore unable to rely on Earth-based weather and space weather prediction.
- Space weather monitoring and forecasting include characterizing the solar wind environment at Mars, monitoring the changes of solar cycle, and the effect of solar activity on Mars' telecommunications systems.
- Characterize the major features of the atmospheric circulation at all levels, together with visible imaging of clouds and "dust devils" on the surface to support surface activities, EDL activities and ground communications.

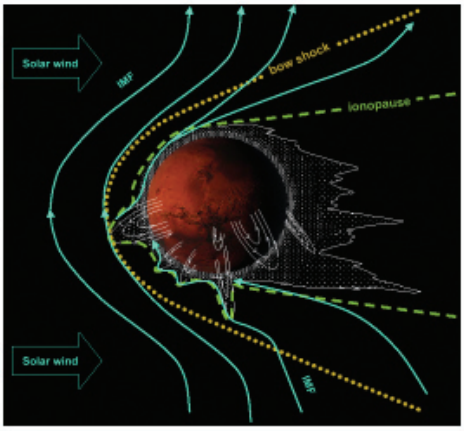
Measurement Strategy

- Temperature, density, winds and composition measurements of the Mars atmosphere together with visible imaging of clouds and "dust devils".
- Space environment measurements include energetic particles, thermal Plasmas (Ions and Electrons), Pick-up Ions, solar X-rays, and magnetic fields.
- Solar EUV imaging for space weather forecasting and solar cycle monitoring. Solar EUV Irradiance measurements to study solar forcing and calibrated radiative inputs for Mars aeronomy models.

Mission Description

- 10 years life time
- High altitude orbit
- Communications relay for future Manned Missions, Mars Scouts and and other Mars orbital missions
- Provide Critical Event Coverage, such as EDL or MOI

Mars L-1 Sentinel Mission



The Mars L1 Sentinel Mission is similar in concept to various L1 Earth-Sun Missions, serving as a space weather sentinel outpost at the Mars-Sun L1 Lagrangian point. Its primary objective is to provide timely global Mars Weather and Space Weather information necessary to support future human exploration of Mars.

Mission Description

- 10 years life time
- Halo orbit about the Mars-Sun L1 Lagrangian point
- Communications relay for future Manned Missions, Mars Scouts and and other Mars orbital missions

Mission Objective

- Astronauts on future Mars missions will require their own, independent weather and space weather prediction, forecasting and nowcasting because statistically more than _of the time Mars is on the far side of the Sun, and therefore unable to rely on Earth-based weather and space weather prediction.
- Space weather monitoring and forecasting include characterizing the solar wind environment at Mars, monitoring the changes of solar cycle, and the effect of solar activity on Mars' telecommunications systems.

Measurement Strategy

- Space environment measurements include energetic particles, thermal Plasmas (Ions and Electrons), Pick-up Ions, solar X-rays, and magnetic fields.
- Solar EUV imaging for space weather forecasting and solar cycle monitoring. Solar EUV Irradiance measurements to study solar forcing and calibrated radiative inputs for Mars aeronomy models.

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Mars Science Laboratory (MSL)

Relevance to Sun-Solar System Connection

• The objective of characterizing the surface radiation environment on Mars has direct relevance to S3C roadmap Objective J, and is being addressed by the Radiation Assessment Detector (RAD) which has leadership and strong involvement from the S3C community. Characterizing and understanding the radiation environment on Mars is fundamental to quantitatively assessing the habitability of the planet, and essential for future manned Mars missions. RAD will provide the essential precursor information necessary to develop this mitigation strategy for these critical human risks.

Science Objective

• The MSL mission is the next NASA Mars rover mission scheduled to be launched in 2009 with the overall science objective to explore and quantitatively assess a potential habitat on Mars. The specific objectives of MSL include assessing the biological potential of the environment, characterizing the geology of the landing region, investigating planetary processes of relevance to past habitability, including the role of water, and characterizing the broad-spectrum of the surface radiation environment, including galactic cosmic radiation, solar proton events, and secondary neutrons.

Mission Description

• 3000 kg spacecraft launched in late 2009 for arrival in 2010
• First planetary mission to use precision landing techniques, steering itself toward the Martian surface similar to the way the space shuttle controls its entry through the Earth's upper atmosphere. Landing method would enable the rover to land in an area 20 to 40 kilometers (12 to 24 miles) long, about the size of a small crater or wide canyon and three to five times smaller than previous landing zones on Mars

Investigations/Instruments

• Mars Science Laboratory Mast Camera
• Laser Induced Remote Sensing for Chemistry and Micro-Imaging,
• Mars Hand Lens Imager,
• Alpha Particle X-Ray Spectrometer,
• X-Ray Diffraction/X-Ray Fluorescence Instrument,
• Radiation Assessment Detector,
• Mars Descent Imager,
• Gas Chromatograph Mass Spectrometer/Tunable Laser Spectrometer
•Pulsed Neutron Source and Detector
•Meteorological Package with Ultraviolet Sensor

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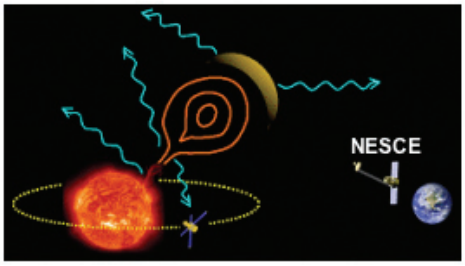
Near-Earth Solar Coronal Explorer (NESCE)



Science Objectives

- To understand how solar energetic particles (SEPs) are produced and accelerated in coronal mass ejection (CME) shocks and flare/CME current-sheets.
- To understand the physical processes for heating and accelerating the fast and slow solar wind in their coronal source regions.

Mission Description

- **Example Mission Design**
  - Delta II 7320-10 Launch Vehicle (~100% mass margin)
  - 650 km Sun Synch orbit
- **Flight System Concept**
  - Payload Mass: 322 kg; Power: 186 W; Data Rate: 417 kbps
    - Advanced Large Aperture UV Coronagraph-Spectrometer
    - Advanced Large Aperture Visible Coronagraph-Polarimeter
  - Total Spacecraft Mass: 715 kg; Power:444 W (20% reserves)
  - Solar array powered, 3-axis stabilized, 15 m/s ΔV

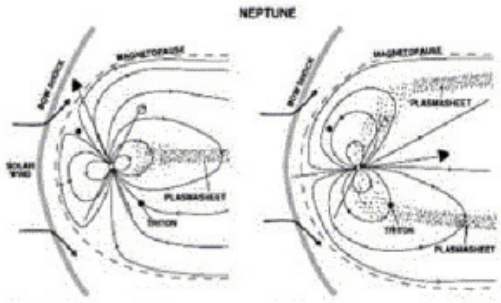
Technology Development

- Mission can be accomplished with no new technology
- Spacecraft Bus can be accomplished with existing technology and well established engineering
- Feasibility proven with two MIDEX Phase-A Concept Studies

Measurement Strategy

- **SEP production in CME shocks and flare/CME current sheets:**
  UV Coronagraph-Spectrometer determines shock-site pre- and post-shock plasma parameters including suprathermal seed particle populations, and derived Mach number and field strengths; current-sheet plasma parameters, and derived reconnection rate, and electric and magnetic field strengths. Visible Coronagraph-Polarimeter provides CME images of the time evolution of electron density structure including inferred magnetic field structure and 2D CME flow speeds.
- **Physical processes of coronal heating & solar wind acceleration:**
  UV spectroscopic determinations of coronal ion and electron densities, outflow speeds and velocity distributions; and detection of ions with a large range of charge to mass ratios. Elemental abundances and charge state determinations are used to identify solar wind source regions. Visible coronal polarimetry provides electron density structure including inferred magnetic field structure and 2D flow speeds. Empirical measurements are used to constrain theoretical models. [37]

Neptune Orbiter



Science Objectives

- Map Neptune's highly asymmetric magnetic field
- Determine the magnetospheric structure as the highly oblique and offset magnetic field rotates with the planet
- Determine the densities, compositions, and temperatures of magnetospheric plasma populations, and their distributions throughout the magnetosphere
- Measure the plasma flows associated with the dynamics of the magnetosphere driven by the planet's rotation and by the solar wind
- Determine whether Triton has an intrinsic magnetic field, and characterize the plasma interaction with Triton and its atmosphere
- Compare the magnetosphere of Neptune with other planetary magnetospheres and compare the Triton-magnetosphere Interaction with the Galilean satellites of Jupiter and with the role of Titan in Saturn's magnetosphere

Mission Description

- Example Mission Design
  - Delta/Altas Launch (Jupiter Gravity Assist Trajectory)
  - 9-12 yrs to Neptune + 2 yrs in orbit
  - Aerocapture, Optical Com, μ-S/C Technology
  - Autonomous operation and navigation
  - Multiple flybys of Triton
- Flight System Concept
  - Fields & Particles Instrumentation (Plasma, Energetic Particle, Magnetic & Electric Fields)

Enabling Technology Development

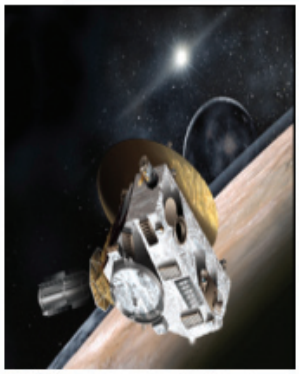
- Aerocapture (0.3 to 0.4 mass ratio)
- Advanced Telecom: Optical or large-diameter inflatable antenna
- Advanced Radioisotope Power
- Autonomous spacecraft operations

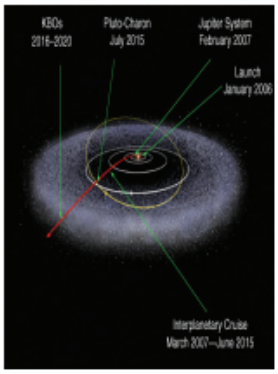
Measurement Strategy

Thermal plasmas, energetic particles, magnetic and electric fields, plasma waves, and auroral measurements (including UV spectral imaging of Neptune and Triton)

Integrated theory and data analysis program involving numerical simulations processes, and energetic-particle acceleration under a variety of planetary magnetic-dipole orientations

Pluto/Kuiper Belt Mission
New Horizons





Measurement Strategy

• The Solar Wind Analyzer around Pluto (**SWAP**) will measure densities and energy spectrum of solar wind as it interacts with Pluto's escaping atmosphere (providing comparison with comets), with Charon (providing comparison with the Moon) and at least one Kuiper Belt Object.

• The Pluto Energetic Particle Spectrometer Investigation (**PEPSSI**) will measure densities and energy spectrum of energetic particles produced in the extensive region of solar wind - atmosphere interaction.

• The Student Dust Counter (**SDC**) will measure density of dust in the interplanetary medium, the products of collisions between planetary bodies.

• The Ultraviolet imaging spectrometer (**Alice**) and Radio Experiment **(REX)** package will probe the atmospheric composition and structure of Pluto during solar and Earth occultations.

• **Ralph** will obtain high resolution color and surface composition maps of the surface of Pluto and Charon with two separate channels.

• The Long Range Reconnaissance Imager (**LORRI**) will provide very high resolution visible maps

Objectives Relating to SSSC Science

•Characterize the neutral atmosphere of Pluto and its escape rate
•Characterize the solar wind interaction with Pluto's escaping atmosphere. The weak magnetic field and tenuous solar wind of the outer heliosphere suggests an extensive, probably asymmetric interaction region with substantial pick-up ions and significant kinetic effects.
•Search for an atmosphere around Charon and characterize the solar wind interaction.
•Conduct similar investigations of one or more Kuiper Belt Objects
•Measure the solar wind conditions, including the effects of interstellar pick-up ions, in the outer heliosphere to Pluto's orbital distance of 32 AU and beyond.

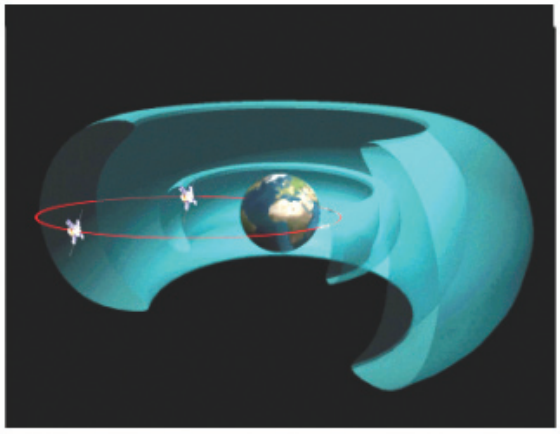
Mission Description

Launched Successfully January 19, 2006
Launch: Cape Canaveral Air Force Station, Florida
Atlas V 551 (1st stage); Centaur (2nd); STAR 48B solid rocket (3rd)
Trajectory:
• To Pluto via Jupiter Gravity Assist (first 23 days of window)
• Direct to Pluto (last 12 days of window)
Secondary Launch Window:
February 2-15, 2007 ; puts New Horizons on a direct-to-Pluto trajectory with arrival in 2019-2020, depending on exact launch date.
Early Cruise: The first 13 months include spacecraft and instrument checkouts, instrument calibrations, trajectory correction maneuvers, and rehearsals for the Jupiter encounter.
Jupiter Encounter: Closest approach scheduled to occur between Feb. 25-March 2, 2007. Moving about 47,000 miles per hour (about 21 kilometers per second), New Horizons would fly 3 to 4 times closer to Jupiter than the Cassini spacecraft, coming within 31.7-32.4 Jupiter radii of the large planet. The spacecraft will transect up to 1000 Jupiter radii down the jovian magnetotail.
Interplanetary Cruise: The ~8-year cruise to Pluto include annual spacecraft and instrument checkouts, trajectory corrections, instrument calibrations and Pluto encounter rehearsals.

Technology Development

• No enabling technology required

Radiation Belt Storm Probes (RBSP)
Living With a Star - Geospace Storm Probes



Science Objectives

• Characterize and understand the variability of energetic radiation belt ions and electrons by identifying and evaluating:
  -Source,
  -Loss, and
  -Transport mechanisms

Mission Description

•Two spacecraft in nearly identical, low-inclination (<18°, 12° goal), highly elliptical (500 km × 5.5 R_E) 'chasing' orbits distinguish spatial from temporal variations.

Measurement Strategy

• Measure temporal variations and radial profiles of energetic charged particles, electric and magnetic fields in response to varying solar wind conditions
•Simultaneous two-point measurements discriminate between temporal and spatial phenomena, distinguish local acceleration from radial transport.
•Evolving spacecraft orbits provide observations over a wide range of radial and azimuthal separations.
• An integral part of the LWS program: simultaneous LWS I-T Storm Probe observations define the ionosphere-thermosphere response.
• Correlative studies with other ground-based and spacecraft assets
• Launch Scheduled for 2011

Enabling and Enhancing Technologies

• Enabling technology development in high-rad avionics
• Enhancing technology to reduce spacecraft cost for multiple spacecraft investigations

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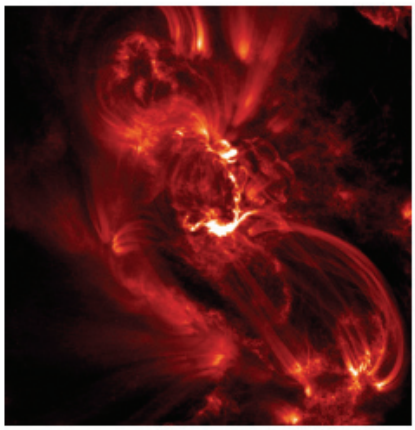
Reconnection And Microscale (RAM)



Minimum Technology Design was Baselined

- Enabling technology required - Large array, small pixel calorimeters for soft x-ray spectroscopy
- New enhancing technology should reduce spacecraft cost by 10%

Science Objectives

- What are the mechanisms that lead to reconnection?
- What micro-scale instabilities lead to global effects?
- Where are the regions of particle acceleration?
- Where are the reconnection regions and what is their topology?

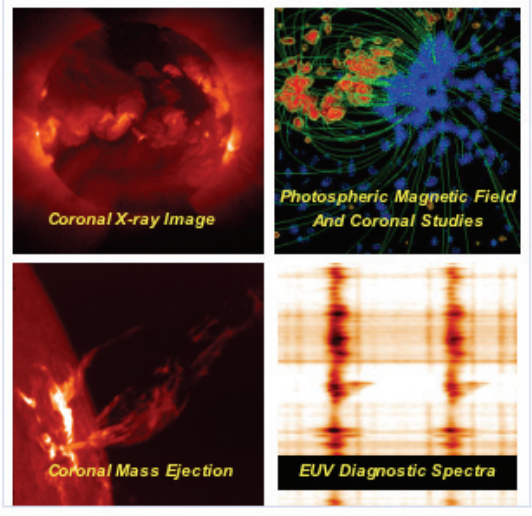
Mission Description

- Mission Design
  - Solar observations from single geosynchronous platform
  - Mission lifetime of 2 years
- Payload
  - High Resolution EUV Imaging instrument
  - EUV spectrograph
  - X-ray calorimeter
  - EUV Intermediate Scale Imager

Measurement Strategy

- Ultra-high resolution (0.02"/pixel) EUV coronal imaging
- High resolution (0.1"/pixel) EUV/UV spectroscopy
- X-ray Imaging Spectroscopy (1"/pixel; (E/DE) ~ 500 @ 1 keV) from 0.2 to 10 keV, with millisecond time resolution.
- Multi-wavelength EUV/UV intermediate scale imager (0.1"/pixel)
- High time resolution in all instruments

Solar-B



Science Objectives:

To follow the flow of magnetic energy from the Sun's photosphere to the corona in order to understand the steady state release of energy, which heats the corona and the transient release of energy that produces CMEs and solar flares.

Mission Description:

- Japan (JAXA) mission with international partners.
- Japan provided spacecraft and M-V launch vehicle.
- Launch September 2006 from Kagoshima, Japan.
- Single satellite in a Sun-synchronous, 600 km circular orbit, for continuous 24 hr coverage.
- Minimum mission lifetime 3 years with 8-year lifetime desirable.
- Three remote sensing telescopes to observe the Sun in the optical (SOT), ultraviolet (EIS), and X_ray (XRT).
- Image motion compensation enables 0.25 arcsec angular resolution in the visible.

Measurement Strategy:

- Three telescopes with overlapping fields of view and capable of simultaneous observations.
- The SOT will measure photospheric vector magnetic fields and granulation dynamics.
- The XRT will measure the coronal response to changes in the photospheric magnetic field and provide coronal temperature and density diagnostics.
- EIS, an imaging spectrometer, will provide spatially resolved temperatures, densities, and velocities of the material in the chromosphere and corona.

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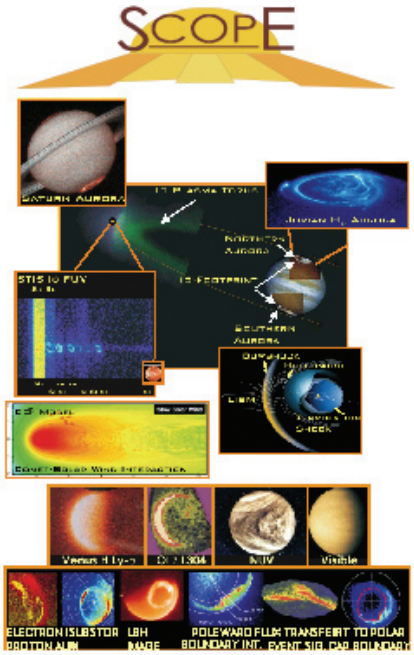
Solar Connections Observatory for Planetary Environments (SCOPE)



Science Objectives

- Compare the global effects of external and internal driving mechanisms on planet and comet near-space environments through observations of auroral, airglow, coronal, and/or internal plasma emissions
- Differentiate features of Jupiter's (and other giant planets') auroral emissions due to internal processes (rotation and internal plasma sources) from those due to the solar wind interaction
- Measure the response of ionosphere-solar wind coupling to changes in solar activity in planet systems without magnetospheres (Mars, Venus, Comets)
- Refine and expand our knowledge of Earth's global geospace response by extending auroral observations into new domains of spatial and spectral resolution
- Directly compare the terrestrial solar interaction with those of superior (Mars-Neptune) planets from opposition campaigns that monitor both systems along the same Sun-planet line
- Map the opacity and velocity structure of the interplanetary hydrogen
- Study the transition region between the heliosphere and LISM

Mission Description

- Dual meter-class telescopes (EUV & UV) covering bandpasses from 55 - 310 nm
- Hubble Space Telescope (HST) - class performance for UV observations. Highest sensitivity and spatial resolution yet achieved below 120 nm
- High ($R<10^5$) spectral resolution measurements of diffuse emissions with 50 times the etendue of HST-STIS.
- Inner solar system observations of Venus, Mercury, and comets to within ~0.35 AU of the Sun
- L1-halo orbit for uninterrupted observations of the Earth's North or South polar regions and a remote perspective on planets giving full hemisphere studies up to rotational poles.
- 5+ years potential operational lifetime

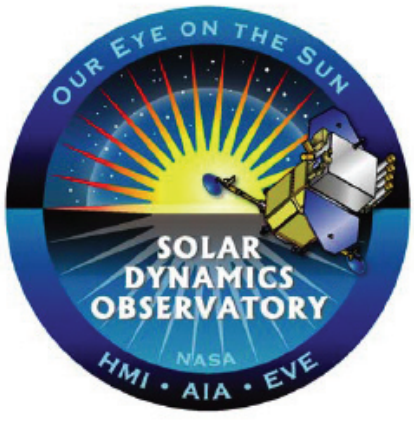
Measurement Strategies

- Global imaging of auroral emissions, upper atmospheric circulation, exospheres and near-space plasma distributions
- Imaging spectroscopy of UV ion-neutral emissions and atmospheric absorption features
- Narrow-field spectroscopy of planetary (auroral-dayglow-coronal) H Ly-α profiles
- Wide-field line profile measurements of diffuse H Ly-α emission from the interplanetary medium (IPM), comets, geocorona,and the heliopause
- Pencil-beam measurement of heliopause and LISM dynamics from H Ly-α and H Ly-β line-of-sight absorption spectroscopy
- High speed photon counting detectors for precision time resolution
- Coordinated SCOPE observations of planetary targets, the IPM and heliopause with existing in situ space probes
- Cross-cutting techniques for characterizing auroral emissions in planetary magnetospheres, such as the development of auroral indices as a function of precipitating species at each of the planets (i.e., hemispheric power, auroral oval location, auroral oval size, etc.)

Technology Requirements

- Light-weight, metal-matrix-composite mirror design
- High- sensitivity/dynamic-range photon counting UV detectors

Solar Dynamics Observatory (SDO)



Science Objectives

- Understand the nature and source of the solar variability that affects life and society
- Make accurate measurements of the solar parameters that are necessary to provide a deeper understanding of the mechanisms that underlie the Sun's variability on timescales ranging from seconds to centuries
- Through remote sensing, monitor and record those aspects of the Sun's variable radiative, particulate, and magnetic plasma outputs that have the greatest impact on the terrestrial environment and the surrounding heliosphere.

Mission Description

- NASA GSFC will manage the mission, build the robust, three-axis stabilized, solar tracking S/C in-house, manage & integrate the instruments, develop/manage the Ground System, receiving continuous 150 Mbps stream to dedicated ground station, & Mission Operations, & perform Observatory environmental testing at GSFC
- August 2008 Atlas V launch from KSC into GEO-Transfer Orbit (GTO), circularize to GEO-Sync Orbit, inclined 28.5 degrees
- Investigations responsible for development of their Instrument & Science Operations Center.

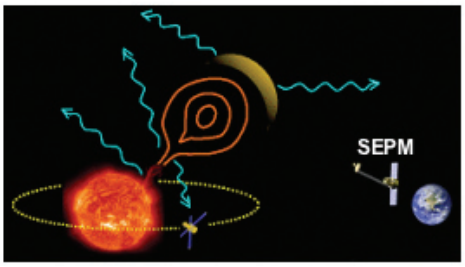
Measurement Strategy

- Helioseismic Magnetic Imager (HMI): Images the Sun's helioseismic and magnetic fields to understand the Sun's interior and magnetic activity
- Atmospheric Imaging Assembly (AIA): Multiple simultaneous, high resolution images of the corona over a wide range of temperatures
- Extreme Ultraviolet Variability Experiment (EVE): Measures the solar extreme ultraviolet (EUV) irradiance to understand variations

Enabling Technology

- **Ka-Band Telecommunications**

Solar Energetic Particle Mission (SEPM)



Science Objectives

- To understand how solar energetic particles (SEPs) are produced and accelerated in coronal mass ejection (CME) shocks and flare/CME current-sheets.
- To understand the physical processes for heating and accelerating the fast and slow solar wind in their coronal source regions.

Mission Description

- **Example Mission Design**
  - Delta II 7320-10 Launch Vehicle (~100% mass margin)
  - 650 km Sun Synch orbit
- **Flight System Concept**
  - Payload Mass: 322 kg; Power: 186 W; Data Rate: 417 kbps
    - Advanced Large Aperture UV Coronagraph-Spectrometer
    - Advanced Large Aperture Visible Coronagraph-Polarimeter
  - Total Spacecraft Mass: 715 kg; Power:444 W (20% reserves)
  - Solar array powered, 3-axis stabilized, 15 m/s ΔV

Technology Development

- Mission can be accomplished with no new technology
- Spacecraft Bus can be accomplished with existing technology and well established engineering
- Feasibility proven with two MIDEX Phase-A Concept Studies

Measurement Strategy

- **SEP production in CME shocks and flare/CME current sheets:** UV Coronagraph-Spectrometer determines shock-site pre- and post-shock plasma parameters including suprathermal seed particle populations, and derived Mach number and field strengths; current-sheet plasma parameters, and derived reconnection rate, and electric and magnetic field strengths. Visible Coronagraph-Polarimeter provides CME images of the time evolution of electron density structure including inferred magnetic field structure and 2D CME flow speeds.
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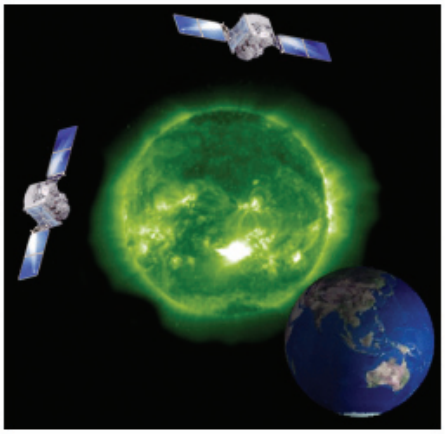
Solar Heliospheric & Interplanetary Environment Lookout for Deep Space (SHIELDS)



Science Objectives

- Understand the evolution of flare- and CME-producing regions by observing the evolution of active regions over their complete lifecycle and observing sub-surface flows
- Determine whether solar and CME observations from 3 points spaced at 120 degrees provide sufficient coverage for forecasts of solar activity, major CMEs & SEP events and "all clears"
- Validate (with in-situ observations) predictive models of the space environment from the Sun to Earth & Mars which use magnetograms created from 3 vantage points spaced at 120 provides as boundary conditions

Mission Description

- **Mission Design**
  - Two identical spacecraft at 1 AU from the Sun, leading and trailing Earth by 120 degrees
  - 2015 launch date with a C_3 of -0.4 using lunar flyby's for separation
  - Delta IV 4040-12 (2,760 kg launch injection mass)
  - 2.5 yr cruise, 2 yrs of operations, & possible 3 year extended ops
- **Flight System Concept**
  - Solar array powered, 3-axis stabilized, 1500 m/s ΔV
  - Payload: 43 kg, 77.9 W, 100 kbps
  - Control: 10 arcsec, Knowledge: < 5 arcsec, Stability: 1.4 arcsec

Enabling Technology Development

- Low mass/power instrumentation
- Advanced communication/DSN

Measurement Strategy

- EUV Imaging of Sun for flare & CME detection& AR evolution
- Coronagraph for CME detection and triangulation
- Radio for strong CME shock detection
- In situ fields & particles to measure space environment at 1 AU
- Filter Magnetograph/helioseismograph for surface magnetic field measurements & surface & sub-surface flows

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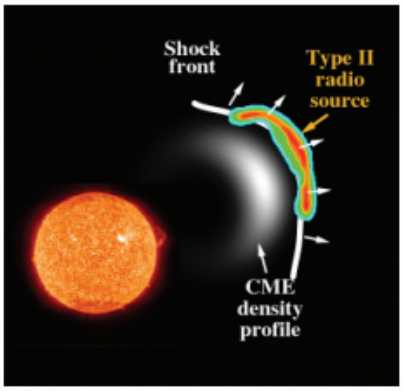
Solar Imaging Radio Array (SIRA)



SIRA will image radio emission from CME driven shocks and other sources between the Sun and 1 AU.

Science Objectives

- Enhance understanding of interplanetary propagation and evolution of coronal mass ejections (CMEs) using radio images of the CME-driven shock & other radio sources
- Enhance understanding of solar energetic particle acceleration & propagation using images of fast-drift & other solar radio bursts
- Apply above items to prediction of hazardous space weather
- Obtain and analyze the 1st full-sky maps from 0.1 to 15 MHz

Mission Description

- Mission Design
  - NASA MIDEX-class mission for aperture synthesis imaging
  - Microsat constellation of 12-16 identical spacecraft
  - Spherical constellation of 10 km diameter in L1 halo orbit
  - Two high-heritage dipole antennas & radio receivers per μsat
  - Direct downlink of data from each microsat to ground station
- Flight System Concept
  - Carrier: 100 kg, 24 W; discarded after microsat deployment
  - Microsat: 54 kg (wet), 90 W, 8 Mbps downlink, ±1 deg (control)
  - ΔV: 100 m/s (carrier), ~7 m/s (microsat)
  - Payload: 10 kg/sat (excluding timing and ranging), 10 W/sat

Measurement Strategy

- Imaging at ~12 frequencies corresponding to ~2 R_{SUN} – 1 AU
- 2-bit Nyquist sampling at each frequency
- ~2.4 GB science data/day/microsat
- "Snapshot" processing on ground for space weather prediction

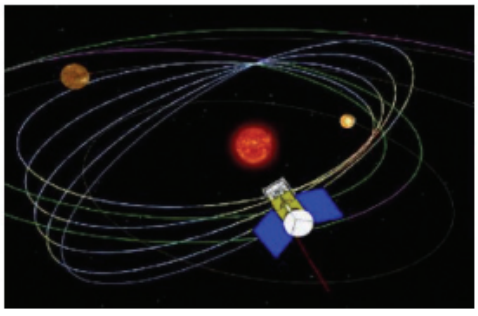
Enabling Technology Development

- Low cost intersatellite ranging to 3 m is simple to build, but has not been tested

Instrument Summary

- Two 10 m crossed Stacer dipoles/μsat
- Two 0.03-15 MHz radio receivers/μsat
- Intersatellite transmissions for ranging, timing, and phase coherence, facilitated by long radio wavelengths (>20 m)

Solar Orbiter



Science Objectives

- How exactly is the solar wind propelled?
- How does the Sun rule interplanetary space?
- How does the Sun's dynamo work?
- How can we predict eruptions on the Sun?
- Can we make long-term forecasts of solar activity?

Mission Description

- ESA mission with launch anticipated in 2015
- 3-axis stabilized spacecraft will use VGA every third orbit to obtain an increasingly slanting solar orbit at 0.2 AU out of the ecliptic plane to heliographic latitudes of 30-38 degrees
- Close approach every 5 months
- Perihelion "Hover" period of orbit will allow imaging of solar storm buildup over several days

Measurement Strategy

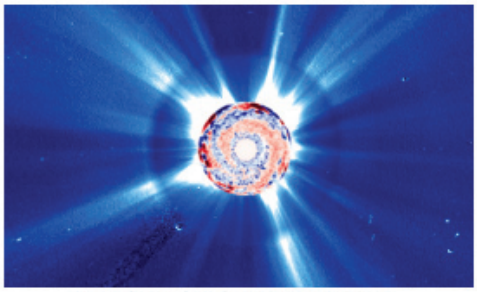
- Observe the charged particles and magnetic fields of the solar wind, radio and magnetic waves in the solar wind, energetic charged particles and neutrons flung out by the Sun, and neutral atoms and dust grains drifting in interplanetary space.
- Observe the Sun's surface and atmosphere from near the Sun at mid latitude.
  - Explore the inner heliosphere in situ to 0.2 AU for the first time
  - Image the solar surface in visible light nad measure magnetic fields using a magnetograph
  - Measure the outer atmosphere by ultraviolet and visible-light coronagraphs
  - A radiometer will measure variations in the total output of solar energy that powers the Earth's weather and life.

Technology

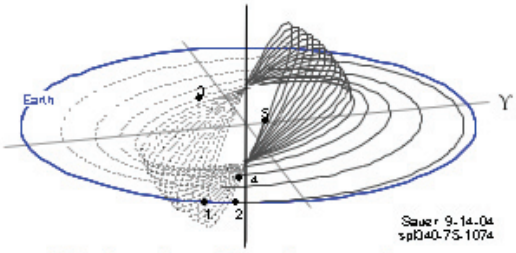
- Solar Electric Propulsion to be validated on ESA SMART-1 mission in 2003
- High temperature thermal management to accommodate solar intensity 25x than seen at Earth

Solar Polar Imager

Observing Solar Activity from a New Perspective



2012 Solar Sail Solar Polar Imager
3:1 Resonance, R= 0.48 AU
75 Degrees Heliographic Inclination



Technology Development

Solar Sail Propulsion-Enabling
Low mass/power Instrumentation

Science Objectives

- What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar dynamo?
- What advantages does the polar perspective provide for space weather prediction?
- What is the azimuthal structure and dynamics of the corona and CMEs?
- How are variations in the solar wind linked to the Sun at all latitudes?
- How are solar energetic particles accelerated and transported in radius and latitude?
- How does the solar irradiance vary with latitude?

Measurement Strategy

- Surface & interior flows for helioseismology
- Polar magnetic fields and flux transport
- Polar coronal imaging in white light and EUV
- UV Spectrometer for outflow velocities
- *In situ* magnetic fields, solar wind and energetic particles (SEPs)
- Total solar irradiance variability

Mission Description

SC in highly inclined ~75° 3:1 resonant heliocentric 0.48 AU orbit
Uses solar sail to reach high inclination in 5-7 years
Collect *in situ* data during cruise
Average data rate > 60 kbps; store and dump, 2 passes/week
Gimbaled antenna for uninterrupted helioseismology data

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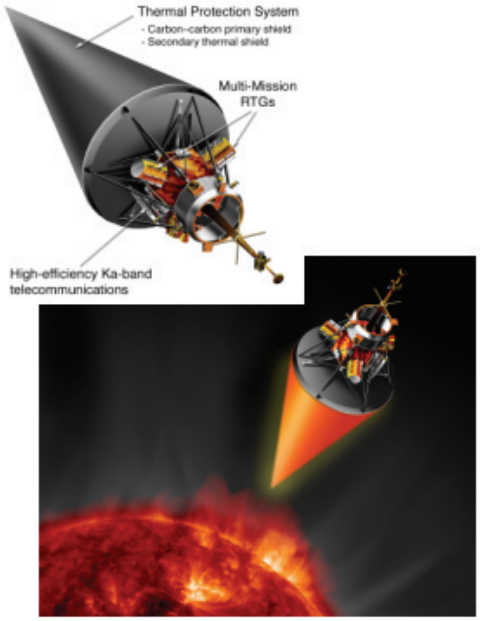
Solar Probe

Heliophysics Flagship Mission



Enabling Technology Development

- Thermal Protection System
- Multi-Mission RTGs

Science Objectives

- Determine the structure and dynamics of the magnetic fields at the sources of the solar wind
- Discover the flow of energy that heats the solar corona and accelerates the solar wind
- Determine what mechanisms accelerate, store, and transport energetic particles
- Explore dusty plasma phenomena and their influence on solar wind and energetic particle formation
- Important for Exploration – Only mission to directly explore region where solar energetic particles are energized

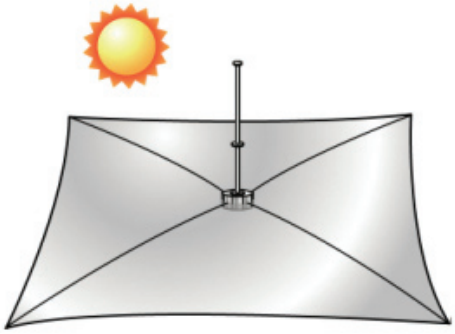
Mission Description

- Example Mission Design
  - Solar polar orbit to within 4 Rs of Sun
  - Jupiter gravity assist
  - Two solar flybys spaced over solar cycle
  - First flyby's solar source regions visible from Earth
- Flight System Concept
  - S/C protected by primary/secondary heat shield system
  - Powered by 3 Multi-Mission RTGs
  - Fully integrated science payload
  - 25 kbps real-time downlink and large data storage

Measurement Strategy

- High resolution in-situ measurements: plasma, suprathermal, and energetic particle distributions and composition; waves and fields; neutrons/gamma rays; dust
- Polar imaging above 20Rs, surrounding white light during flyby
- Supporting remote sensing from near-Earth imagers

Solar Sail Demonstration (SSD)



Mission Objectives

- Validate solar sail design tools and fabrication methods
- Validate controlled deployment
- Validate in-space structural characteristics
- Validate solar sail attitude control
- Validate solar sail thrust performance
- Characterize the sail's electromagnetic interaction with the space environment

Mission Description

- **Mission Design**
  - Deploy and operate 40+ m solar sail
  - Sun-synchronous circular orbit, 1000 to 1500 km
  - Pegasus XL launch
  - 3 month mission (additional 3 months optional)
- **Flight System Concept**
  - 3-axis stabilized
  - Pointing control and stability: 0.5°
  - Pointing knowledge: 0.1°
  - Payload: 69 kg, 82 W, 27.5 kbps
  - ΔV: 400 to 650 m/s (dependant upon altitude)

Enabling Technology Development

- Sail Propulsion System with integral Sail Attitude Control System
  - •reflective area > 1600 m^2
  - •areal density ≤ 25 g/m^2
- Analytical models for sail structural, attitude control, and thrust performance

Measurement Strategy

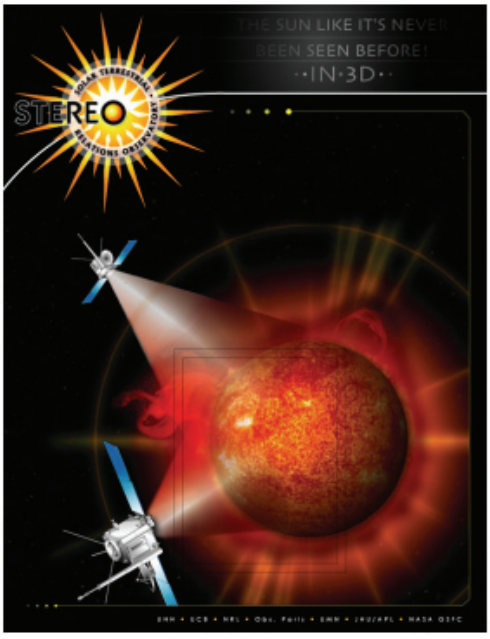
• Integral sensors on Solar Sail

• Sail Imaging Metrology System (SIMS) to validate deployment, and determine static and dynamic shape of deployed sail

• Electromagnetic Characterization Suite (ECS) to measure large scale induced currents and surface charging

• GPS Receiver, ground tracking, acclerometers to provide precision orbit determination for thrust validation

Solar TErrestrial RElations Observatory (STEREO)



Utilizing two identical observatories for stereoscopic solar observations.

Science Objectives

• Understand the causes and mechanisms of coronal mass ejection (CME) initiation.
• Characterize the propagation of CMEs through the heliosphere.
• Discover the mechanisms and sites of energetic partide acceleration in the low corona and the interplanetary medium.
• Improved determination of the structure of the ambient solar wind.

Mission Description

• STP mission scheduled for launch in 2006
• Two functionally identical spacecraft in heliocentric orbits at 1 AU (22°/yr drift from Earth orbit leading/lagging configuration).

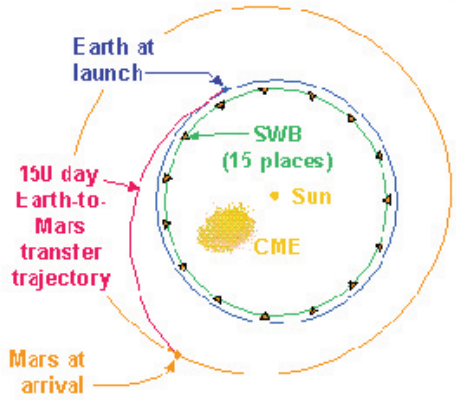
Each Observatory:

Volume:	1.2 w x 2.0 l x 1.5 h meters
Dry Mass:	A: 535 kg B: 561 kg
Power:	509 W (EOL)

Measurement Strategy

• Determine the CME initiation time to an accuracy of order 10 minutes.
• Determine the location of CME initiation to within +/- 1 degree of solar latitude and longitude.
• Determine the evolution of the CME mass distribution as it propagates from the low corona to 1 AU.
• Determine the CME speed as it propagates from the low corona to 1 AU.
• Determine the direction of CME propagation as the CME evolves from the low corona to 1 AU.
• Characterize energetic particle distribution functions in-situ for electrons and ions of interest at partide energies typical of solar energetic particle populations.
• Determine the location of particle acceleration in the low corona and through the interplanetary medium.
• Obtain a time series of the solar wind temperature at two points separated in solar longitude.
• Obtain a time series of the solar wind density at two points separated in solar longitude.
• Obtain a time series of the solar wind speed at two points separated in solar longitude.
• Obtain a time series of the solar wind magnetic field at two points separated in solar longitude.

Solar Weather Buoys (SWBs)



Science Objectives

- Space Science: Understand for the first time the physics determining the longitude extent and evolution of large solar disturbances - Solar energetic particles (SEP) and Coronal Mass Ejections (CME) - as they propagate past 1AU and out into the heliosphere.
- Exploration: SWBs will be a proof-of-concept for an SEP/CME warning system to space assets at the Earth, Moon, Mars and in transit among them.

Mission Description

- Mission Design
  - Lunar swingbys used to inject 12 to 15 small satellites into a solar orbit of ~0.9 AU semi-major axis
  - Launched in 2012 (TBD) on a Delta II
  - Continuously monitor the environment for flares, SEPs and CMEs
- Flight System Concept
  - Selected redundancy to achieve a 10-12 year mission life (6-8 years to deploy all the satellites, 4 years of full operations)
  - Instrument Payload: 10 kg, 5 W, ~10kb/day
  - Attitude relative to the Sun: 10° control, 5° knowledge

Measurement Strategy

- Energetic protons and electrons (solid-state detectors)
  - Fluence of 20-100 MeV protons
  - Onset of 100-300 keV electron beams (1 min resolution)
- Solar wind plasma (electrostatic)
  - Velocity, density, temperature
  - CME velocities to 1500 km/s
- Interplanetary magnetic field (flux gate)
  - Vector components 0.1-100 nT
  - <1 min time resolution
- Solar hard x-rays (non-imaging spectrometer)
  - Flare timing (<1 minute) for identification
  - Spectral hardness (20-80 keV)

Enabling Technology Development

- All instruments are at a Technology Readiness Level of 7 or higher

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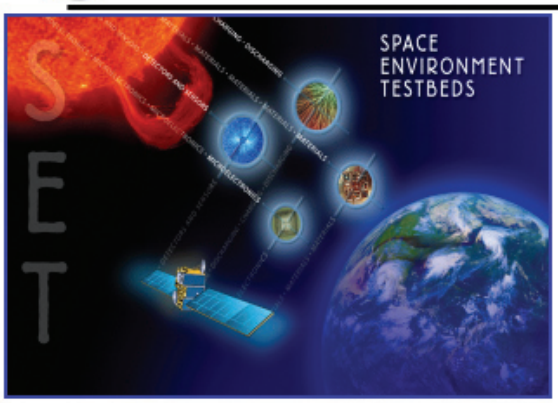
Space Environment Testbeds



Technology Enabling: Sustained access to space to accelerate the maturity of technologies for flight programs

Investigation Categories

- Characterize space environment in presence of the spacecraft
- Define the mechanisms for materials degradation and the performance characterization of materials designed for shielding from ionizing radiation
- Accommodate and/or mitigate space environment effects for detectors and sensors
- Provide performance improvement methodology for microelectronics used in space
- Accommodate and/or mitigate charging/discharging effects on spacecraft and spacecraft components

Project Goal: Improve the engineering approach to accommodation and/or mitigation of the effects of solar variability on spacecraft design and to minimize space weather effects on space hardware during operations.

Objectives

- Define the mechanisms for induced space environment and effects
- Reduce uncertainties in the definitions of the induced environment and effects on spacecraft and their payloads
- Improve design and operations guidelines and test protocols so that spacecraft anomalies and failures due to environmental effects during operations are reduced

Description

- Define investigation project topics through community workshops
- Acquire investigations through NASA Research Announcement (NRAs) and partnerships
- Transitions results of investigations (products) to user community

Science Investigations

1) Flight Investigations

- Collect data in space to validate the performance of new technology vulnerable to effects of the solar varying environments and instrument for LWS science missions
- Collect data in space to validate new and existing ground test protocols or mechanism models for the effects of solar variability of emerging technologies and components

2) Data Investigations

- Improve, develop, and validate engineering environment models, tools, and databases for reliable spacecraft design and operations

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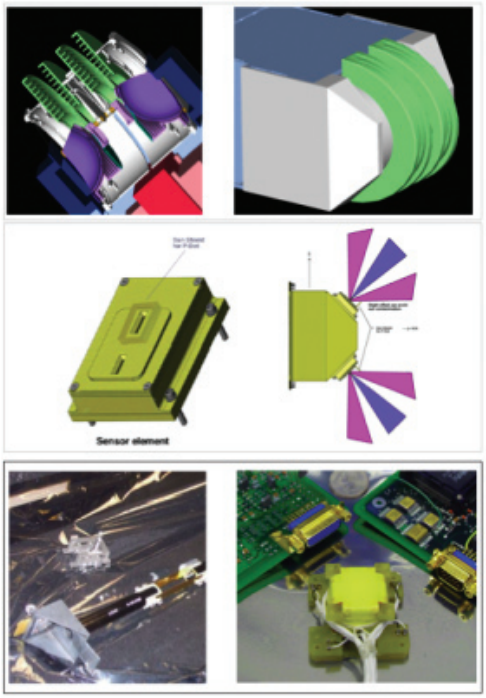
Space Physics Package and Interface



Science Objectives

- In situ field, plasma,and particle environment measurements in a modular package

Mission Description

- **Instrument Types**
  - Plasma Velocity Analyzer
  - Energetic Particles Analyzer
  - AC-DC Magnetometer, Plasma Wave Receiver
- **Flight System Concept**
  - Cost-effective modular and reconfigurable in-situ instrument suite for interplanetary and solar wind interactions with magnetospheres and ionospheres
  - Common CDH handles instrument data processing
    - Implements centralized onboard decision making and intelligent data compression
  - Near term implementation
    - Heterogeneous instrument electrical interfaces accommodated via centralized flexible interfaces
  - Intermediate/far term implementation
    - Instruments adhere to selected standard electrical interfaces and protocols to facilitate "plug and play"
    - permit reliable/flexible/low cost integration, test and software development

Enabling Technology Development

- Radiation-hardened miniaturized, highly-integrated, low-power microelectronics
- Radiation-hardened power-efficient high-performance data processors
- "Plug-and-play" instrument interfaces
- Miniature high-voltage power supplies

Measurement Strategy

- Support diverse missions with modular package

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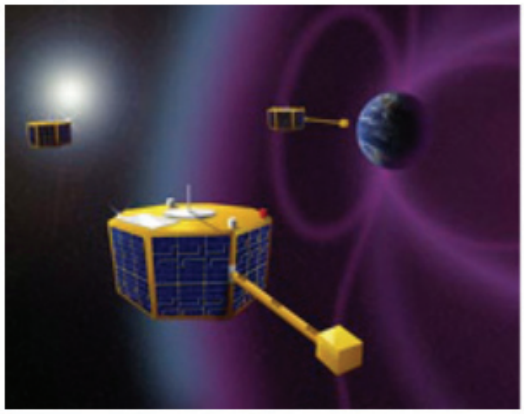
ST-5 (Microsat Technology Constellation Validation Mission)



Mission Objectives

Demonstrate and flight qualify several innovative technologies and concepts for application to future space missions.

Mission Description

- Launch March 2006
- Launch Vehicle: Pegasus XL rocket
- Launch Site: Vandenberg AFB, Lompoc, California
- Mission Duration: 90 days
- Ground Contact: 10-30 Minutes 2-3 Times Per Day
- Operations: Autonomous Constellation Management / "Lights Out" Operations

Orbit:

- Perigee (lowest orbital altitude): 300 km (186 miles)
- Apogee (highest orbital altitude): 4500 km (2796 miles)
- Orbital inclination: 105.6 degrees (Sun synchronous)
- Orbital period: 136 minutes
- Number of orbits per day: about 10.5
- Constellation configuration: "String of Pearls"

Enabling Technology Development

- Cold Gas Micro Thruster (CGMT)
- X-Band Transponder
- Variable Emittance Coatings for Thermal Control
- CMOS Ultra-Low Power Radiation Tolerant Logic (CULPRiT)

Other technologies:

- Miniature magnetometer
- Miniature spinning sun sensor
- Spacecraft deployment mechanism
- Magnetometer deployment boom
- Nutation Damper

Measurement Strategy

• Launch three miniature spacecraft, called micro-sats, to test innovative concepts and technologies in the harsh environment of space. During flight validation of its technologies, ST5 may measure the effect of solar activity on the Earth's magnetosphere, the region of upper atmosphere that surrounds our planet.

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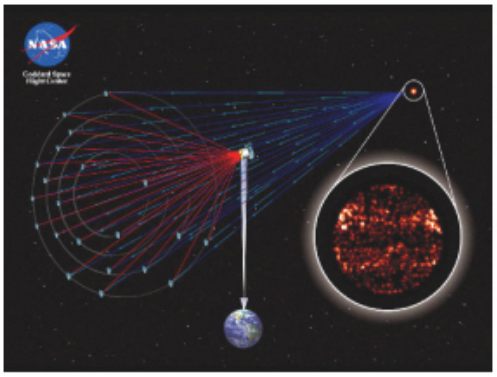
Stellar Imager (SI)
Heliophysics Flagship Mission



Science Objectives

- develop and test a predictive dynamo model for the Sun (and Sun-like stars) by observing the patterns in surface magnetic fields throughout activity cycles on a large sample of Sun-like stars.
- image the evolving dynamo patterns on nearby stars by repeatedly observing them with ~1,000 resolution elements on their surface using UV emission to map the magnetic field.
- image the structure and differential rotation of stellar interiors by the asteroseismic technique of acoustic imaging, achieving at least 30 resolution elements on stellar disks with 1-min. time resolution in one or more broad optical pass bands.

Mission Description

- **Example Mission Design**
  - a 0.5 km diameter space-based UV-optical Fizeau Interferometer, located near Sun-earth L2 to enable precision formation flying
  - 20-30 primary mirror elements focusing on beam-combining hub
  - mission duration: 5 – 10 years
- **Flight System Concept**
  - formation-flying, 3-axis S/C: 20-30 "mirrorsats", 1-2 hubs

Technology Development

- Precision formation flying with low-mass, efficient propulsion
- Optics control and beam combining with ~5nm precision

Measurement Strategy (UV/optical interferometric imaging)

- angular resolution of images better than 0.1 milli-arcsec
- obtain images of stars within ~1% of their rotation period to freeze source variability and avoid image smearing by rotation
- compile at least ~20 images within a stellar rotation period to measure surface differential rotation and field evolution
- revisit targets during 3-6 month intervals over 5-10 years.
- determine internal structure and rotation of select stars with <50,000 km resolution in and below the deep convective zone

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Sun-Earth Coupling by Energetic Particles (SECEP)

Mission: Measure, understand, and predict global atmospheric effects of energetic particle precipitation as they vary over the solar cycle.

Science Objectives

Measure, understand, and predict solar cycle variations in:

- Energetic particle precipitation (EPP) in the earth's atmosphere
- Atmospheric NO_y production/Hoy modification from EPP
- Global mesospheric and stratospheric ozone impact from EPP-produced NO_y.
- Meteorological parameters (wind, temperature, tracers) controlling atmospheric transport, and resulting from ozone modification.

Mission Description

~800 km, sun-synchronous, polar earth orbit
3-year minimum, 6-year goal

Measurement Strategy

- Stellar occultation instrument similar to ATMOS, HALOE, or SOFIE (NO, NO2, ClONO2, N2O5, HNO3, O3, CH4, H2O, OH, T)
- Day and night wind measurements, ~100 km down to ~25 km or lower if possible – e.g. Doppler interferometer similar to HRDI or TIDI
- Particle instruments similar to MEPED
- Temperature measurements 20-100 km, e.g., TIMED/SABER-type instrument
- Auroral imager

Enabling and Enhancing Technology Development

IR and UV stellar occultation; UV and IR static interferometry, IR detector array technology

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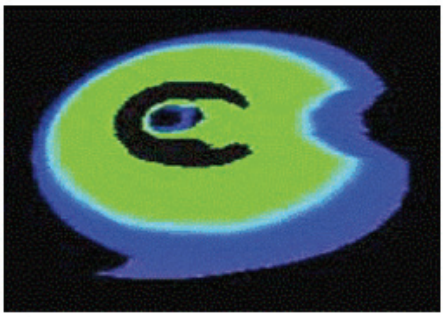
Sun-Earth Energy Connector (SEEC)



Studying the plasmasphere is one aspect of tracing the flow of radiant EUV energy from the Sun to determine its effect on the Earth.

Technology Requirements

- Ionospheric 911Å imaging system
- Simultaneous Sun and Earth viewing at >3RE
- Optics-free photoelectron spectrometer

Science Objectives

- Quantify the relationships between solar radiation and space weather on local and planetary scales by:
  - Specifying solar EUV radiation variability and its source mechanisms
  - Simultaneously mapping the neutral and plasma near-Earth space environments
  - Establishing instantaneous relationships among solar radiation, precipitating energetic particles, and the space environment

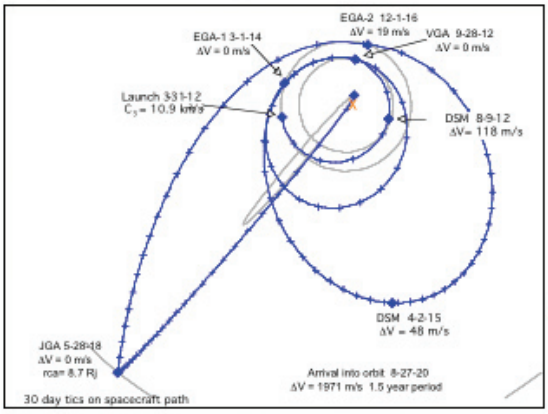
Mission Description

- MIDEX or STP class mission
- Orbit at >3RE, ~50° inclination
- Simultaneous imaging of the Sun's outer atmosphere and Earth's neutral atmosphere, day-night ionosphere, and plasmasphere

Measurement Strategies

- Simultaneous global images of the Sun and Earth
- High-angular-resolution images to observe local thermosphere, ionosphere, and plasmasphere weather
- Simultaneous high-accuracy solar EUV irradiance spectrum made with order-free spectrometer
- Development of new versions of neutral density and plasmaspheric-ionospheric models

Telemachus



*Applicable Technology Development**

- Gimbaled Engine
- Space Storable Prop S/S

* Back-up design solutions are available

Science Objectives

- Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments (*Space Science Enterprise Strategic Plan, October 2003*)
- Reveal through helioseismology how convection and rotation couple and magnetic flux accumulates in the polar regions (solar dynamo)
- Uncover the mechanism(s) in the polar regions of the Sun that accelerate the solar wind and energetic particles and expel plasma and magnetic fields (CMEs)
- Exploit the polar viewpoint to examine the distribution of radio and x-ray emission simultaneously from all solar longitudes
- Determine the physics of the strongest stream/stream plasma interactions and transient shocks where they are first formed in the heliosphere

Mission Description (Intermediate Term)

- **Example Mission Design (2012 launch)**
  - Delta IV Launch, 2061 kg @ C_3 = 10.9 km²/s² (10.0 min)
  - VEEJGA Trajectory with Perihelion ΔV
    - 8.4 yr cruise, 3 yr science ops
    - 0.2 x 2.5 AU Final Orbit, Period: 1.5 years
  - 90° Heliographic Inclination
    - 3 years (2 orbits) in polar science orbit
- **Flight System Concept**
  - Dual Mode: 3-Axis and Spin-Stabilized spacecraft operations
  - Solar Arrays (Ultraflex, Rigid Panel)
  - Payload: 33 kg, 38 W, 8 kbps
  - 2495 m/s ΔV
  - 30 arcsec (control), 10 arcsec (knowledge)

Measurement Strategy

- Continuous science except for 2 years beyond 3 AU (JGA)
- Optimized Solar and heliospheric imagers (Doppler magnetograph, two white light)
- Basic, proven fast plasma, magnetic field and energetic particles *in situ* detectors
- Improved plasma elemental and isotopic composition for coronal diagnostics and interstellar/cometary/"inner source" pickup ions
- Sensitive radio directional spectrograph and x-ray spectrometer

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

Science Objectives

•THEMIS answers fundamental outstanding questions regarding the magnetospheric substorm instability, a dominant mechanism of transport and explosive release of solar wind energy within Geospace.
•THEMIS will elucidate which magnetotail process is responsible for substorm onset at the region where substorm auroras map (~10Re): (i) a local disruption of the plasma sheet current or (ii) that current's interaction with the rapid influx of plasma emanating from lobe flux annihilation at ~25Re.
•Correlative observations from long-baseline (2-25 Re) probe conjunctions, will delineate the causal relationship and macroscale interaction between the substorm components.

Mission Description

•Five identical probes measure particles and fields on orbits which optimize tail-aligned conjunctions over North America. Ground observatories time auroral breakup onset. Three inner probes at ~10Re monitor current disruption onset, while two outer probes, at 20 and 30Re respectively, remotely monitor plasma acceleration due to lobe flux dissipation. THEMIS will be launched October, 2006 as part of the Explorer Program.

Technology

No enabling technology required

Flight Instruments

- Fluxgate magnetometers (FGM)
- Electrostatic analyzers (ESA)
- Solid state telescopes (SST)
- Search coil magnetometers (SCM)
- Electric field instruments (EFI)

Ground Instruments

- Fluxgate magnetometers (FGM)
- All-sky white light imagers

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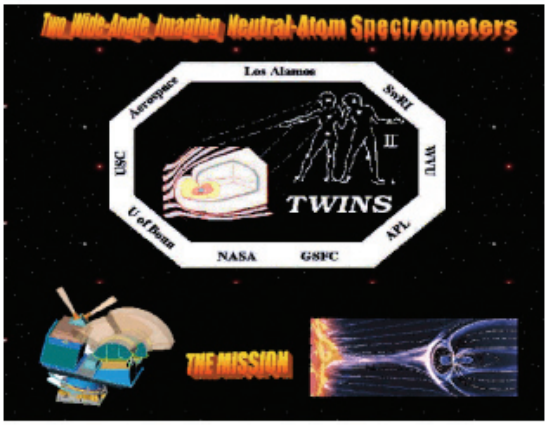
Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS)



Science Objectives

• The TWINS instruments are awaiting launch
•Enable the 3-dimensional visualization and the resolution of large scale structures and dynamics within the magnetosphere for the first time
• Establish global connectivities and causal relationships between processes in different regions of the magnetosphere
• Ion Dynamics: view global dynamics, composition, and energization of ions throughout the magnetosphere
• Plasma Origins and Destinies: trace sources, transport, and sinks of plasma populations
• Magnetospheric Evolution: observe the evolution of the global magnetospheric structure

Mission Description

• Stereoscopically imaging the magnetosphere and the charge exchange neutral atoms over a broad energy range (~1-100 keV) using two identical instruments on two widely spaced high-altitude, high-inclination spacecraft.
• Mission of Opportunity on two nadir pointing Molniya orbit spacecraft at 7.2 Re x 1000 km x 63.4 degree inclination

Technology

No enabling technology required

Measurement Strategy

• Neutral atom imager
• Lyman Alpha Detector
Both mounted on rotating actuator platform to allow 360 degrees azimuthal viewing

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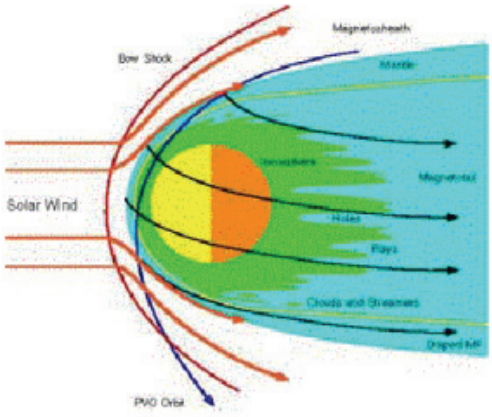
Venus Aeronomy Probe



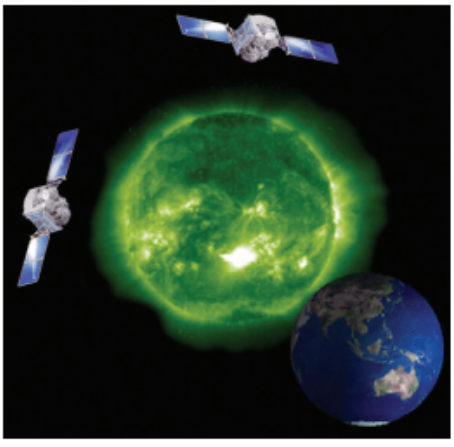
Science Objectives
- Determine Mechanisms for Energy Transfer From the Solar Wind to the Ionosphere and Upper Atmosphere
- Measure the Charged Particles Responsible for Auroral-Type Emissions and Infer their Acceleration Mechanisms
- Determine Formation Processes for Ionospheric Magnetic Flux Ropes, Ionospheric "Holes" on the Nightside and the Loss of Ionospheric Plasma in the Form of Streamers, Ray and Clouds

Mission Description
- Example Mission Design
  - Small Delta II
  - 1-Year Flight Time, 1year OPS
  - High Inclination Elliptical Orbit
    - 150 km x12,000 km
- Flight System Concept
  - Spin-Stabilized Platform
  - Floating Potential Neutralization
  - Solar Array Implementation

Measurement Strategy
- In-situ Plasma, Magnetic and Electric Fields and Plasma and Radio Wave Measurements
- In-situ Neutral Gas Composition, Density, Temperature, and Winds Measurements
- Remote Observations using a UV Spectral Imager, Fabry-Perot Interferometer, Energetic Neutral Atom Imager, Ionospheric Sounder

Technology Development
- Low Mass/Power Instrumentation
- Intelligent Instruments
- Non-Disruptive Floating Potential Neutralization

WHOLE SUN SENTINELS



Fundamental Question:
- Discover, understand and model the dynamically evolving whole Sun and inner heliospheric environment.

Technological Requirements:
- No new technologies are required.
- Possible use of SEP propulsion.

Science Objectives:
- Determine the dynamic evolution of photopsheric, coronal and inner heliospheric magnetic fields and plasmas.
- Determine the characteristics and structure of CMEs and flares that produce high quantities of SEPs.
- Determine the dynamic solar/heliospheric connection and the origin of the slow solar wind.

Possible Mission Scenario:
- One or two spacecraft in 1 AU orbit leading/lagging Earth by 120 degrees.
- Simple imaging and in-situ fields and particles instruments.
- Single Delta II class launch vehicle.

Measurement Strategy:
- Photospheric/coronal magnetic fields
- Chromospheric/coronal plasma structures
- Simple fields and particles in-situ observations.
- Possible two ventage points to cover 2pi solar observations when combined with from Earth imaging.

Current Status:
- Sentinels Science and Technology Definition Team has been convened to refine science goals and implementation possibilities. STDT report expected in Winter 2005.

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E. Acronyms

AAAS	American Association for the Advancement of Science
AAMP	Auroral Acceleration Multi-Probe
ACE	Advanced Composition Explorer
ADAM	Aeronomy and Dynamics at Mars
AIM	Aeronomy of Ice in the Mesosphere
AISR	Applied Information Systems Research
AMISR	Advanced Modular Incoherent Scatter Radar
APIO	Advanced Planning and Integration Office
ATST	Advanced Technology Solar Telescope
AU	Astronomical Unit
BC	Bepi-Colombo
C/NOFS	Communication/Navigation Outage Forecast System satellite
CAIB	Columbia Accident Investigation Board
CCD	Charge-Coupled Device
CCMC	Coordinated Community Modeling Center
CEDAR	Coupling, Energetics and Dynamics of Atmospheric Regions
CINDI	Coupled Ion-Neutral Dynamics Investigation
CIRB	Cosmic Infrared Background
CISM	Center for Integrated Space-Weather Modeling
CME	Coronal Mass Ejection
CNES	Centre National d'Etudes Spatiales
COMSTAC	Commercial Space Transportation Advisory Committee
CSEM	Center for Space Environment Modeling
CULPRIT	CMOS Ultra Low-Power Radiation Tolerant
CY	Calendar Year
DASI	Distributed Arrays of Small Instruments
DBC	Dayside Boundary Constellation
DLR	Deutschen Zentrum fÜr Luft und Raumfahrt
DSN	Deep Space Network
DoD	Department of Defense
DoE	Department of Energy
E/PO	Education and Public Outreach
EAR	Export Administration Regulations
EDL	Entry, Descent, and Landing
EELV	Evolved Expendable Launch Vehicle
EIT	Extreme-ultraviolet Imaging Telescope
ENA	Energetic Neutral Atom
E/PO	Education and Public Outreach

EPP	Energetic Particle Precipitation
ESA	European Space Agency
ESF	Equatorial Spread-F
ESSP	Earth System Science Pathfinder
EUV	Extreme Ultraviolet
EVA	Extravehicular Activities
EXP	Explorer Missions
EXT	Externally Funded Partnership Missions
FAA	Federal Aviation Administration
FASR	Frequency Agile Solar Radiotelescope
FAST	Fast Auroral Snapshot
FLG	Flagship Missions
FS	Farside Sentinel
FUV	Far Ultraviolet
FiMS	Fellowships in Mathematics and Science
GCR	Galactic Cosmic Ray
GEC	Geospace Electrodynamic Connections
GEM	Geospace Environment Modeling
GEMINI	Geospace Magnetosphere-Ionosphere Neutral Imagers
GI	Guest Investigator
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GSRI	Geospace System Response Imager
GSP	Geospace Storm Probes – GSRI, ITSP and RBSP
GeV	Giga Electron Volt
HIGO	Heliospheric Imager and Galactic Observer
HS	Heliostorm
IACG	Interagency Consultative Group
IBEX	Interstellar Boundary Explorer
IE	Io Electrodynamics
IGY	International Geophysical Year
IH Sentinels	Inner Heliospheric Sentinels
IHS	Inner Heliospheric Sentinels
ILWS	International Living With a Star
IMAGE	Imager for Magnetosphere-to-Aurora Global Exploration mission
IMC	Inner Magnetospheric Constellation
IMF	Interplanetary Magnetic Field
INSPIRE	Interactive NASA Space Physics Ionosphere Radio Experiments
IR	Infrared

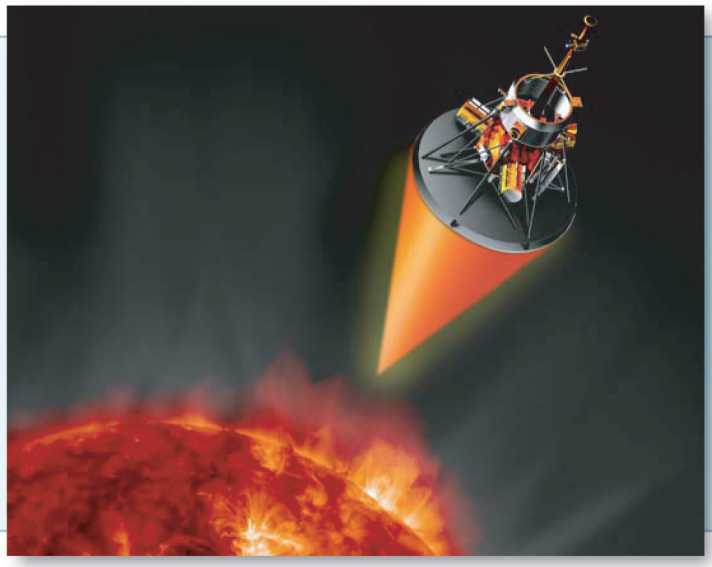
ISAS	Institute of Space and Astronautical Sciences
ISP	Interstellar Probe
ISS	International Space Station
I-T	Ionosphere-Thermosphere
ITAR	International Traffic in Arms Regulations
ITM	Ionosphere Thermosphere Mesophere
ITMC	Tropical ITM Coupler
ITMC/W	Tropical ITM Coupler/Waves
ITMW	Ionosphere Thermosphere Mesosphere Waves
ITSP	Ionosphere Thermosphere Storm Probes
IVM	Ion Velocity Meter
ISP	Interstellar Probe
JAXA	Japan Aerospace Exploration Agency
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
JPO	Jupiter Polar Orbiter/JUNO
JRO	Jicamarca Radio Observatory
keV	Kilo Electron Volt
L1 SCE	L1 Solar Climate Connection Explorer
L1D	L1-Diamond
LASCO	Large Angle and Spectrometric Coronagraph
LCAS	Low Cost Access to Space
LIRA	Lunar Imaging Radio Array
LISM	Local Interstellar Medium
LPE	Low-Power Electronics
LRO	Lunar Reconnaissance Orbiter
LWS	Living With a Star
MA	Mars Aeronomy
MagCon	Magnetospheric Constellation
MARIE	Mars Radiation Environment Experiment
MARS	Mars Atmospheric Reconnaissance Survey
MC	Magnetospheric Constellation
MD	Mars Dynamics
MDI	Michelson Doppler Imager
MEMS	Micro-Electro-Mechanical Systems
MeV	Mega Electron Volt
MGS	Mars Global Surveyor
MHD	Magnetohydrodynamics
MIDEX	Medium-class Explorer
MIO	Magnetosphere-Ionosphere Observatory

MIT	Magnetosphere, Ionosphere, and Thermosphere
MMS	Magnetospheric Multiscale Mission
MO&DA	Mission Operations and Data Analysis
MOO	Mission of Opportunity
MSL	Mars Science Laboratory
MTRAP	Magnetic Transition Region Probe
NASA	National Aeronautics and Space Administration
NESCE	Near Earth Solar Coronal Explorer
NH	New Horizons - Pluto/Kuiper Belt Mission
NO	Neptune Orbiter
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NWM	Neutral Wind Meter
PA	Public Affairs
PASO	Particle Acceleration Solar Orbiter
PEPPSI	Pluto Energetic Particle Spectrometer Science Investigation
PI	Principal Investigator
PMC	Polar Mesospheric Clouds
POETRY	Public Outreach, Education, Teaching and Reaching Youth
PPARC	Particle Physics and Astronomy Research Council
RAD	Radiation Assessment Detector
RAM	Reconnection and Microscale Probe
RASA	Russian Aviation and Space Agency
RBSP	Radiation Belt Storm Probes
RE	Earth Radii
REU	Research Experiences for Undergraduates
RFA	Research Focus Area
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RTG	Radioisotope Thermoelectric Generator
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SCOPE	Solar Connection Observatory for Planetary Environments
SDO	Solar Dynamics Observatory
SEC	Sun-Earth Connection
SECEF	Sun-Earth Connection Education Forum
SECEP	Sun Earth Coupling by Energetic Particles
SEEC	Sun-Earth Energy Connector
SEP	Solar Energetic Particle
SEPM	Solar Energetic Particle Mission
SET	Space Environment Testbeds
SHECon	Sun-Heliosphere-Earth Constellation

SHIELDS	Solar Heliospheric & Interplanetary Environment Lookout for Deep Space
SHINE	Solar, Heliosphere and Interplanetary Environment
SI	Stellar Imager
SIRA	Solar Imaging Radio Array
SMD	Science Mission Directorate
SMEX	Small Explorer
SO	Solar Orbiter
SOHO	Solar and Heliospheric Observatory
SON	Student Observing Network
SP	Solar Probe
SPI	Solar Polar Imager
SPP	Space Physics Package
SR&T	Supporting Research and Technology
SSB	Space Studies Board
SSD	Solar Sail Demo
ST-5	Space Technology 5
ST-9	Space Technology 9
STDT	Science and Technology Definition Team
STEM	Science, Technology, Engineering and Mathematics
STEREO	Solar-Terrestrial Relations Observatory
STP	Solar-Terrestrial Probe
SWAP	Solar Wind Around Pluto
SWB	Solar Weather Buoys
TE	Titan Explorer
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics
TLM	Telemachus
TR&T	Targeted Research and Technology
TRACE	Transition Region and Coronal Explorer
TRL	Technology Readiness Level
TWINS	Two Wide-angle Imaging Neutral-atom Spectrometers
UAF	Univ. of Alaska, Fairbanks
UV	Ultraviolet
VAP	Venus Aeronomy Probe
VIS	Visible
VSE	Vision for Space Exploration
VXO	Virtual Observatories
ViSBARD	Visual System for Browsing, Analysis, and Retrieval of Data
WSS	Whole Sun Sentinels
XML	Extensible Markup Language
XUV	Extreme Ultraviolet

Heliophysics Landmark Discovery Missions

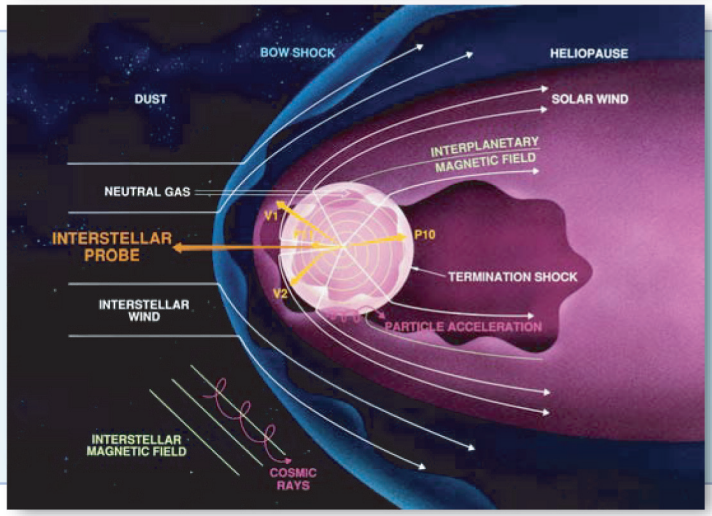
NEAR/INTERMEDIATE-TERM



Solar Probe

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

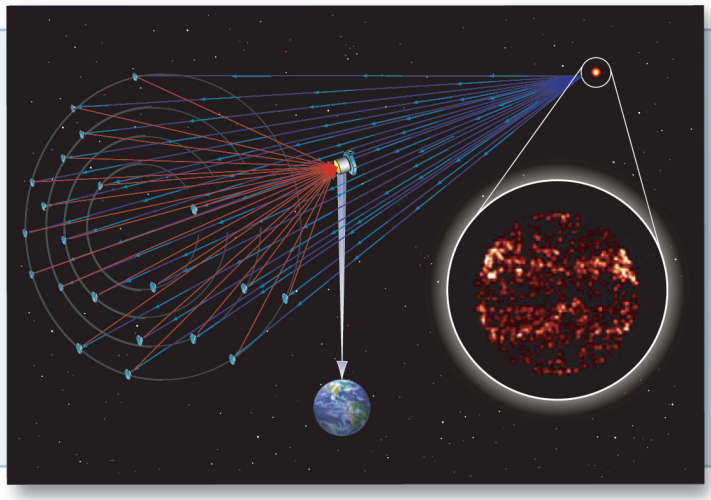
FUTURE



Interstellar Probe

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

FAR-TERM

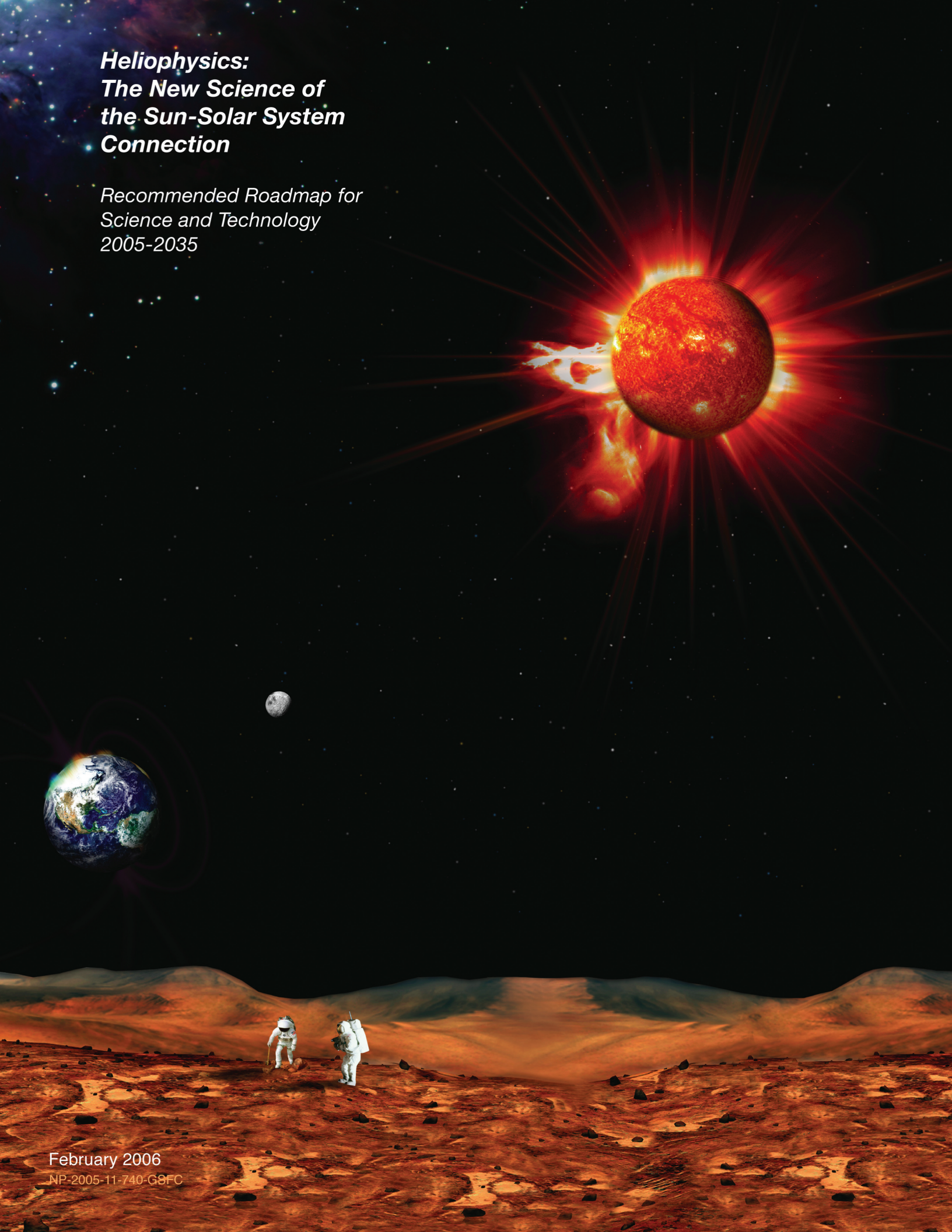


Stellar Imager

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

Heliophysics: The New Science of the Sun-Solar System Connection

Recommended Roadmap for Science and Technology 2005-2035



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