An Assessment of the Solar and Space Physics Aspects of NASA's Space Science Enterprise Strategic Plan

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INTRODUCTION

Recently, NASA's Office of Space Science (OSS) released its *Space Science for the 21st Century: The Space Science Enterprise Strategic Plan*, (the *Enterprise Plan*),[1] which includes a summary of planned solar and space physics activities to be initiated by NASA in the period 1995 to 2000. Publication of the *Enterprise Plan* occurred prior to the release of CSSP/CSTR's report, *A Science Strategy for Space Physics* (the *Science Strategy*).[2] The purpose of this short report is to comment on the extent to which the OSS *Enterprise Plan* corresponds to the recommendations made in CSSP/CSTR's *Science Strategy* for scientific research in solar and space physics during the coming decade. CSSP/CSTR's intent in this assessment is to identify, for NASA's benefit, a more comprehensive agenda of solar and space physics activities that might be included in updates to the *Enterprise Plan*.

SUMMARY OF CSSP/CSTR'S SCIENCE STRATEGY

CSSP/CSTR's *Science Strategy* recommends the major directions for scientific research in space physics for the coming decade. As a field of science, space physics has passed through the stage of simply looking to see what is out beyond Earth's atmosphere. It has become a "hard" science, focusing on understanding the fundamental interactions between charged particles, electromagnetic fields, and gases in the natural laboratory consisting of the galaxy, the Sun, the heliosphere, and planetary magnetospheres, ionospheres, and upper atmospheres.

The several subfields of space physics share the following objectives:

- To understand the fundamental laws or processes of nature as they apply to space plasmas and rarefied gases both on the microscale and in the larger, complex systems that constitute the domain of space physics;

- To investigate the links between changes in the Sun and the resulting effects at Earth, with the eventual goal of predicting the significant effects on the terrestrial environment; and

- To continue the exploration and description of the plasmas and rarefied gases in the solar system.

CSSP/CSTR's *Science Strategy* identifies five scientific topics to be addressed in space physics research in the coming decade:

1. *Mechanisms of solar variability.* The Sun is a variable star on time scales of milliseconds to centuries or more. Its emissions vary throughout the electromagnetic spectrum, as do its particle (thermal plasma and energetic) outputs. The solar magnetic field, generated in the Sun's interior, holds many of the keys to understanding these variations that influence Earth's space environment and its climate.

2. *The physics of the solar wind and the heliosphere.* The solar wind, the extended atmosphere of the Sun that reaches beyond the solar system, is responsible for a host of effects on all planetary bodies and on the local interstellar medium. It is still not known what drives this wind and its variations. Extreme solar-wind disturbances cause the most severe "space weather" around Earth.

3. *The structure and dynamics of magnetospheres and their coupling to adjacent regions.* The distortions of planetary magnetic fields caused by their interaction with the solar wind are responsible for the "magnetospheric" effects that contribute to space weather. All manifestations of this coupling, from the auroral emissions that appear in the polar regions of the upper atmosphere to the radiation environments of our Earth satellites, vary continually in response to the changing boundary conditions produced by the Sun. This complex, three-dimensional system is also constrained by the atmosphere and ionosphere at its innermost boundary. Synergistic observations and modeling efforts are revealing the manner in which these near-planet space systems work.

4. *The middle and upper atmospheres and their coupling to regions above and below.* The lower boundary region of near-Earth space is constantly buffeted by variable energy inputs from the Sun and the magnetosphere above, and from the lower atmosphere below. Significant deficiencies exist in our knowledge of the internal workings of this region and its role in determining magnetospheric response to solar wind variations. These deficiencies result from both the difficulty of making measurements there and the region's intrinsic complexity.

5. *Plasma processes that accelerate very energetic particles and control their propagation.* Galactic cosmic rays are samples of matter from outside the solar neighborhood that provide clues to subjects ranging from particle acceleration processes in the cosmos to the physics of stellar interiors.

For each of these topics, CSSP/CSTR's *Science Strategy* presents the scientific background, discusses why the topic is important, describes the current program for research on the topic, and then recommends high-priority research activities for the future. As the *Science Strategy* points out, "The specific programs required to obtain answers to the questions raised under each of the [above] key topics . . . are quite different. However, they are united by four common elements or themes that the CSSP and the CSTR consider to be the most important research emphases for space physics in the next decade."[3]

These themes, paraphrased from the *Science Strategy* (pp. 6-7), are as follows:

1. *Complete currently approved programs.* The space physics community must reap the benefits of the nation's investment in existing approved programs by enhancing data analysis and interpretation efforts and by supporting essential observational programs that require long-duration databases. A stable program of research permits the most efficient management and execution of high-priority research. Older missions that are productive and competitive in their scientific return should not be terminated prematurely. In addition to the obvious scientific return, ongoing programs provide the basis for developing future research directions.

2. *Exploit existing technologies and opportunities to obtain new results in a cost-effective manner.* Much technology is already in place to take the next observational steps required to address many of the important questions outlined in CSSP/CSTR's *Science Strategy*. However, adaptation of instrumentation to the new generation of smaller spacecraft requires special support. Ground-based facilities, suborbital platforms, and opportunities for space physics payloads to "hitchhike" on other spacecraft are valuable means for achieving space physics science objectives, as are extended and/or redirected missions.

3. *Develop the new technology required to advance the frontiers of space physics.* To achieve several high-priority objectives, or to lower the cost of projects, the limits of technology must be pushed. Areas for development include global and high-resolution imaging techniques, high-temperature-tolerant devices for operation near the Sun, and methods to enable access to difficult-to-reach regions of the middle atmosphere.

4. *Support strongly the theory and modeling activities vital to space physics.* The importance of modeling and theory in both stimulating and interpreting space physics measurements must be recognized. From models of space weather to models of the microscopic behavior of plasmas involved in the triggering of solar flares and magnetospheric disturbances, state-of-the-art work is being done that increases our scientific understanding in step with measurements made in space, while developing the necessary framework for future missions.

CSSP/CSTR's COMMENTS ON NASA's OSS ENTERPRISE PLAN

NASA's OSS *Enterprise Plan* begins by describing the foundation of its space science strategy in terms of its relevance to the United States, its mission and goals, its key assumptions and considerations, and the principles on which the plan is based. The CSSP and the CSTR recognize the thought and effort that were put into formulating these introductory sections, which generally give a clear sense of what lies behind NASA's space science endeavor.

With regard to the plan's degree of consistency with the research directions emphasized in CSSP/CSTR's *Science Strategy*, released after publication of the *Enterprise Plan*, the CSSP and the CSTR note the following:

- The *Enterprise Plan*'s section titled "Sun-Earth-Heliosphere Connection" is in accord with CSSP/CSTR's strategy in many respects, especially in its acknowledgment of and support for the original three space physics solar-terrestrial probe mission concepts (TIMED, HESI, and MI[4]) that were developed over the past few years through broad-based space physics community prioritization exercises. Whether or not all of these missions are realized as solar-terrestrial probes, their science goals are timely and are key to advancing the Solar Connections Program. Indeed, funding for the TIMED mission began this year, and the recently selected MIDEX mission, IMAGE, addresses many of the science goals envisioned for MI. However, to accomplish its scientific objectives, the HESI mission must be launched during the peak of solar activity. That is no longer possible using either solar-terrestrial probes or the MIDEX line, and therefore requires an alternate strategy if it is to be carried out during this solar cycle.

- The explicit commitment in the *Enterprise Plan* to NASA's participation in the National Space Weather Program[5] is in line with one of the *Science Strategy*'s overall objectives for space physics. Indeed, many missions currently under way to explore solar connections, as well as missions in the concept phase, will provide the key information that will be needed for future space weather research and development projects, including space weather forecasting services. This example of the broad relevance of the solar connections missions deserves greater emphasis in the *Enterprise Plan*, especially in view of the increasing commercial use of space and the projected international space station activities.

- NASA's OSS future mission plan (see table on p. 12 of the *Enterprise Plan*), including solar probe, contains the basic mission elements necessary for accomplishing the goals outlined in CSSP/CSTR's *Science Strategy*, but other

missions in the solar probe class should also be identified. For example, a Mercury orbiter and an interstellar probe are long-awaited space physics missions that have been repeatedly identified in National Research Council reports[6,7] as the means to investigate the ionosphere's role in magnetospheric behavior (Mercury has essentially no ionosphere, but has a magnetosphere), and to explore the nature of the heliosphere's interface with the galaxy, respectively. These missions and others are mentioned below.

RECOMMENDATIONS FOR ADDITIONS TO NASA's FUTURE PLANS FOR EXPLORATION OF SUN-EARTH-HELIOSPHERE CONNECTIONS

Overall, the scientific priorities summarized in the "Sun-Earth-Heliosphere Connections" portion of the *Enterprise Plan* compare favorably with those expressed in CSSP/CSTR's *Science Strategy*. However, the CSSP and the CSTR recommend that subsequent updates of the solar and space physics portion of NASA's *Enterprise Plan* mention the following:

- The innovative suborbital program (e.g., Flare Genesis balloon observations of evolving solar active regions, sounding rocket campaigns in support of the ISTP program, campaigns to observe "sprites" and "jets"), with clear acknowledgment of the contributions the suborbital program makes to the instrument capabilities of the solar connections endeavor, including both training and hardware development;

- The diverse and productive space physics Explorers—SAMPEX, ACE, FAST, and eventually TRACE and IMAGE, as well as the STEDI missions (TERRIERS and SNOE)—emphasizing how Explorers are especially suited to achieving focused space physics objectives in creative and effective ways. The adoption of open data policies and the major outreach and educational components of the space physics Explorers are also noteworthy;

- The unprecedented combination of the ISTP GGS (Wind, Polar), Geotail, and SOHO missions with supporting ground-based observing and theory programs, pointing out their connection to the interagency National Space Weather initiative and the importance of their operation into the next solar maximum;

- The expected contributions from the rapidly developing field of helioseismology. Ground-based and SOHO helioseismic observations show a potential for improving understanding of the interior of the Sun and the origins of solar and stellar activity;

- The expected contribution of TIMED extreme ultraviolet wavelength measurements to studies of solar variability and its effects on the atmosphere;

- Recent measurements of cosmic rays from suborbital platforms, with a description of how such data are helping to elucidate nucleosynthesis; and

- Space physics discoveries from the Galileo mission at Jupiter, emphasizing especially what researchers are learning from comparative planetology studies.

In addition, the *Enterprise Plan* should discuss expectations from the Rosetta-Champollion and Cassini missions for space physics. It should also summarize the breakthroughs in understanding that are being made possible through theory and modeling programs and ground-based observations.

The CSSP and the CSTR also recommend that the solar and space physics community be marshalled to provide the latest information related to the above activities for inclusion in the next version of the *Enterprise Plan*. In addition, the CSSP and the CSTR recommend that an updated plan's description of future programs include the following:

- *Campaigns focused on study of how the Sun's magnetic field is generated and what causes solar variability.* Unraveling the origin of the solar magnetic field is a grand challenge for space physics with astrophysical implications. To enable understanding of solar activity in all its forms, such campaigns must include spacecraft in addition to a solar probe (e.g., a stereoscopic solar imager), as well as suborbital and ground-based instrument development, and supporting theory and modeling.

- *Missions utilizing multipoint measurements with clusters of small spacecraft to explore three-dimensional structure and to distinguish temporal and spatial domains, particularly at boundary layers in space plasmas.* These missions both push the limits of technology (particularly the miniaturization of instruments and spacecraft subsystems) and provide essential information for understanding how energy is transferred between regions of space. The aborted launch in June 1996 of Ariane-5 and subsequent loss of the Cluster mission component of the ISTP adds to the importance of making new efforts in this area.

- *Missions to probe middle-atmosphere dynamics, making use of innovative techniques to gain in situ access to that region.* (However, problems experienced with the Tethered Satellite System experiment are likely to affect future plans for exploration using the space shuttle.)

- *Missions to solar system bodies that interact differently with the solar wind than does Earth,* thereby providing lessons in comparative planetology from a solar connections perspective (e.g., "magnetospheric" and aeronomical exploration of Mercury, Mars, and Pluto can help reveal how Earth's strong planetary field and ionosphere determine its unique space environment).

- *Missions to interstellar space, beyond the heliosphere.* This frontier between the realms of solar and space physics and astrophysics is likely to yield many surprises.

- *Programs that bring together the astrophysical, planetary, Earth science, and space physics communities in a coordinated effort to solve the problems of solar systems on a more general level* (e.g., the interactions between planets and their stars, and between stellar winds and the surrounding interstellar medium, should also be parts of the "origins" theme science within the recently restructured OSS).

In summary, the CSSP and the CSTR find that the solar and space physics aspects of NASA's present *Science Enterprise Strategic Plan* are much in line with research recommended in CSSP/CSTR's *Science Strategy*. At the same time, the CSSP and the CSTR recommend that the above new elements be included in NASA's next vision for exploration of the Sun-Earth-heliosphere connection.

NOTES

1. National Aeronautics and Space Administration, *Space Science for the 21st Century: The Space Science Enterprise Strategic Plan*, Washington, D.C., September 1995.

2. Space Studies Board and Board on Atmospheric Sciences and Climate, National Research Council, *A Science Strategy for Space Physics*, National Academy Press, Washington, D.C., 1995.

3. Space Studies Board and Board on Atmospheric Sciences and Climate, National Research Council, *A Science Strategy for Space Physics*, National Academy Press, Washington, D.C., 1995, p. 6.

4. Acronyms are spelled out in the appendix.

5. The National Space Weather Program is a recently initiated interagency endeavor to coordinate and exploit research related to the coupled solar-terrestrial system and its consequences for Earth's environment.

6. Space Studies Board and Board on Atmospheric Sciences and Climate, National Research Council, *A Science Strategy for Space Physics*, National Academy Press, Washington, D.C., 1995.

7. Task Group on Solar and Space Physics, Space Science Board, National Research Council, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995-2015*, National Academy Press, Washington, D.C., 1988.

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APPENDIX
Glossary

A B C D E F G H I J K L M
N O P Q R S T U V W X Y Z

ACE: Advanced Composition Explorer, whose objective is to determine and compare the elemental and isotopic composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and galactic matter. The mission is scheduled for launch in 1997.

Cassini: A major Saturn orbiter mission scheduled for launch in October 1997. Upon arrival at Saturn in 2004, it will deploy the ESA's Huygens Titan atmospheric probe and will conduct complex, multidisciplinary observations of the planet's atmosphere, rings, magnetosphere, and satellites.

Cluster: A four-spacecraft ESA mission built in collaboration with NASA that was lost during an aborted launch attempt of the Ariane-5. Cluster would have made 4-point identical particle and field measurements to allow separation of spatial and temporal structure in the high-latitude magnetosphere. A Cluster replacement mission is currently under study.

CSSP: Committee on Solar and Space Physics, a standing committee of the Space Studies Board of the National Research Council

CSTR: Committee on Solar-Terrestrial Research, a standing committee of the Board on Atmospheric Sciences and Climate of the National Research Council.

ESA:	European Space Agency
Explorer:	A continuing line of highly focused and low- to moderate-cost astrophysics/space physics missions that includes three mission classes, in order of decreasing size and cost: MIDEX, SMEX, and STEDI
FAST:	Fast Auroral Snapshot Explorer, a SMEX mission for space physics
Flare Genesis:	A suborbital, long-duration balloon program focused on the study of developing solar active regions
Galileo:	A major Jupiter orbiter mission, launched aboard the space shuttle Atlantis in October 1989. When it reached Jupiter in December 1995, it deployed an atmospheric entry probe and then conducted complex, multidisciplinary observations of the planet's atmosphere, rings, magnetosphere, and satellites.
Geotail:	Japan's contribution to the ISTP mission set, this spacecraft is in a highly elliptical low-inclination orbit that probes the deep magnetotail region of Earth's magnetosphere. NASA participates in this mission through science, instrumentation, and management contributions.
GGS:	Global Geospace Science program. The U.S. contribution to ISTP, this program includes the Wind and Polar spacecraft provided by NASA.
HESI:	High-energy solar imager, a concept for a mission envisioned as a possible solar-terrestrial probe focused on the study of solar flares
IMAGE:	The Imager for Magnetopause-to-Aurora Global Exploration is a MIDEX-class mission selected by NASA in 1996 that will provide the first-ever global images of key regions of Earth's magnetosphere as it responds to variations in the solar wind. IMAGE will use three different experimental techniques to carry out its mission: radio sounding, ultraviolet imaging, and neutral atom imaging (neutral atom imagers detect neutral atoms created from magnetospheric ions via the process of charge exchange).
Interstellar Probe:	A concept for a mission that would explore the outer heliosphere and beyond
ISTP:	International Solar-Terrestrial Physics program, a multination space physics mission and ground-based research activity focused on understanding the energy flow from the Sun to Earth's magnetosphere and upper atmosphere. GGS is the U.S. contribution to the ISTP program.

MI:	Magnetospheric imager, a concept for a solar-terrestrial probe mission that would use new techniques to provide the first moving images of changes in Earth's magnetosphere as it responds to highly variable injections of plasma from the Sun. MI will observe emissions of energetic neutral atoms and extreme and far ultraviolet photons to produce simultaneous images of various components of the magnetosphere.
MIDEX:	Mid-size Explorer, intended to provide research opportunities in the areas of astrophysics and space physics. Plans call for about one MIDEX mission to be launched per year, with development cost capped at no more that $70 million (FY1994 dollars) each, excluding the costs of the launch vehicle and mission operations and data analysis. Mission operations are expected to be completed within 2 years.
NASA:	National Aeronautics and Space Administration
OSS:	Office of Space Science (NASA)
Pluto Express:	A mission to conduct the first reconnaissance of Pluto and its large moon Charon with low-mass flyby spacecraft, will use advanced technologies and is intended to serve as a pathfinder for low-cost exploration of the outer solar system. The mission, planned for 2003, will complete the exploration of the last unvisited planet and address fundamental questions about the origin of the solar system.
Polar:	Polar is the second to be launched of the two NASA spacecrafts in the GGS program, which is the U.S. contribution to ISTP. The Polar spacecraft is measuring the entry, energization, and transport of plasma into the magnetosphere and the global energy deposition into the upper atmosphere. It is also being used to investigate the output of plasma from the ionosphere to the magnetosphere. Polar was launched on February 24, 1996.
Rosetta-Champollion:	An approved ESA mission, scheduled for launch in January 2003, to rendezvous with a comet by means of an ESA orbiter spacecraft and two surface science packages. NASA participation will include the provision of one surface science package, Champollion (in cooperation with Centre National d'Etudes Spatiales and possibly other partners); instruments for the surface science package and orbiter; and mission support.
SAMPEX:	Solar Anomalous and Magnetospheric Particle Explorer, the first of NASA's SMEX missions. SAMPEX observations are providing information on the cosmic abundances of elements and their isotopes, the composition of the local intersteller gas, the solar composition and the mechanisms responsible for solar atmospheric heating, and electron energy injection into the Earth's upper atmosphere.

SMEX:	NASA's small explorer program provides frequent flight opportunities for highly focused and relatively inexpensive spacecraft weighing 180 to 250 kg. Each mission is expected to cost approximately $50 million for design, development, and operations through the first 30 days in orbit.
SNOE:	Student Nitric Oxide Explorer. Part of the STEDI program, SNOE is a small scientific spacecraft designed for launch on an ultralight expendable launch vehicle. The scientific goals of SNOE include (1) measurement of nitric oxide density in the lower thermosphere (90 to 200 km) and (2) analysis of the energy inputs from the Sun and magnetosphere that create nitric oxide and cause its abundance to vary dramatically.
SOHO:	Solar and Heliospheric Observatory. An ESA mission with NASA involvement, SOHO will contribute to helioseismology and heliospheric research. SOHO was launched in November 1995.
Solar-terrestrial probe:	Proposed series of small spacecraft missions dedicated to solar and space physics. The first such missions would include TIMED, HESI, and MI.
Space station:	A large, Earth-orbiting crewed platform planned by NASA with substantial international involvement. The space station is expected to be deployed in the early years of the new millennium.
STEDI:	Student Explorer Demonstration Initiative, the smallest of the Explorer missions. The STEDI program is designed to involve students intensively in the design, building, and operation of small spacecraft. At a cost of less than $10 million each, STEDI missions are the next step up in mission capability from a sounding rocket and are nominally to be launched on Pegasus vehicles.
TERRIERS:	Tomographic Experiment using Radiative Recombinative Ionospheric Extreme-ultraviolet and Radio Sources (a terrier is also the mascot of Boston University, which is the host university for this STEDI mission). The TERRIERS spacecraft will make daily global measurements of Earth's ionosphere and thermosphere.
TIMED:	Thermosphere-ionosphere-mesosphere energetics and dynamics mission. A concept for a solar-terrestrial probe focused on measuring the energy inputs to the upper atmosphere and their variations.
TRACE:	Transition Region and Coronal Explorer, a SMEX mission scheduled for launch in late 1997 that will observe the Sun to study the connection between its magnetic fields and the heating of the Sun's corona.

Ulysses: A joint NASA and ESA mission to explore the heliosphere over the full range of solar latitudes and to provide an accurate assessment of the total solar environment. Ulysses has completed its first solar polar pass and is in the process of its second. It has provided evidence of a dramatically different heliospheric environment that exists away from the ecliptic plane.

Wind: A spacecraft focused on the measurement of the solar wind upstream of Earth's magnetosphere, designed to provide information on the prevailing interplanetary conditions during the ISTP program. Wind and Polar are part of the GGS program, NASA's contribution to ISTP.