Space Science

Strategic Plan

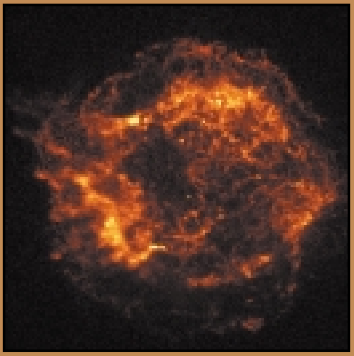
the space science enterprise

november 2000

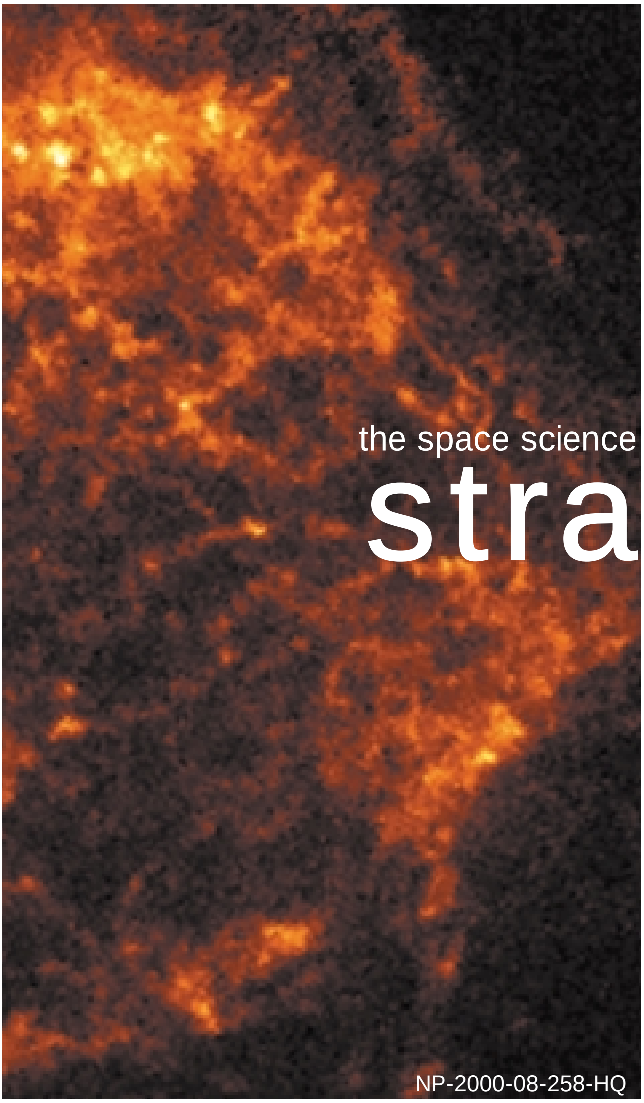
Dedicated to the memories of

Herbert Friedman and John A. Simpson

– Pioneers of Space Science–



Cassiopeia A: The 320-year-old remnant of a massive star that exploded. Located in the constellation Cassiopeia, it is 10 light years across and 10,000 light years from Earth. This X-ray image of Cassiopeia A is the official first light image of the Chandra X-ray Observatory. The 5,000-second image was made with the Advanced CCD Imaging Spectrometer (ACIS). Two shock waves are visible: a fast outer shock and a slower inner shock. The inner shock wave is believed to be due to the collision of the ejecta from the supernova explosion with a circumstellar shell of material, heating it to a temperature of ten million degrees. The outer shock wave is analogous to a tremendous sonic boom resulting from this collision. The bright object near the center may be the long sought neutron star or black hole that remained after the explosion that produced Cassiopeia A. (Credit: NASA/CXC/SAO)



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National Aeronautics and
Space Administration

NP-2000-08-258-HQ

November 2000

Dear Colleagues and Friends of Space Science,

It is a pleasure to present our new Space Science Strategic Plan. It represents contributions by hundreds of members of the space science community, including researchers, technologists, and educators, working with staff at NASA, over a period of nearly two years.

Our time is an exciting one for space science. Dramatic advances in cosmology, planetary research, and solar-terrestrial science form a backdrop for this ambitious plan. Our program boldly addresses the most fundamental questions that science can ask: how the universe began and is changing, what are the past and future of humanity, and whether we are alone. In taking up these questions, researchers and the general public—for we are all seekers in this quest—will draw upon all areas of science and the technical arts. Our Plan outlines how we will communicate our findings to interested young people and adults.

The program that you will read about in this Plan includes forefront research and technology development on the ground as well as development and operation of the most complex spacecraft conceived. The proposed flight program is a balanced portfolio of small missions and larger spacecraft. Our goal is to obtain the best science at the lowest cost, taking advantage of the most advanced technology that can meet our standards for expected mission success. In driving hard to achieve this goal, we experienced some very disappointing failures in 1999. But NASA, as an R&D agency, makes progress by learning also from mistakes, and we have learned from these.

Over the coming years, I invite you to watch as our plans come to fruition. This is your program, and we are managing it for you to answer the profoundest questions that we all share. I fully expect exciting surprises as our voyage of discovery continues to expand our knowledge about the history and future of our universe and of humankind within it.

Edward J Weiler

Edward J. Weiler
Associate Administrator for Space Science

the space science enterprise seeks to

- how the universe began and evolved
- how we got here
- where we are going
- and whether we are alone

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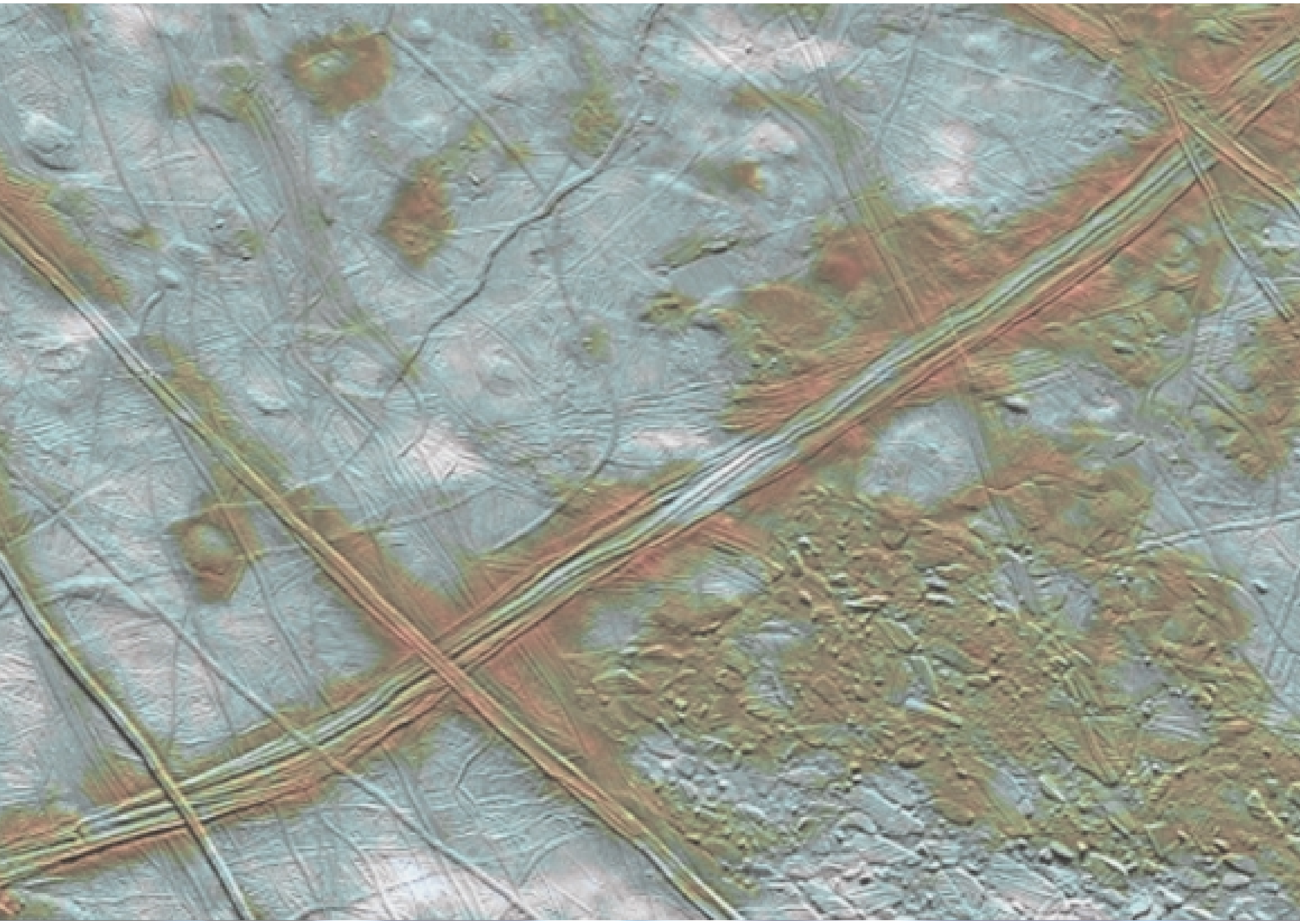


the space science enterprise

our goals

Section I-1

introduction

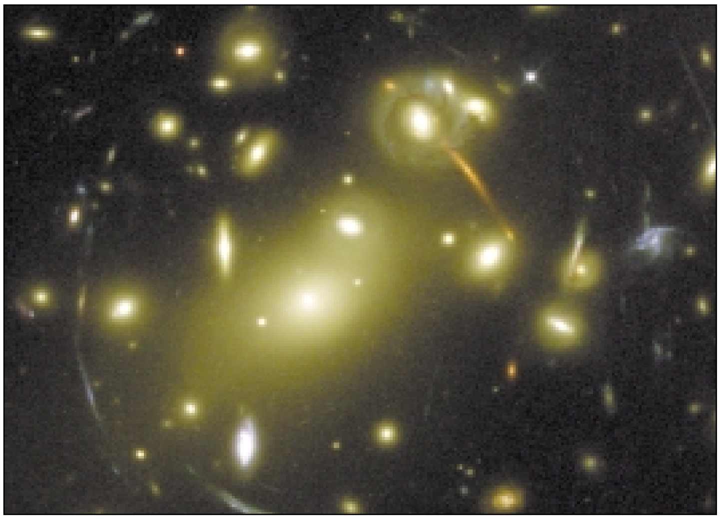
Thousands of years ago, on a small rocky planet orbiting a modest star in an ordinary spiral galaxy, our remote ancestors looked up and wondered about their place between Earth and sky. On the threshold of the 21st century, we ask the same profound questions:

- How did the universe begin and evolve?
- How did we get here?
- Where are we going?
- Are we alone?

Today, after only the blink of an eye in cosmic time, we are beginning to answer these profound questions. Using tools of science that range from abstract mathematics and computer modeling to laboratories and observatories, humans are filling in the details of the amazing story of the universe. In the last 40 years, space probes and space observatories have played a central role in this fascinating process. Today, NASA addresses these four profound questions through its many space science activities.

How did the universe begin and evolve? We seek to explain the earliest moments of the universe, how stars and galaxies formed, and how matter and energy are entwined on the grandest scales. We study astrophysical objects, such as neutron stars and black holes, with extreme conditions that demonstrate fundamental laws of physics at work. We study the behavior of matter, radiation, and magnetic fields under less severe conditions, in the giant laboratory of our Solar System. The understanding thus gained applies directly to the history and behavior of stars and galaxies.

How did we get here? We investigate how the chemical elements necessary for life have been built up and dispersed throughout the cosmos. We look for evidence about how the Sun has behaved over time and what effect this has had on Earth and everything on it. We send probes to other planets to learn about their similarities and differences as keys to how they formed and evolved, and study the comets and asteroids in our Solar System for clues to their



Following the successful December 1999 servicing mission, the Hubble Space Telescope observed the gravitational bending and focusing of light from very distant objects by a massive foreground cluster of galaxies.

effects on the evolving Earth. We carry out ground-based research on the environmental limits of life to learn how it might have arisen and evolved on early Earth.

Where are we going? Our ultimate place in the cosmos is wrapped up in the fate of the universe. Nearer to home, the variability of our Sun and vulnerability of Earth to possible impacts by small Solar System bodies are being investigated. We are comparing the climate histories of Earth and its sibling planets. Humanity has taken its first steps off our home world, and we will contribute to making it safe to travel throughout the Solar System and will ascertain what resources possible destinations could offer to human explorers.

Are we alone? Beyond astrophysics and cosmology, there lies the central human question: Are we on Earth an improbable accident of nature? Or is life, perhaps even intelligent life, scattered throughout the cosmos? We seek to explain how planets originated around our Sun and other stars—planets that might support life. We observe nearby stars for indirect evidence of other planets, and look to the future when advanced observatories in space might be able to directly image such relatively small objects across the vast interstellar void. Beginning with life found in astonishing places on Earth, we conjecture about what kinds of environments could bear and support life, and how common habitable planets might be. Is there now, or has there ever been, life in our own Solar System other than on Earth?

Answers to these deep questions will not be extracted from narrow

Some Recent Space Science Discoveries

In recent years, space research has returned momentous results. Observations from the Hubble Space Telescope have yielded much better estimates of the age and size of the universe and the amount of matter within it, while x-ray observations from the Rossi X-ray Timing Explorer have led to the discovery of magnetars, a special type of neutron star that has the most powerful magnetic field known. By mapping the structure of leftover radiation from the Big Bang, NASA balloon-borne experiments have provided the first firm evidence to date for the “inflation” theory in cosmology. Exotic objects like black holes, for most of a century just a prediction of abstract mathematics, are now known to be commonplace. We are revealing secrets of the inconceivably luminous quasars and gamma ray bursters, now known to be in the remotest regions of the early universe. The Chandra X-ray Observatory has revealed a new class of medium mass black holes. Dozens of planet-like objects have been discovered around other stars, suggesting that our Solar System is not unique. Interest in the possibility of life elsewhere than on Earth has been galvanized by images of Mars from the Mars Global Surveyor and by evidence from the Galileo spacecraft that Jupiter’s moon, Europa, might have a liquid water ocean under an icy outer crust. The structure of our own star, the Sun, and its complex effects on Earth are becoming much better understood. U.S. instruments on the European Solar and Heliospheric Observatory and the Japanese Yohkoh mission have detected “rivers” of flowing gas beneath the Sun’s surface, as well as new predictors for the occurrence of solar activity that can affect Earth. We have learned much about causes of the solar wind, and even traced individual solar disturbances all the way from the Sun to Earth.

inquiries, but will be built up by combining innumerable individual clues over the years to come. The broad outlines of much of the puzzle are discernible now, but a clear picture of the whole awaits years of varied research that will undoubtedly produce many surprises along the way.

This Space Science Enterprise Strategic Plan tells about the science goals and objectives that will lead us toward answers to the fundamental questions. It lays out our near-term program of activities to pursue these goals and objectives. It tells how we will invent and demonstrate the new technologies that we need to pursue our ambitious vision, and how we will contribute to human space flight. And it explains how we plan to share the excitement and understanding from our discoveries with teachers, schoolchildren, and the general public.

In Part I of the Plan, we describe our science goals and objectives, outline how progress in technology goes hand in hand with our ability to pursue them, and then present our approach to sharing our findings with the public on whose behalf we are conducting this important task of discovery.

In Part II we present in more detail our plans and hopes for the program. We describe some exciting recent accomplishments and projects currently under development, general principles that guide us in structuring and carrying out the program, and our specific mission and research plans for new activities beginning in 2003. In subsequent sections we give more detail about the technology program that supports our bold vision, about our basic research programs, and about our public education and outreach programs. NASA cannot succeed without the active participation of scientists, technologists, and engineers all over the U.S. and collaboration with other nations as well. We therefore describe our many partnerships within the Federal Government, across the country, and around the world. The last section of Part II presents a vision of the future of the scientific exploration of the cosmos.

Astrobiology: Science of Synthesis

Answering our fundamental questions will call on all of modern science's tools of inquiry, ranging from astronomy, biology, and chemistry, through zoology. To gather these capabilities together and focus them on our fundamental questions, NASA is nurturing a new multidisciplinary science, Astrobiology. The place of life in the universe and its roots in the origin of the cosmos itself are the themes that run through this Strategic Plan to weave the Space Science Enterprise's many programs together into a unified voyage of discovery.

Section I-2

goals and objectives

The Space Act of 1958, which charters NASA as a Federal agency, defines a broad spectrum of goals and purposes for the Agency. The NASA Strategic Plan separates responsibility for its programs into Strategic Enterprises, which identify at the most fundamental level what we do and for whom. Each Strategic Enterprise has a unique set of goals, objectives, and strategies that address the requirements of its primary external customers.

Within NASA's Enterprise structure, the space sciences are gathered together into the Space Science Enterprise. These space sciences include space astronomy, planetary exploration, the physics of the Sun and the space between the Sun and planets, and fundamental physics experimentation carried out in space. This document is the enterprise-level Strategic Plan for the Space Science Enterprise.

The Agency Plan establishes a three-part Agency mission: advancing and communicating knowledge, human exploration of space, and developing new technology. Our Enterprise's programs contribute directly to these three Agency missions. Our role in technology development serves not only our Enterprise's and NASA's purposes, but also the broader purpose of strengthening our Nation's technology base.

NASA Mission

- To advance and communicate scientific knowledge and understanding of Earth, the Solar System, and the universe
- To advance human exploration, use, and development of space
- To research, develop, verify, and transfer advanced aeronautics and space technologies

The Space Science Enterprise's foremost role in support of the NASA mission is the discovery of new scientific knowledge about the universe. The Space Science Enterprise will:

> *Discover how the universe began and evolved, how we got here, where we are going, and whether we are alone.*

The Space Science Enterprise works closely with the scientific community to articulate science goals that directly support the Agency research mission. To address the other elements of the NASA mission, we also establish Enterprise goals for education and public outreach, support to human space flight, and technology. These four goals define the framework for formulating and managing the space science program.

Within this context, all of our strategic planning and management, including selections for mission implementation and related research activities, are

Table I—Enterprise Goals and Objectives

NASA Mission	Enterprise Goals	Enterprise Objectives
To advance and communicate scientific knowledge and understanding of Earth, the Solar System, and the universe	Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life	Science Objectives • Understand the structure of the universe, from its earliest beginnings to its ultimate fate • Explore the ultimate limits of gravity and energy in the universe • Learn how galaxies, stars, and planets form, interact, and evolve • Look for signs of life in other planetary systems • Understand the formation and evolution of the Solar System and Earth within it • Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our Solar System • Understand our changing Sun and its effects throughout the Solar System • Chart our destiny in the Solar System
	Share the excitement and knowledge generated by scientific discovery and improve science education	Education and Public Outreach Objectives* • Share the excitement of space science discoveries with the public • Enhance the quality of science, mathematics, and technology education, particularly at the pre-college level • Help create our 21st century scientific and technical workforce
To advance human exploration, use, and development of space	Use robotic science missions as forerunners to human exploration beyond low-Earth orbit	Human Space Flight Objectives • Investigate the composition, evolution, and resources of Mars, the Moon, and small bodies • Develop the knowledge to improve space weather forecasting
To research, develop, verify, and transfer advanced aeronautics and space technologies	Develop new technologies to enable innovative and less expensive research and flight missions	Technology Objectives* • Acquire new technical approaches and capabilities • Validate new technologies in space • Apply and transfer technology * Associated activities are discussed in Sections I-3 and I-4

Table II—Science Objectives and Research Focus Areas

Science Objectives	Research Focus Areas
Understand the structure of the universe, from its earliest beginnings to its ultimate fate	• Identify dark matter and learn how it shapes galaxies and systems of galaxies • Determine the size, shape, age, and energy content of the universe
Explore the ultimate limits of gravity and energy in the universe	• Discover the sources of gamma ray bursts and high energy cosmic rays • Test the general theory of relativity near black holes and in the early universe, and search for new physical laws using the universe as a laboratory • Reveal the nature of cosmic jets and relativistic flows
Learn how galaxies, stars, and planets form, interact, and evolve	• Observe the formation of galaxies and determine the role of gravity in this process • Establish how the evolution of a galaxy and the life cycle of stars influence the chemical composition of material available for making stars, planets, and living organisms • Observe the formation of planetary systems and characterize their properties • Use the exotic space environments within our Solar System as natural science laboratories and cross the outer boundary of the Solar System to explore the nearby environment of our galaxy
Look for signs of life in other planetary systems	• Discover planetary systems of other stars and their physical characteristics • Search for worlds that could or do harbor life
Understand the formation and evolution of the Solar System and Earth within it	• Inventory and characterize the remnants of the original material from which the Solar System formed • Learn why the planets in our Solar System are so different from each other • Learn how the Solar System evolves
Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our Solar System	• Investigate the origin and early evolution of life on Earth, and explore the limits of life in terrestrial environments that might provide analogues for conditions on other worlds • Determine the general principles governing the organization of matter into living systems and the conditions required for the emergence and maintenance of life • Chart the distribution of life-sustaining environments within our Solar System, and search for evidence of past and present life • Identify plausible signatures of life on other worlds
Understand our changing Sun and its effects throughout the Solar System	• Understand the origins of long- and short-term solar variability • Understand the effects of solar variability on the solar atmosphere and heliosphere • Understand the space environment of Earth and other planets
Chart our destiny in the Solar System	• Understand forces and processes, such as impacts, that affect habitability of Earth • Develop the capability to predict space weather • Find extraterrestrial resources and assess the suitability of Solar System locales for future human exploration

> Another major function of the triennial review of our Enterprise Strategic Plan is to articulate nearer-term focus areas for research that provide more specific guidance over 5-10 year periods.

founded on our science goals and objectives (Table I). While these are formulated at a high enough level that we expect them to remain stable over many decades, we continue to refine their articulation. In doing so, we work with our research community to update our strategic plan, rephrasing our objectives periodically to reflect our growing knowledge.

Another major function of the triennial review of our Enterprise Strategic Plan is to articulate nearer-term focus areas for research that provide more specific guidance over a 5-10 year period (Table II). These research focus areas are derived from our science objectives in consultation with our research communities, and are phrased to help mission and research decisionmaking and progress assessment.

The next two sections (I-3 and I-4) describe the roles of technology and education and public outreach in the space science program. Part II of the plan presents the program itself, beginning in section II-1 with our fundamental principles. Sections II-2 and II-3 of the plan describe our current program and our proposed flight mission program for the future. To be as clear as possible about how these missions will advance us toward our long-range science aspirations, the presentation organizes the missions in these sections by the eight Enterprise science objectives laid out above. Appendix A maps the missions onto the more specific Enterprise research activity areas. The remainder of Part II presents our programs in technology, basic research, and education and public outreach, as well as our overall strategies for partnering with other entities to reach our goals.

Section I-3

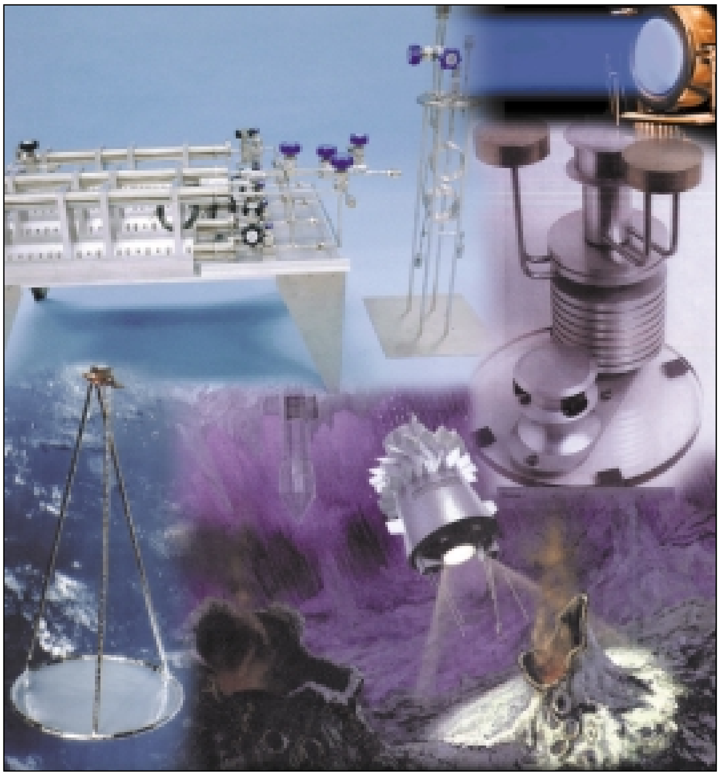
the role of technology

The space science technology development program develops and makes available new space technologies needed to enable or enhance exploration, expand our knowledge of the universe, and ensure continued national scientific, technical, and economic leadership. It strives to improve reliability and mission safety, and to accelerate mission development. Since the early 1990’s, the average space science mission development time has been reduced from over nine years to five years or less, partly by integration and early infusion of advanced technologies into missions. For missions planned in the years 2000 to 2004, we hope to further reduce development time to less than four years.

Our technology program encompasses three key objectives. First, we strive to develop new and better technical approaches and capabilities. Where necessary, we then validate these capabilities in space so that they can be confidently applied to science flight projects. Finally, we use these improved and demonstrated capabilities in the science programs and ultimately transfer them to U.S. industry for public use.

To achieve the technology goals for meeting future space science missions capability requirements for-

Enterprise Technology Objectives	Enterprise Technology Activities
Acquire new technical approaches and capabilities	• Focus technology development on a well-defined set of performance requirements covering the needs of near-term to mid-term strategic plan missions ("mission pull") • Guide basic technology research to meet projected long-range needs ("vision pull") • Promote partnerships with other agencies, industry, academia, and foreign collaborators to take advantage of capabilities developed elsewhere
Validate new technologies in space	• Identify technologies of high value to future Enterprise missions and fund their development to the point that they are ready for ground or space demonstration • Formulate, develop, and implement cost-effective space demonstrations of selected technologies on suitable carriers
Apply and transfer technology	• Use new technologies, in multiple missions where possible, to reduce costs and shorten mission development time across the program • Maximize benefits to the Nation by stimulating cooperation with industry, other Government agencies, and academia



The Space Science Enterprise provides requirements to, and in turn benefits from, a broad spectrum of Agencywide technology programs.

mulated in science roadmaps, the Enterprise technology strategy is to:

Focus technology development on science program requirements. When near-term Enterprise mission concepts are defined sufficiently to begin detailed scoping of their instrumentation, systems, and infrastructure, performance requirements are derived. Technology development is focused on meeting the identified requirements ("mission pull" technologies). Basic technology research is focused on perceived longer range technology needs (they are characterized with less precision than near-term requirements). These longer range needs are generated from advanced mission concepts developed by mission study groups working with science advisory groups. Identified needs are then used to allocate support for maturation of more revolutionary technical approaches ("vision pull" technologies). The balance between "mission pull" and "vision pull" contributes to program agility and results in long-term continuing progress of the overall program notwithstanding short-term changes in circumstances.

Fund technologies of high value to future Enterprise missions to the point that they are ready for ground or space demonstration. A large number of technology concepts are given the benefit of exploratory research in the expectation that a fraction of these will emerge as promising. It is critical that these promising candidates for use in missions are identified and funded to the point where they are tested in a relevant environment on the ground, adopted by a flight project for further maturation, or are proposed as a candidate for space flight validation.

Formulate and implement cost-effective space demonstrations of selected technologies on suitable carriers. Project managers need assurance that adopted new technology will perform in the relevant space environment. In many cases this environment can be simulated on the ground in a satisfactory manner. Often this is not the case, however. It is necessary to identify those technologies that require space flight demonstration and perform these demonstrations.

Use these technologies in multiple missions to reduce costs and shorten mission development time across the program. Since the early 1990's, the average science mission development time has been reduced from over nine years to five years. Although many factors can compress mission development time, infusion of validated new technology in the early mission phases can facilitate this. We compare requirements for future missions to look for common needs that can be met through a coordinated technology development effort. Where possible, we sequence missions so that later projects build on technology developed and successfully demonstrated for earlier ones.

Promote partnerships with other agencies, industry, and academia to take advantage of external capabilities. Technology infusion succeeds best through formal and informal interactions between mission developers, scientific principal investigators, and technology providers. In the early phases of development, detailed analyses and trade-off studies are conducted to determine technical feasibility and to establish technology priorities.

> Technology infusion succeeds best through formal and informal interactions between mission developers, scientific principal investigators, and technology providers.

Joint activities and partnerships with universities, industry, and other Government agencies can be particularly important in speeding identification and realization of the most attractive technology for specific needs. Technical capabilities can sometimes be efficiently acquired through cooperation with international partners. In conducting cooperative activities in technology, the Enterprise protects proprietary data and intellectual property.

Maintain excellence by engaging the outside community in technology development and evaluation. The Enterprise integrates industry, academia, and other Federal agencies' laboratories into the program. Industry, for example, develops valuable technology by using internal resources (IR&D and profit dollars), and through service to non-NASA customers. Similarly, the university community holds a vast and unique technological resource. University groups, receiving significant funding from other sources, are often leaders in essential technology areas. This approach—of using a mix of dedicated peer-reviewed efforts at NASA Centers, other Government agencies, industry, and universities—ensures that the "best and brightest" are tapped for the required developments. This approach dovetails with the practices of following parallel paths in early development followed by descoping and down-selecting. Independent merit review will be used to assure excellence in both internal NASA and external technology development efforts. These reviews will consider whether work is "best-in-class," contributes to specific, documented, and otherwise unaddressed Enterprise requirements, and is advancing significantly the state-of-the-art.

Section I-4

the role of education an

Space science missions have revealed the universe through new eyes and opened up new worlds to explore and understand. They have shown us that black holes really exist and have given us fundamental new information about the origin and evolution of planets, stars, galaxies, and the universe itself. They have opened up the tantalizing prospect of searching for life beyond Earth. By engaging the imaginations of teachers, students, and the general public, space science has demonstrated extraordinary potential for strengthening interest in science and improving the quality of science, mathematics, and technology education in America. By attracting bright individuals to advanced study in technical fields, space science also plays a significant role in ensuring a continuing cadre of trained scientists, engineers, and technologists to meet our society’s needs in the 21st century.

d public outreach

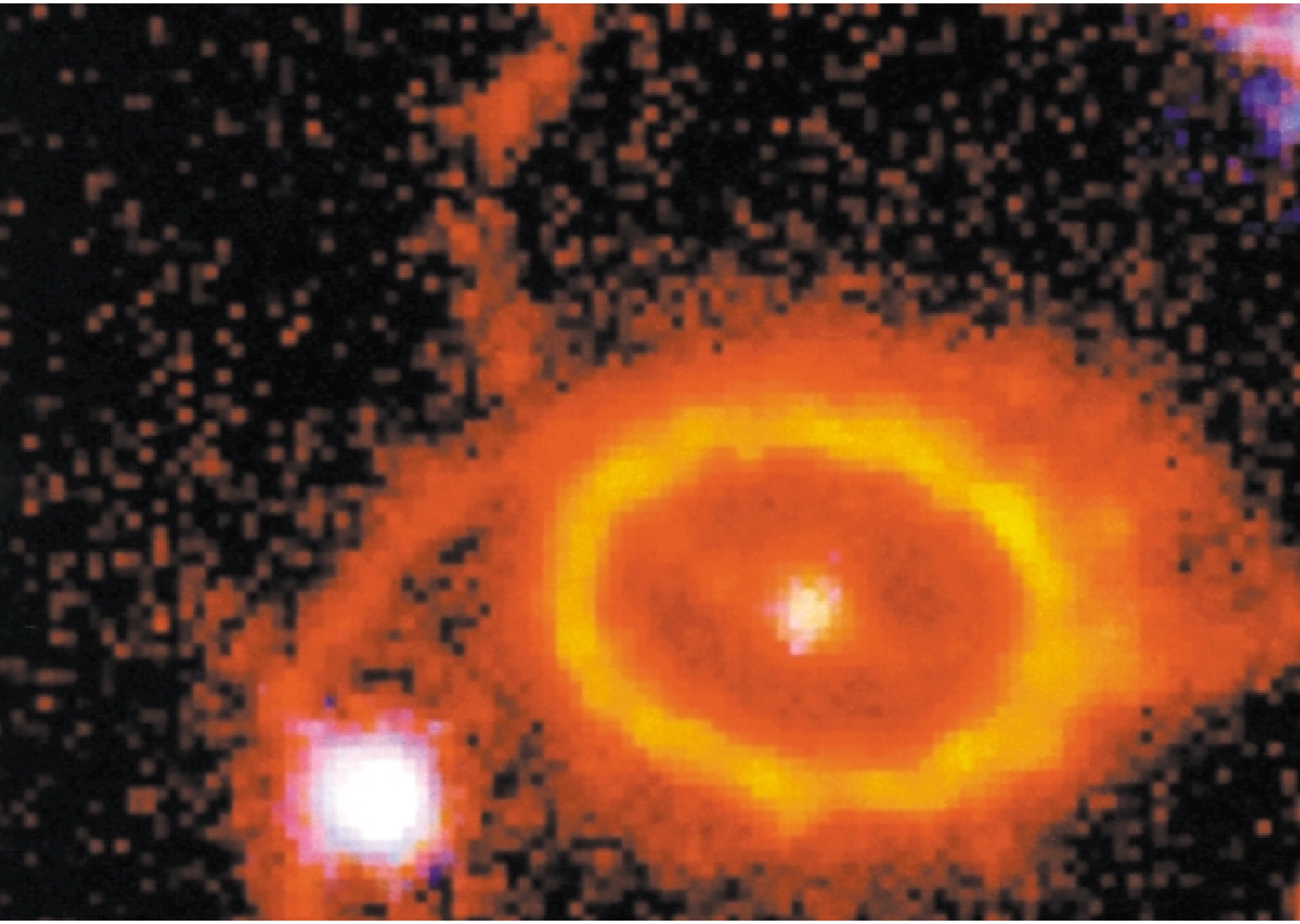
To meet our goals and objectives, we integrate education and public outreach into all space science missions and research programs. The resulting program is an important element of NASA's overall education effort, and was designed in close collaboration with the NASA Office

Education and Public Outreach Objectives	Education and Public Outreach Activities
Share the excitement of space science discoveries with the public Enhance the quality of science, mathematics, and technology education, particularly at the pre-college level Help create our 21st century scientific and technical workforce	• Incorporate a substantial, funded education and outreach program into every space science flight mission and research program • Increase the fraction of the space science community that contributes to a broad public understanding of science and is directly involved in education at the pre-college level • Establish strong and lasting partnerships between the space science and education communities • Develop a national network to identify high-leverage education and outreach opportunities and to support long-term partnerships • Provide ready access to the products of space science education and outreach programs • Promote the participation of underserved and underutilized groups in the space science program by providing new opportunities for minorities and minority universities to compete for and participate in space science missions, research, and education programs • Develop tools for evaluating the quality and impact of space science education and outreach programs

Children from the Daniel Boone Regional Library, Columbia, Missouri (a Space Place partner), displaying their own spacecraft—all made from recycled materials.

of Human Resources and Education and the Office of Equal Opportunity Programs. NASA mandates that the Agency "involve the education community in our endeavors to inspire America's students, create learning opportunities, enlighten inquisitive minds," and "communicate widely the content, relevance, and excitement of NASA's missions and discoveries to inspire and to increase understanding and the broad application of science and technology."

It is our fundamental premise that all Americans should be able to participate in the adventure of exploring and understanding the universe. The Enterprise works closely with both the space science and education communities to identify education and outreach opportunities focused on the needs of educators and the general public. Establishing productive, long-term partnerships between educators and space scientists helps maintain this focus. Our education and outreach information and materials are made readily available in a variety of formats useful to educators and suitable for bringing the accomplishments of the Space Science Enterprise to the general public.



the space science enterprise

our program

Section II-1

recent accomplishments

In section II-3 of this Strategic Plan, we will present missions under study for development over the 15-year period from 2003 through about 2018. To understand these plans and how they were derived, it helps to review the progress we have made since our last plan was released in late 1997. In *Recent Accomplishments* in this section, we highlight achievements since the last Plan. Then, in *Missions Currently Under Development*, we describe missions in an advanced study stage today that we will begin to implement before the end of 2002. Some of the missions described there will be launched after 2002 and most will be operating in 2003 and beyond. Missions are presented in **bold** when they are first introduced.

and current program

Recent Accomplishments

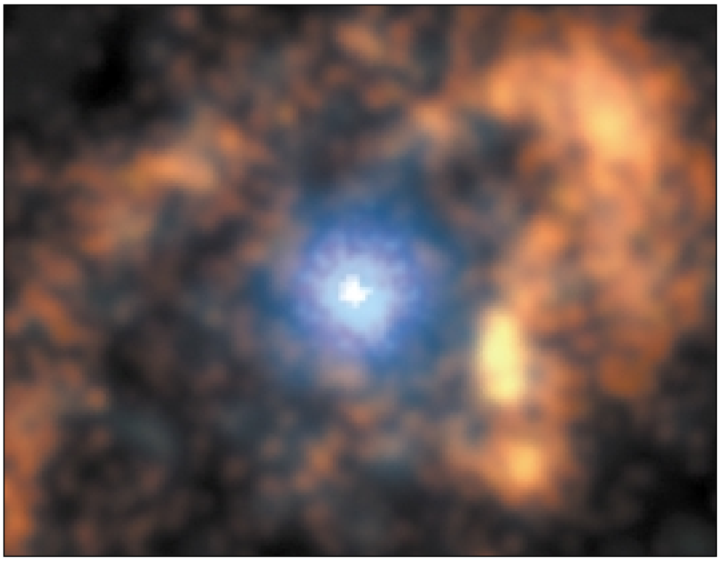
The Space Science Enterprise has made exciting advances in many goal areas during recent years. In this subsection, we briefly describe progress in astrophysics and cosmology, Solar System exploration, technology, and education and public outreach programs.

How did our universe, starting with what we have come to call the "Big Bang," a featureless process that produced only the lightest elements, come to be the place that we know, rich in the rest of the chemical elements from which stars, planets, and life itself formed? The opportunity to put instruments in space that observe at many wavelengths has provided us with an explosion of evidence addressing these questions.

In the late 1980's, the **Cosmic Background Explorer (COBE)** satellite gave us a glimpse of the beginnings of structure very early in the history of the universe, a view sharpened by the subsequent **BOOMERANG** balloon-borne observations. The **Compton Gamma Ray Observatory (CGRO)** observed evidence for the synthesis of heavy elements in supernova explosions and their subsequent spread throughout the Milky Way. It observed large numbers of mysterious gamma ray bursts; believed now to originate in very distant sources, these brief gamma ray "flashes" must represent enormous amounts of emitted energy. Vast amounts of energy in gamma rays are also seen to be coming from the jets in distant galaxies.

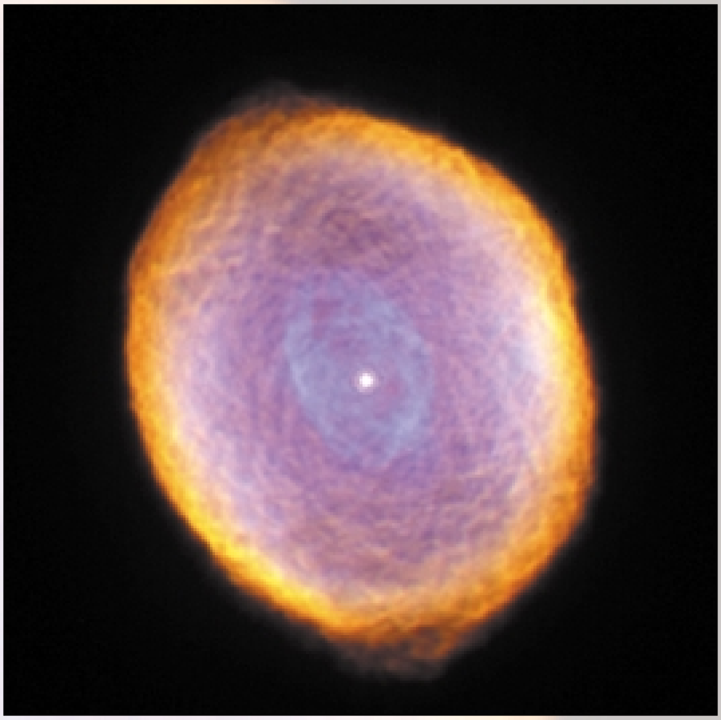
Two x-ray satellites, the **Rossi X-ray Timing Explorer (RXTE)** and the Japanese-U.S. **ASCA** mission, have helped us understand disks of accreting material in binary systems and provided evidence for spinning black holes in active galactic nuclei.

Recently, the newly launched **Chandra X-ray Observatory (CXO)** is showing us details of the



The Chandra x-ray image shows the complex region around Eta Carinae, a massive supergiant star that is 7,500 light-years from Earth. The outer horseshoe shaped ring is about two light-years in diameter and was probably caused by an outburst that occurred more than a thousand years ago.

structure and composition of objects we could only begin to see a few years ago. For example, Cassiopeia-A is a supernova remnant already known to be a powerful emitter of radio waves. A CXO x-ray image of it (shown on the Plan cover) shows with remarkable clarity, not only the wispy structure characteristic of a supernova remnant, but also what appears to be a neutron star at the center, the remaining densely packed core of the original star. These exciting results are showcased through a nationally-distributed planetarium show "Journey to the Edge of Space and Time," co-produced by the Boston Museum of Science, which takes hundreds of thousands of viewers per year on a spectacular voyage from the Milky Way to the farthest reaches of our universe.

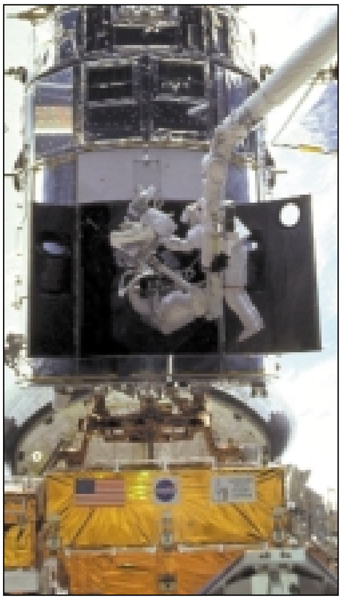


Glowing like a multi-faceted jewel, the planetary nebula IC 418 lies about 2,000 light-years from Earth in the constellation Lepus. The Hubble Space Telescope reveals some remarkable textures weaving through the nebula. Their origin is still uncertain.

New results on the elemental and isotopic composition of solar particles, galactic cosmic rays, and the solar wind are being achieved by the **Advanced Composition Explorer (ACE)**. The observations have shown that galactic cosmic rays are boosted to their enormous energies from the debris of supernovae, but long after the supernova explosions themselves. In a surprising and unrelated discovery, ACE found that the solar wind came to a virtual standstill for two days in May 1999. This event, believed to be related to a massive ejection of material from the Sun, strongly affected Earth's magnetosphere.

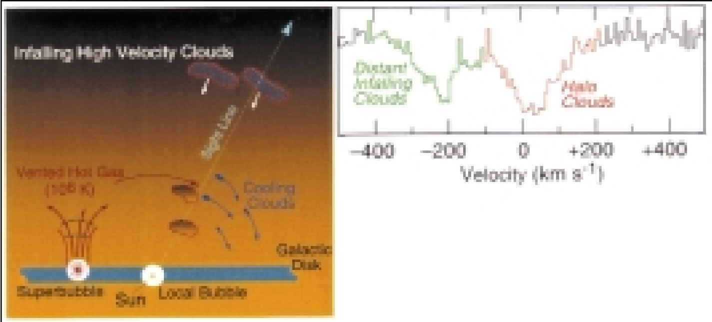
Another recent mission, the **Submillimeter Wave Astronomy Satellite (SWAS)** studies the processes of star formation by observations of water, molecular oxygen, isotopic carbon monoxide, and atomic carbon. Results of observations of dark interstellar clouds, evolved stars, external galaxies, and planetary nebulae confirm some of our ideas about interstellar chemistry, but have contradicted our expectations about the amount of oxygen and water in many cool molecular clouds.

NASA has made rapid advances in its goal toward tracing our cosmic roots through a better understanding of the formation of galaxies,



Astronauts replace gyroscopes inside the Hubble Space Telescope during the HST-3A mission.

stars, heavy elements, and planetary systems. Discoveries by the **Hubble Space Telescope (HST)** have invigorated astronomy in many areas. Astronomers have observed details of the surfaces or outer layers of Mars, Saturn, Jupiter, Uranus, and Pluto through visible, ultraviolet, and infrared images taken by HST. The crisp resolution of HST has revealed various stages of the life cycle of stars in images of galactic nebulae. After a multi-year observing and analysis program, HST has enabled us to refine our estimate of the Hubble Constant, the rate at which the universe is expanding. This determines the age of the universe since the Big Bang to a precision of 10 percent, compared to the previous factor-of-two uncertainty. Thousands of never before seen galaxies have been observed in the Hubble Deep Fields, doubling the number of far-flung galaxies available for deciphering the history of the universe. HST continues to hold the fascination of students, teachers, and the public, making the "New Views of the universe" traveling exhibit a highly popular destination for museum and science center visitors nationwide. Two versions of the exhibit, appropriate for large and small museums, are now traveling around the country, allowing visitors to experience Hubble's discoveries and knowledge through interactive learning.



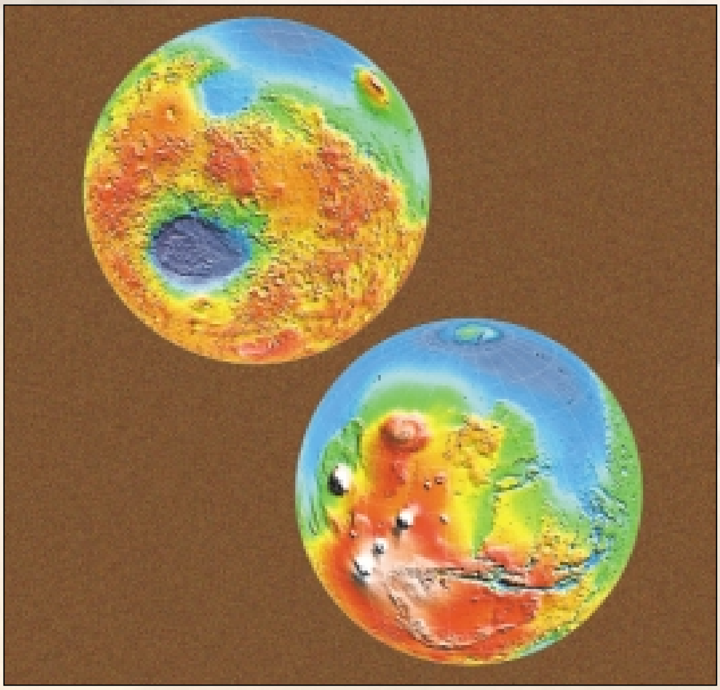
Galactic assembly and reconstruction: A typical high-latitude sight line through the Milky Way encounters interstellar clouds near the galactic plane and distant clouds in the outer regions of the galactic halo. Distant clouds fall in on the galaxy from the outside (assembly), while nearby gas is circulated and energized by supernovae (reconstruction). FUSE can diagnose these processes by examining the absorption of light passing through these clouds.

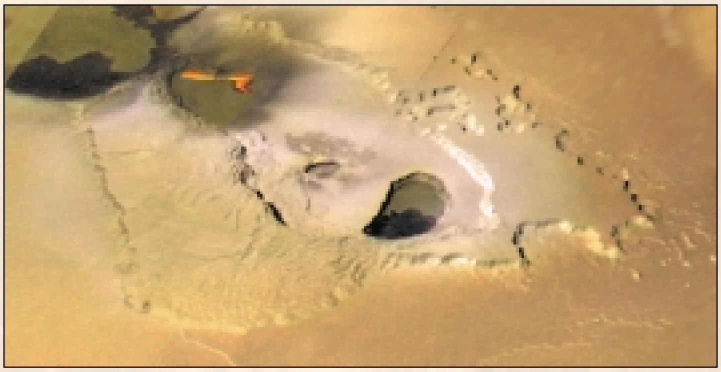
The **Far Ultraviolet Spectroscopic Explorer (FUSE)** is providing very high resolution ultraviolet spectra of the interstellar medium, giving information on the chemical content of material between stars and galaxies. The ultimate goal is to discover the conditions at the time of the Big Bang and how the universe has evolved since then.

Over the past few years, NASA-supported ground-based research has discovered dozens of sub-stellar companions orbiting nearby stars.

Turning to the Solar System, data from the Mars Orbiter Laser Altimeter (MOLA) instrument on the **Mars Global Surveyor** spacecraft show evidence for an ancient ocean basin around the planet's north pole. These data, which comprise over 200 million high-precision measurements of the height of Mars' surface, indicate an ancient shoreline about 18,000 km long. The amount of water that would have been contained in the ocean is about what would be expected on the basis of other geological features such as the outflow channels that drain into the northern lowlands of the planet.

Since its continuation in 1998 as the **Galileo Europa Mission (GEM)**, Galileo has concentrated on intensive study of Jupiter's ice-covered satellite Europa. It has been known for nearly 30 years that Europa is covered with a crust of water ice; what is not known is whether the ice extends all the way down to bedrock or floats on an ocean of liquid water. The possibility of a liquid ocean is extremely exciting because of the implications for Europa as a possible habitat for life. GEM has yielded several lines of evidence that support the hypothesis of liquid water





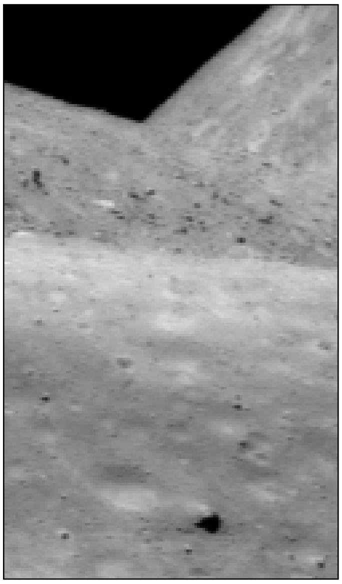
Top:
Global topographic map of Mars. The Mars Orbiter Laser Altimeter (MOLA) instrument on the Mars Global Surveyor spacecraft suggests what was once a vast ocean (blue indicates lower elevations).

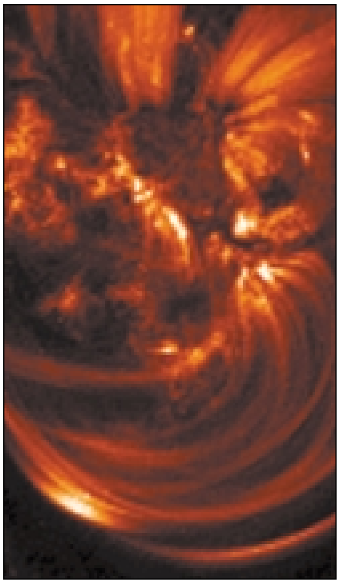
Bottom:
Eruption in Tvashtar Catena, a chain of volcanic calderas (craters) on Jupiter's moon Io, as seen by NASA's Galileo spacecraft. The temperature of the lava is much higher than is typical for volcanic eruptions on present-day Earth.

beneath its icy crust. Galileo has also obtained dramatic images of other satellites of Jupiter, including vulcanism on the satellite Io.

The **Cassini** mission to Saturn, launched in 1998, has successfully completed three gravity assist maneuvers, two at Venus and one at Earth. A fourth and final gravity assist maneuver at Jupiter in December 2000 will put Cassini on a trajectory for arrival at Saturn in July 2004.

The first two **Discovery** missions were **Mars Pathfinder** and the **Near Earth Asteroid Rendezvous (NEAR)**. Pathfinder dramatically brought Mars exploration to television viewers and Internet users all over the world with its close-ups of the Mars surface. After missing its first rendezvous with asteroid 433 Eros in 1998, NEAR has returned to be successfully placed into orbit around the asteroid and return high quality images, spectra, and altimetry.



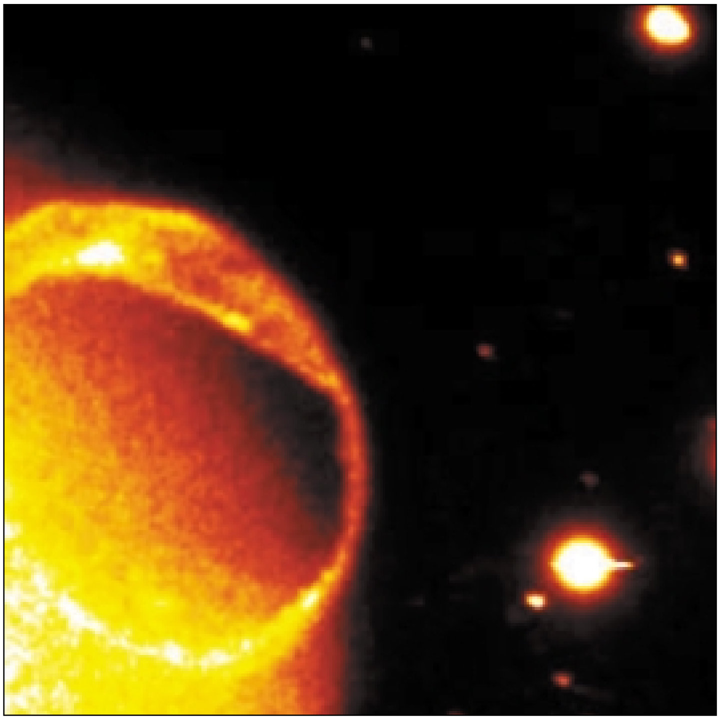


Left: This NEAR-Shoemaker image taken from an orbital altitude of 38 kilometers brings home the irregularity of the tiny world called Eros. Looking down the length of the asteroid, one sees near, middle, and far horizons. The whole scene is about one kilometer across.

Right: The million-degree solar plasma shown by TRACE shows a set of loops, possibly brought on by a large flare occurring a few hours earlier.

Lunar Prospector, the third Discovery mission, successfully completed global spectroscopy and gravitational mapping of the Moon. The highlight of this mission was the discovery of evidence for trapped hydrogen, possibly in the form of water ice, in permanently shadowed craters near both lunar poles. Lunar Prospector epitomized the “faster, better, cheaper” goals of the Discovery program. It was developed, from project initiation to launch, in less than three years; it successfully completed all of its scientific goals; and it was by far the least expensive planetary exploration mission ever flown by NASA. **Stardust**, the fourth Discovery mission, was launched in January 1999. It will collect a sample of dust from the coma of comet Wild-2 in 2004 and return the sample to Earth for detailed analysis in 2006.

In 1998, the **Transition Region and Coronal Explorer (TRACE)** joined an international fleet of spacecraft, including the **International Solar Terrestrial Program (ISTP)** satellites **Wind** and **Polar**, **Yohkoh**, **Ulysses**, and ACE, for coordinated multi-



The IMAGE spacecraft observed highly dynamic auroral activity over the terrestrial pole during the major geomagnetic storm that occurred May 2000.

dimensional study of the Sun-Earth connection and the impacts of solar variability on Earth. At the very low cost of a Small Explorer mission, TRACE has provided dramatic, high resolution motion pictures of evolving structures in the solar atmosphere that clearly show the effects of magnetic activity. The Polar spacecraft obtained the first global images of Earth's space environment using fast neutral atoms instead of light to "see" the plasma motions. The ESA **Solar and Heliospheric Observatory (SOHO)**, in which NASA is a major collaborator, has provided evidence for streams of hot plasma under the solar surface, as well as dramatic movies of massive blobs of ionized gas, a billion tons in size, being expelled from the Sun.

The **Fast Auroral Snapshot Explorer (FAST)** satellite, which measures particles and fields in Earth's auroras with fast time resolution and high spatial resolution, has found the origin of long-wavelength radio emission from these regions. This process, which depends on the geometry of magnetic and electric fields, may explain previously mysterious particle acceleration in astrophysical plasmas in many settings outside the Solar System. The **Imager for Magnetospheric to Aurora Global Exploration (IMAGE)** is giving us a new perspective on the response of Earth's magnetosphere to the solar wind using a combination of neutral atom, ultraviolet, and radio imaging techniques.

These measurements are being complemented by data from U.S. instruments on ESA's **Cluster-II** mission, which consists of four identical spacecraft flying in formation between 25,000 and 125,000 km above Earth.

The popularity of total solar eclipses has provided unique, high-leverage opportunities to highlight solar and geospace research conducted by missions such as SOHO, TRACE, and IMAGE. Eclipse webcast events produced by the Live@The Exploratorium program from the path of totality offer participating space scientists the chance to discuss their research with thousands of visitors at museum sites around the country and through the Internet.

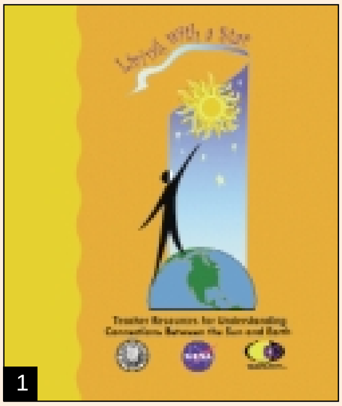
The New Millennium Program for flight technology validation was initiated with the **Deep Space 1 (DS-1)** mission. DS-1 successfully validated all twelve new technologies onboard for demonstration. Some of these technologies will enable future spacecraft to be built smaller and less expensively; others will increase spacecraft navigation autonomy, reducing operations costs.

Deriving the full benefit of the public investment in space science requires that its discoveries be shared with all Americans. Since the publication of the 1997 Space Science Enterprise Strategic Plan, we have made major progress toward incorporating **Education and Public Outreach** into every facet of our programs. This section highlights a few examples of Education and Public Outreach programs connected with flight missions. In addition, an active public information program, including widely reported Space Science Update press events, has helped bring results of space science missions to public attention through print and electronic media. All flight missions are now required to have substantive, funded education and public outreach programs as integral components. Participants in research grant programs are also strongly encouraged to include an education and outreach component as part of their research proposals. As a result, literally hundreds of education and public outreach activities of many different types are now underway in communities across the country. These activities have already benefited many students and educators and have reached a large segment of the public.

New Technologies Successfully Space-Validated by Deep Space 1

Ion Drive for Primary Propulsion
Solar Concentrator Arrays
Autonomous Navigation
Ion and Electron Spectrometer
Small Deep Space Transponder
Ka-Band Solid State Amplifier
Beacon Monitor Operations
Autonomous Remote Agent
Low Power Electronics
Power Actuation and Switching Module
Multifunctional Structure
Miniature Integrated Camera
and Imaging Spectrometer

During a highly successful primary mission, DS-1 tested 12 advanced technologies in space.



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Examples of Education and Public Outreach Activities Underway

1. A teacher resource directory provides access to space science education and outreach products for use by educators.
2. We have used workshops for teachers in communities across the country and national education conferences to test and distribute education products to tens of thousands of teachers.
3. Space science-centered exhibits are on display at a number of major science museums, and space science-based shows are playing at large and small planetariums across the country.

4,5. The internet is being routinely used as a tool for disseminating space science classroom materials and bringing major space science events to the public.

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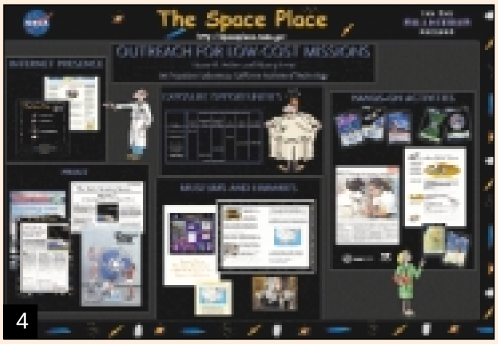

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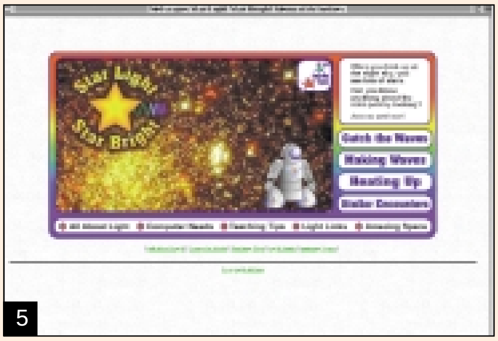

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Missions Currently Under Development

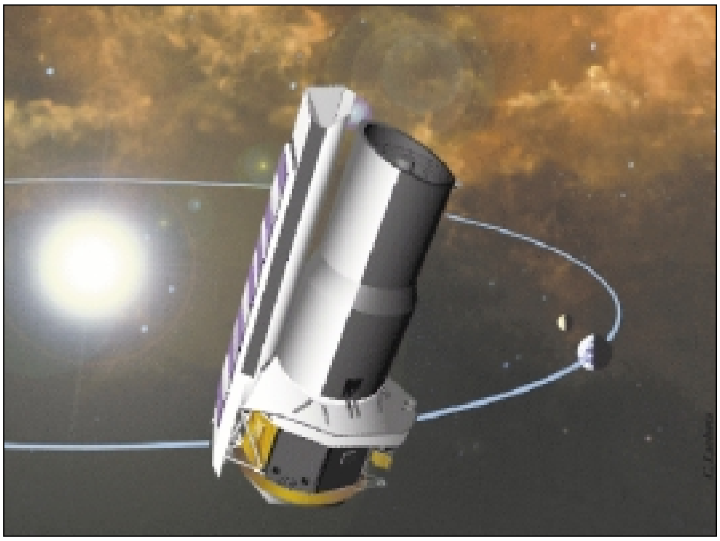
Building on the exciting results of missions completed or still operating, many missions that were only proposals in our 1997 plan are graduating from their study phases into development and will be launched within the next few years.

The **Microwave Anisotropy Probe (MAP)** Explorer will measure fluctuations in the microwave background on angular scales much finer than COBE, fluctuations out of which the largest structures in the universe—the super-clusters of galaxies—eventually emerged. MAP should enable us to measure directly the size and contents of our universe at an age of only 300,000 years. Later, with even finer angular resolution and sensitivity, the European Space Agency (ESA)/NASA **Planck** mission will provide precision measurements of dark-matter, baryon, vacuum-energy densities, and the Hubble constant, and thus forecast the ultimate fate of the universe. Planck's polarization measurement capabilities will allow new and unique tests of cosmological inflation and perhaps measure its energy scale.

HST's new instruments are expected to continue the observatory's spectacular accomplishments.

HST's new instruments are expected to continue the observatory's spectacular accomplishments. These upgrades include the installation of the Advanced Camera for Surveys, a new cooling system to reactivate the Near Infrared Camera and Multi Object Spectrometer, the Cosmic Origins Spectrograph, and the Wide Field Camera-3. The next major space observatory will be the **Space Infrared Telescope Facility (SIRTF)**. Once in operation, SIRTF will contribute extensively to the understanding of formation of stars and planets and will investigate the formation and early evolution of luminous galaxies.

While SIRTF will have unsurpassed sensitivity throughout the infrared wavelength regime, the



SIRTF is the final element in NASA's family of "Great Observatories," and consists of a cryogenic telescope and science instruments for infrared imaging and spectroscopy.

Stratospheric Observatory for Infrared Astronomy (SOFIA) will complement the space mission with much better spatial and spectral resolution for the detailed study of bright objects. A key scientific goal of SOFIA will be the investigation of conditions within the interstellar medium that enable the formation of stars and planets. As an aircraft, rather than a space observatory, SOFIA has several unique characteristics. It can continually upgrade its instrumentation and serve as a critical training ground for new generations of instrument builders.

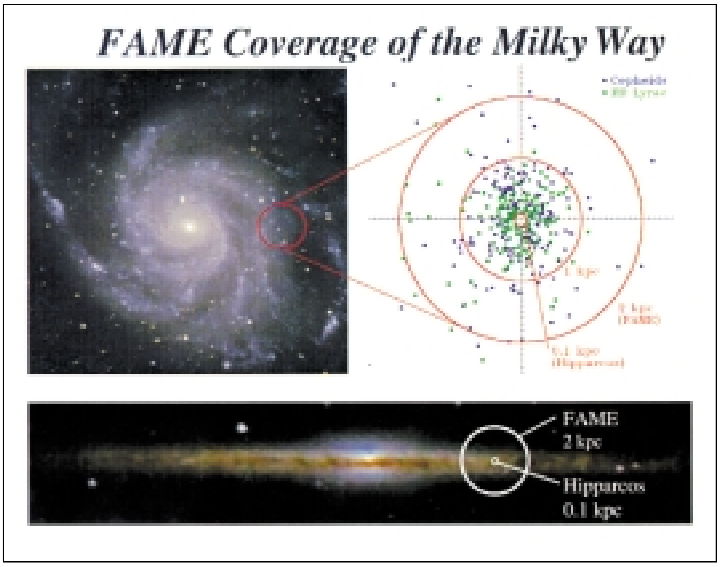
The ESA-led **Far-Infrared and Submillimeter Telescope (FIRST)** will be able to observe very dusty galaxies with active star formation out to large distances, and therefore early in the universe. FIRST will also be able to study molecule formation in the dense molecular clouds in our own galaxy where stars and perhaps planets are forming.

The **Keck Interferometer**, a ground-based facility, will combine the infrared light collected by the world's two largest optical telescopes, the twin 10-meter Keck telescopes on Mauna Kea in Hawaii, to undertake a variety of astrophysical investigations.

SOFIA will involve educators directly in its research programs by flying them on the observatory itself and centering its education and public outreach programs on these opportunities.

The most violent events in the Universe emit bursts of gamma rays for a few seconds. Observations with the Italian/Dutch Beppo-SAX satellite, complemented with results from the Compton Gamma Ray Observatory (CGRO), have shown that these mysterious events occur early in the history of galaxies and are clues to major events in their evolution. The Explorer mission **Swift**, and later the **Gamma Ray Large Area Space Telescope (GLAST)** will enable us to unlock the mysteries of these dramatic stellar explosions. Because of their great distances from us, spectral studies of these explosions will allow us to probe the intervening infrared background light, which absorbs the higher energy gamma ray photons through electron-positron pair production. GLAST will also study the nature of cosmic jets and relativistic bipolar flows emanating from distant active galactic nuclei, and determine how much of the general all-sky diffuse gamma ray background is due to such sources, which were unresolved by instruments of the Compton Gamma Ray Observatory. In addition, GLAST will pursue the surprising discovery of the trickle of high energy gamma rays observed to continue to issue from some gamma ray bursters, sometimes for hours.

Explorer missions with targeted science objectives will complement major missions and in some cases provide key information that will help maximize the scientific return from them. The **Galaxy Evolution Explorer (GALEX)** will use high resolution ultraviolet spectroscopy and imaging to observe star formation over 80 percent of the lifetime of the universe, the period that spans the origins of most stars, elements, and galaxy disks and over which galaxies have evolved dramatically. The **Full-Sky Astrometric Explorer (FAME)** will be a space astrometry mission that offers the unique opportunity to measure the positions, proper motions, parallaxes, and photometry of forty million stars to unprecedented accuracy. Through these data, the variability of 40,000 solar type stars will be characterized, the frequency of solar type stars orbited by brown dwarf and giant planet companions will be determined, and the distance scale of the universe will be improved. The **Cosmic Hot Interstellar Plasma Spectrometer (CHIPS)** will carry out spectroscopy of the diffuse background in the extreme ultraviolet to determine the evolution of the million degree gas that lies outside the Solar System. This will lead to an understanding of key mechanisms responsible for recycling gas within the interstellar medium.



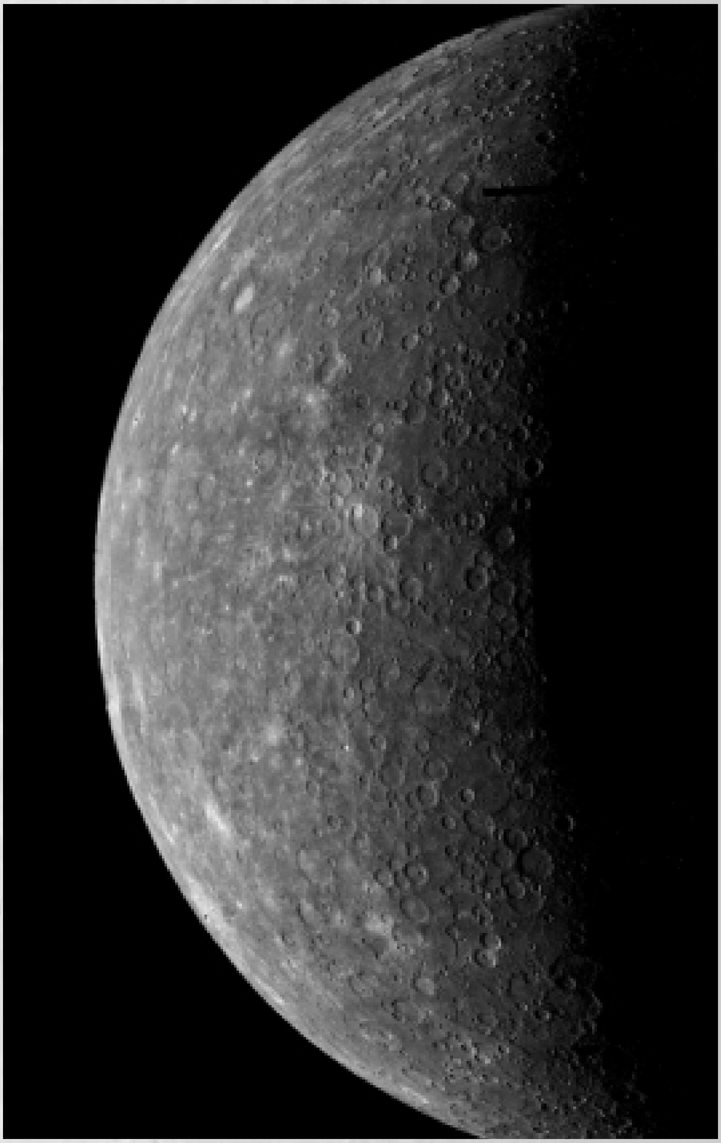
The innermost and outermost circles outline the volume covered by the Hipparcos and FAME missions, while the symbols mark the positions of two types of stars that can be used as cosmic yardsticks.

Planning and development continues for new missions in the **Mars Exploration Program (MEP)**. The losses of the Mars Climate Orbiter and Mars Polar Lander in 1999 were severe blows to the program, but scientific interest in Mars as a laboratory for comparative planetology and as a possible home for past or present life continues undiminished. Responding to reviews of these failures, we are planning a flight program firmly based on scientific objectives and will execute it at a pace consistent with technical readiness and available resources. Return of samples to Earth for analysis remains an important objective, but near-term missions will focus on orbital science, in situ analysis on the surface, and characterization of possible landing sites. The next mission will be an orbiter to be launched in 2001, and two enhanced rovers will follow in 2003.

The Galileo Europa Mission's intensive study of Europa has yielded evidence for a global liquid water ocean beneath the icy crust. Although this evidence is not conclusive, this would be such a momentous discovery that we are planning a **Europa Orbiter** mission system to obtain a definitive answer. Advanced technologies needed for this mission are being developed, and implementation of this follow-on mission could begin in the 2002-2003 timeframe.

A number of new **Discovery** missions that address related topics are in development. The **Comet Nucleus Tour (CONTOUR)** will fly by the nuclei of at least two comets at different evolutionary stages. CONTOUR will analyze the surface structure and composition of these nuclei to probe the diversity of comets. **Deep Impact** will excavate a crater in comet Temple-1 to study the structure of the cometary nucleus and to compare its interior composition with that of its surface. The objective of doing so is to gain a better understanding of the history of primordial material from the outer Solar System. As one component of the mission's public outreach program, the International Astronomical League will set up opportunities around the world to allow the public to observe the impact.

Another Discovery mission now under development, the **Mercury Surface, Space Environment,**



Mariner 10's first image of Mercury, acquired on March 24, 1974. Closer study of Mercury's high density, global magnetic field, and ancient surface will provide important clues for understanding the evolution of the inner Solar System.

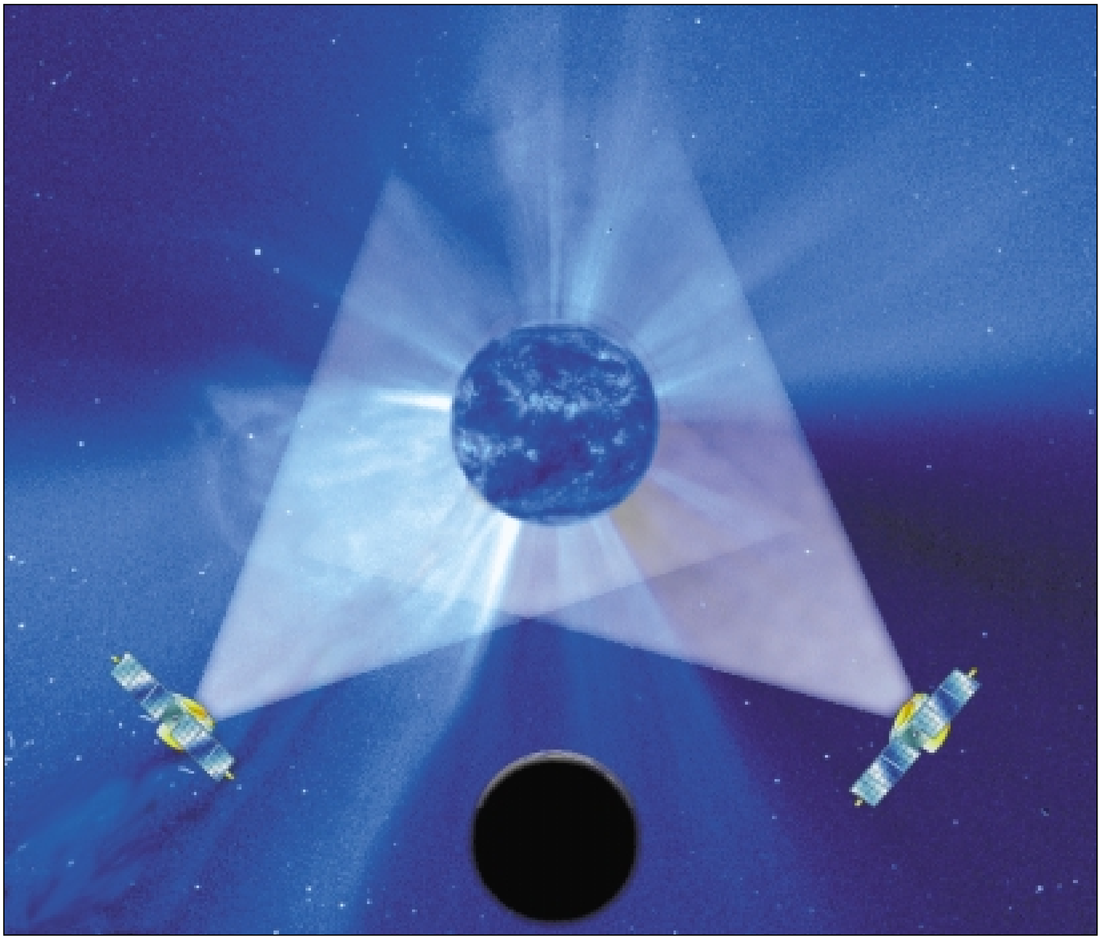
Geochemistry and Ranging (MESSENGER) mission, will study how the inner Solar System formed by analyzing the physical properties and chemical composition of the closest planet to the Sun. The planet Mercury will be the focus of an ambitious education and public outreach program aligned with National Science Education Standards for teaching and learning under the auspices of the American Association for the Advancement of Science, the Challenger Center for Space Science Education, and several other national partners.

New insight into the material from which the Sun itself originally formed, still preserved in the outer atmosphere of the Sun, will be obtained by the **Genesis** mission when it collects and returns to Earth samples of the solar wind that streams out from the Sun.

The Galileo Europa Mission's intensive study of Europa has yielded evidence for a global liquid water ocean beneath the icy crust.

The Sun profoundly affects all the bodies in the Solar System, as well as the space between them. To explain these effects, we need to understand both the inherent characteristics of the Sun and how its emissions interact with the rest of the Solar System. Missions currently under development will advance our knowledge of the Sun's interior dynamics. Coordinated measurements of events that originate on the Sun, propagate through interplanetary space, and ultimately impact on Earth's magnetosphere and upper atmosphere are enabling us for the first time to determine cause and effect unambiguously. This research will be pursued within the new **Living with a Star** initiative, which will accelerate some currently planned missions and support new ones now being defined. For Living with a Star, the University of California-Berkeley Space Science Laboratory and the Lawrence Hall of Science are developing elementary and middle school activities highlighting the impact of the active Sun on Earth and society. These activities will be part of the "Great Explorations in Math and Science" series, which is already used by thousands of school districts nationwide.

The **Solar Terrestrial Probe (STP)** program is a line of missions that study the Sun-Earth system. The STP program seeks to understand solar variability on time scales from a fraction of a second to many centuries. It will also correlate cause (solar variability) with effect over vast distances. The STP program will begin with the launch of the **Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED)** mission, which will provide a first global characterization of the region where the atmosphere tails off into space. TIMED will be followed by two missions that will address solar variability from different perspectives. NASA's contribution to **Solar-B** (a mission of the Japanese Institute of Space and Astronautical Science) will be the second STP mission. Solar-B will investigate the creation and destruction of the Sun's magnetic field and provide quantitative measurements of the photospheric field with greatly improved spatial resolution. The third STP mission is the **Solar Terrestrial Relations Observatory (STEREO)**, two identical spacecraft that will observe the Sun stereoscopically for the first time. STEREO will track the origin, propagation, and



STEREO will measure coronal mass ejections from the Sun in three dimensions for research to increase reliability of space weather alerts.

evolution of coronal mass ejections, powerful disturbances that travel from the Sun to Earth's orbit and beyond.

Explorer program missions now under development will supplement the STP missions. The **High Energy Solar Spectrographic Imager (HESSI)** will explore the basic physics of particle acceleration and energy release in solar flares using simultaneous, high resolution imaging and spectroscopy in x-rays and gamma rays with high time resolution. The **Two Wide-angle Imaging Neutral-atom Spectrometer (TWINS)** mission, in combination with IMAGE, will enable a three-dimensional visualization of Earth's magnetosphere and resolution of large scale structures and dynamics within it by applying techniques similar to those of the IMAGE mission from two widely spaced high-altitude, high-inclination spacecraft.

The frequent access to space provided by smaller space missions has accelerated scientific and technical innovation in the space sciences. Balloon-borne payloads provide similar benefits at still lower cost. Observing from the top of the stratosphere, a new generation of **Ultra-Long Duration Balloons (ULDB's)** that offer 100 days or more of observing time per flight is now under development. We expect this new capability to enable important and very cost-effective observations in such diverse areas as solar physics and infrared and hard x-ray astronomy.

All of the missions under development include substantial education and public outreach components that are well integrated with the activities of the science and technical teams. In support of these space science education and outreach efforts, we have established a national network of 10 institutions across the country to serve as a bridge between the education, public outreach, and space science communities. The goals of this institutional infrastructure are to improve effectiveness of the space science community's participation in education and public outreach, to coordinate the diverse education and public outreach activities undertaken by space science researchers across the country, and to assure national availability of the resulting programs and products.

Section II-2

principles and processe

Our approach to accomplishing Enterprise science goals is founded on a set of fundamental principles that encompass the role of space science within NASA, program planning and structure, project management axioms, our relationship to our scientific stakeholders, the role of technology, our responsibilities to the public, and guidelines for international cooperation. This section presents these principles and then describes our strategic and tactical planning processes.

S

General Principles

Use scientific merit as the primary criterion for program planning and resource commitment. The Space Science Enterprise is first and foremost a science program, among many activities conducted by NASA. The scope of NASA's mission as provided in the Space Act of 1958 ranges from pure knowledge to advancing the state of practical know-how in many areas for the benefit of U.S. industry. In this context, NASA's space science programs also contribute to other national purposes as secondary objectives. The primary means for establishing merit for Enterprise programs are open solicitation and competitive peer review.

Base the Enterprise Strategic Plan on science goals and objectives,

Peer Review

It is Enterprise policy that funding to support research and mission development be allocated by processes that use peer review to establish scientific merit. NASA uses the following uniform, Agencywide definition for peer review:

> *Peer review is a scientific evaluation by an independent in-house specialist, a specialist outside of NASA, or both, of proposals submitted in response to NASA research announcements, announcements of opportunity, and cooperative agreement notices. Peer review is also used to evaluate unsolicited proposals. Peer reviews evaluate relevance to NASA's objectives, intrinsic merit that includes scientific or technical merit of research methods, the researcher's capabilities and qualifications, and cost.*

All selected science investigations must achieve a top rating for peer reviewed science merit. In making final selections, however, other factors besides science merit also have a role. These factors include alignment with Enterprise goals, national and Agency policy, program balance, available budgets, technological readiness, various types of risk, and contributions to education and public outreach.

For the special class of the New Millennium technology flight validation missions, technology considerations provide the primary selection criteria.

and structure its research and flight programs to implement these goals. These plans are developed every three years. Science objectives are set in partnership with the scientific community, and mission formulation is based on these science objectives within policy and budget constraints established by the Administrator, the President's Office of Management and Budget (OMB), and Congress. In planning, the first rule is to complete missions already started, except in the case of insuperable technical or cost obstacles. The Enterprise defines missions via its strategic planning process (generally larger missions) and incorporates missions formulated by the scientific community (e.g., Explorer and Discovery). While recognizing that not all scientific objectives can be attained by small missions, the Enterprise emphasizes the "faster, better, cheaper" paradigm, where appropriate, to accelerate exploitation of new technological and scientific opportunities.

Aggregate consecutive missions that address related science objectives into "mission lines." It is much easier to explain broad science objectives and a program of related missions to Agency stakeholders and the general public than it is to convey the significance of individual missions, which is often much more technical. Further, a stable funding profile for a series of related missions promotes continuity and flexibility in budget and technology planning. In structuring the flight program into mission lines, the first priority is to preserve and extend existing lines. The second priority is to develop and establish new mission lines corresponding to new high priority science objectives. This is done by identifying and advocating compelling pathfinder missions for the new lines.

Preserve safety as NASA's number one priority; this includes mission success for robotic flight projects. Properly implemented, the "faster, better, cheaper" approach does not jeopardize this priority. Projects will not be approved for implementation until a clear technology path to successful implementation is demonstrated. Each Enterprise flight project will maintain reserves appropriate to its level of technical risk, and testing and reviews will be adequate to provide positive engineering assurance of sound imple-

Mission Formulation

Strategic, or *NASA-formulated*, missions are defined by NASA, with guidance from members of the space science community. Science payloads and investigations are then selected competitively by means of peer review in accordance with the principles set forth in NASA's Science Policy Guide. Examples of this category of missions are major space observatories, Mars Exploration Program missions, and Solar Terrestrial Probes.

Community-formulated missions, in contrast, are designed totally by science community-industry teams and selected by NASA through competitive peer review as complete packages. These missions add flexibility, rapid response to new opportunities, and frequent access to space. This category of missions includes the Explorer and Discovery lines.

All selected and implemented missions, whether NASA-formulated or community-formulated, address science goals and objectives in the Enterprise Strategic Plan.

mentation. In the event of project cost growth, reserves will be maintained by reallocation of resources within the project's science theme area, by schedule delays, or by descoping. If these measures are not sufficient, or if the necessary descoping diminishes expected scientific returns below the project's science requirements floor, the mission may be canceled. Resource shortfalls will not be relieved by deviating from proven space system engineering and test practices.

Ensure active participation of the research community outside NASA because it is critical to success. The outside community contributes vitally to strategic and programmatic planning, merit assurance via peer review, mission execution through participation in flight programs, and investigations supported by research grants programs. In addition, NASA science and technology programs conducted at the universities play an important role in maintaining the Nation's academic research infrastructure and in developing the next generation of science and engineering professionals, whether they pursue space research careers of their own or apply their technical skills elsewhere in the economy.

Maintain essential technical capabilities at the NASA Centers. NASA has significant scientific and technological capabilities at its Centers. NASA Center scientists provide enabling support to the broader research community by serving as project scientists and operating unique Center facilities, and compete with external researchers for funding to conduct their own original research. Center staff maintain "corporate memory" for Enterprise programs and provide essential engineering support as well.

Apply new technology aggressively, within the constraints of prudent stewardship of public investment. Research in space science pushes the boundaries of our technical capabilities. The relationship between science and technology continues to be bi-directional: scientific goals define directions for future technology investment and development, while emerging technology expands the frontier of possibilities for scientific investigation (sections I-3 and II-4). To maintain the balance between risk and reward, new technologies are demonstrated wherever possible via validation in flight before incorporation into science missions. This policy is implemented through the New Millennium program, in which technology demonstration is the primary objective and science plays a secondary role.

Share the results and excitement of our programs through the formal education system and public engagement. A fundamental consideration in planning and conducting all of our programs is the recognition that the national investment in space science is a public trust and the public has a right to benefit from our work. To discharge this commitment, we use not only print and electronic news media, but also museum and other exhibits and material for formal pre-college education. To ensure infusion of fresh results from our programs into these educational efforts, our policy is that each flight project must have an education and outreach component. The Enterprise has established a nationwide support infrastructure to coordinate the planning, development, and dissemination of educational material (sections I-4 and II-6).

Structure cooperation with international partners to maximize scientific return within the framework of Enterprise Strategic Plan priorities. The Space Act of 1958 provides that NASA shall cooperate in peaceful space activities with other nations. Today, most of the Enterprise's flight programs have international components (section II-7). In establishing these cooperative relationships, as indeed in all other aspects of our program, funding is allocated to U.S. participants in international programs through competitive peer review. Foreign participants in U.S. missions are likewise selected on the basis of merit. In general, NASA seeks to lead where possible, and participate with our partners through collaborative roles in other deserving areas.

Strategic Planning

From its beginnings, NASA space science has based its planning on a foundation provided by the National Academy of Sciences. The Academy's Space Studies Board (formerly the Space Science Board) and its committees critically assess the status of various space science disciplines, identify the most promising directions for future research, outline the capabilities required, identify technologies needed to attain those capabilities, and examine the role of each mission in the context of the total space science program. Enterprise science goals, objectives, and missions can all be traced to Academy recommendations.

Synchronized with the triennial revision of the Agency Strategic Plan mandated by the Government Performance and Results Act of 1993 (GPRA), the Enterprise revises its own Strategic Plan at the same interval. In addition to general information about program and planning processes, the Enterprise Plan lays out science goals and science objectives and mission plans for the near- and mid-term. The near-term is a five-year period that starts approximately two fiscal years from the date of issue of the Plan, while the mid-term extends about a decade beyond that. The Enterprise Plan describes near-term missions and how they address science goals and objectives in more detail than it does mid-term missions, which are presented briefly and schematically. Each release of the Plan also presents information about the Enterprise's technology needs and activities and a review of education and public outreach goals and programs.

The Enterprise works with the space science community to develop each Enterprise Strategic Plan. This work is done through NASA-formed advisory committees (the Space Science Advisory Committee and its subcommittees) with assistance from ad hoc planning groups, input from the general science community, and technical support from NASA's Centers. Development of the 2000 Plan illustrates the process.

Work on the 2000 plan began in late 1998, when the Enterprise's Science Board of Directors initiated the development of science and technology roadmaps for each Enterprise science theme (Astronomical Search for Origins, Structure and Evolution of the Universe, Solar System Exploration, and Sun-Earth Connection). These roadmaps—which were developed by roadmapping teams that included scientists, engineers, technologists, educators, and communicators of science—address science goals, strategies for achieving these goals, missions to implement these strategies, technologies to enable these missions, and opportunities for communicating with the public. Each roadmapping team was either built from or overseen by its theme subcommittee of the Space Science Advisory Committee. The teams each held a series of meetings to obtain science priority views from community scientists, hear advocacy presentations for specific missions, examine technology readiness for alternative mission options, and discuss relative science priorities, balance, and optimum activity sequencing in light of this information. One technique used to foster convergence was taking straw polls among team members during successive meetings.

At the end of the roadmapping period, each of the four theme roadmapping activities submitted a summary document outlining science and mission recommendations to the Space Science Advisory Committee and to Enterprise Headquarters management. Enterprise management then combined the mission recommendations of the roadmapping teams into an integrated mission plan, guided by the current OMB five-year budget profile, realistic estimates of most likely future resource availability beyond that, and additional Agency-level and Administration guidance. Likewise, science goals in the roadmaps were used to examine and restate those presented in the 1997 Enterprise Plan.

An integrated roadmap was presented and discussed at a planning workshop that expanded the membership of the Space Science Advisory Committee with other community members and representatives from the technology and education and public outreach communities. Attendees at the workshop also analyzed and revised the proposed updated science objectives, and derived a new set of shorter-term research activity areas. The resulting consensus mission plan and goals, objectives, and research activities serve as the nucleus for the current Strategic Plan.

A draft of this Plan was provided to the Space Studies Board and its committees for review and feedback, and guidance received was used in finalizing the Plan. The findings and recommendations of the Academy's recently completed ten-year astronomy and astrophysics survey were consulted to assure consistency with the draft Plan. Finally, the Space Science Advisory Committee had an opportunity to review the revised Plan and suggest any final changes before the Plan went to press.

Tactical Planning and Budgeting

Congress appropriates funding to NASA for its programs on a yearly basis. While each Administration-submitted budget provides a five-year profile for the Agency's programs, only the first is implemented each year by Congress. Somewhat more than a year before the beginning of a fiscal year, the Enterprise assembles a detailed budget proposal for submission to the Agency Administrator. Preparation of this budget, while based on the Enterprise Strategic Plan, is also guided by the previous year's budget estimate for the new year, policies and guidance provided by the Administrator and the OMB, and the current budget and technical status of missions in development or operating. Ongoing program balance and technology readiness are also considered. A GPRA performance plan for the same fiscal year is assembled in parallel with the new Enterprise budget request. Twelve months before the beginning of the new fiscal year, both the Agency budget and its GPRA performance plan are submitted to the OMB, and after a period of negotiations and adjustments, the President submits NASA's budget request with those of other Federal agencies to Congress for action.

Government Performance and Results Act of 1993 (GPRA)

This legislation requires each Federal agency to periodically develop and deliver to Congress three documents:

- A strategic plan that presents goals and objectives over a five year period; this plan must be revised at least every three years;
- A yearly performance plan that projects which measurable outcomes that support goals and objectives of the strategic plan will occur during the upcoming fiscal year; the performance plan is to be closely coordinated with the requested budget; and
- A yearly performance report, to be delivered six months after the end of the fiscal year in question, that summarizes the agency's achievements against projections in that fiscal year's performance plan.

Section II-3

flight program: 2003 and

Here we present missions that we expect to graduate from the study and design phase and begin building in 2003 and beyond. We have grouped these projects to show how they address our science objectives. While the section mentions for context some of the missions that will already be under development or flying by 2003, those that will proceed from study and preliminary design to implementation (detailed design and fabrication) beginning in 2003 are named in **bold** when they are first mentioned under each objective. Note, however, that although many of our missions address more than one science objective, no effort has been made to mention every mission in every connection in which it can make a contribution.

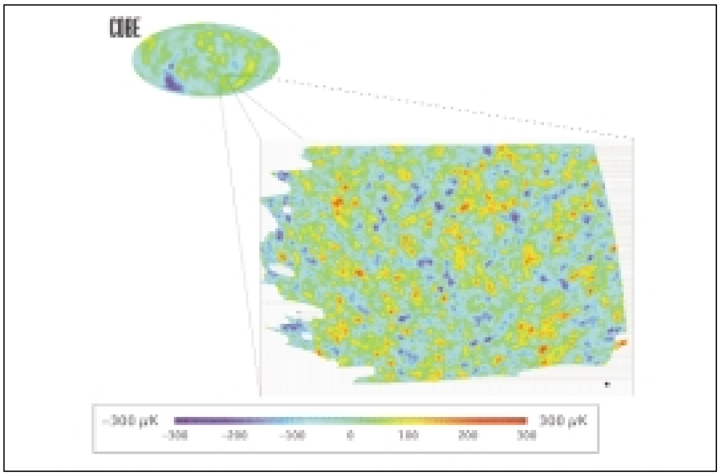
d beyond

This section emphasizes missions that will begin implementation in the period 2003-2007. Planning for the period 2008 through the following decade is necessarily less certain. The end of each subsection also presents ideas for missions in this more remote timeframe based on reasonable extrapolations from our current scientific understanding and nearer-term mission plans. These future mission concepts are also introduced in **bold** in their part of each subsection.

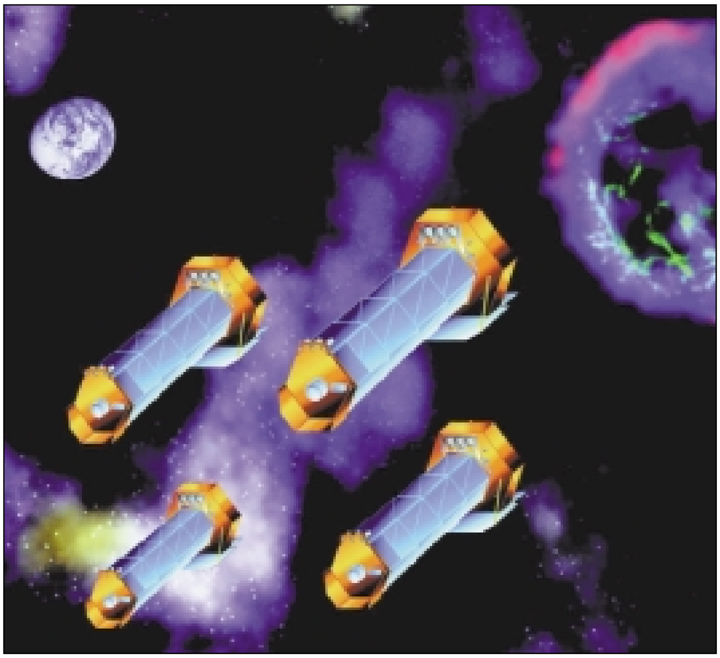
OBJECTIVE ONE: Understand the structure of the universe, from its earliest beginnings to its ultimate fate

The universe we see today is rich in structure, containing hundreds of billions of galaxies, each with hundreds of billions of stars. Clusters and super-clusters of galaxies are interspersed with vast, virtually empty voids, and the galaxies themselves can appear totally isolated or in the process of merging with local companions. Yet observations to date of the very early universe show it to have been very smooth and almost featureless. How did the later structure, the basic extragalactic building blocks of the universe, come to be? What laws of physics worked to fill the gap between the primitive universe and the complexity we observe in the present?

With the Cosmic Background Explorer (COBE), we have cap-



Detailed analysis of the cosmic microwave background can determine the geometry of the universe to high precision and shed light on the nature of the matter and energy that fill the universe. BOOMERANG observed this background over approximately 2.5 percent of the sky with angular resolution 35 times finer than COBE, and MAP and Planck will continue to extend and refine these measurements.



The Constellation-X spacecraft will work in unison to simultaneously observe the same distant objects. By combining their data, these satellites become 100 times more powerful than any previous single x-ray telescope.

tured a glimmer of the earliest clumpings in the remnant primordial fireball through ripples in today's pervasive microwave background. Balloon-borne instruments such as BOOMERANG map a small portion of the cosmic microwave background radiation, the fossil remnant of the Big Bang. The Microwave Anisotropy Probe (MAP) Explorer and the ESA/NASA Planck mission will extend these measurements and permit precise determination of a number of critical cosmological parameters that constrain models of the early universe.

But there is a missing link between the first condensations of matter after the Big Bang and the galaxies and clusters we see in the present. With the ability to identify the dark matter and learn how it shapes the galaxies and systems of galaxies, we will begin to determine the size, shape, and energy content of the universe. Ground-based surveys such as the Two Micron All Sky Survey (2MASS), Sloan Digital Sky Survey (SDSS), and Explorer-class space missions will provide an inventory of low-mass objects in the neighborhood of the Sun. Mass in the gaseous state will be studied at a variety of wavelengths, corresponding to the temperature of the gas. These range from millimeter waves observed by ground-based interferometers to the x-rays from hot cluster gas seen by the Chandra X-ray Observatory (CXO).

An important advance will be to estimate the total mass in galaxies, clusters of galaxies, and even in non-luminous, dense regions by measuring the gravitational bending of light from background galaxies. Observing this "gravitational lensing" is among many motivations for the **Next Generation Space Telescope (NGST)**, along with investigating the birth of galaxies, the fundamental structures of the universe. These observations must be made at near-infrared wavelengths and require a telescope with a large aperture (for sensitivity to faint objects), excellent angular resolution, and the stable images of a space observatory.

The evolution of the universe will also be probed by **Constellation-X**, the x-ray equivalent of a very large optical telescope. It will improve significantly on the spectral information returned by the current ESA X-ray Multi-Mirror Mission (XMM) and complement the high spatial resolution of CXO. Constellation-X will explore the epoch of formation of clusters of galaxies and how they evolve. The mission will trace black hole evolution with cosmic time and provide new insight into the contribution that the accretion of matter around black holes and other compact objects makes to the total energy output of the universe. Technological advances that will be needed for Constellation-X are under development: x-ray optics, x-ray calorimetry, reflection gratings, detectors for high-energy x-rays, cryogenic coolers, and focusing optics for hard x-rays.

For Possible Implementation After 2007

The very highest energy cosmic rays are extremely rare, and a huge detector would be needed to observe any significant number of them. Earth's atmosphere, with millions of square kilometers of exposed area and an interaction target up to 10^{13} tons, can act as a giant detector for the extreme energy cosmic rays and neutrinos. We do not know where these particles come from or how they are accelerated. It has been suggested that they might come from the annihilation of space-time defects formed at the beginning of the universe, so observing these mysterious particles with an **orbiting wide-angle light collector** could probe the Big Bang itself.

Beyond 2007, expected advances in detectors, interferometry, lightweight optics and cryogenics will allow a mission that can extend the Hubble Space Telescope-like (HST) resolution into the mid- and far-infrared to resolve the infrared background and to learn the history of energy generation and chemical element formation

Cosmic Journeys

The new Cosmic Journeys initiative is a series of major astrophysics observatories that will address aspects of three Enterprise science objectives:

- Understand the structure of the universe, from its earliest beginnings to its ultimate fate;
- Explore the ultimate limits of gravity and energy in the universe; and
- Learn how galaxies, stars, and planets form, interact, and evolve.

Beyond the fundamental scientific importance of these goals, can we discover new physics that we could use? For example, to send machines or people beyond our Solar System to even the nearest star at today's fastest speeds would take tens of thousands of years. As a result, we are particularly interested in the physics of these extreme phenomena:

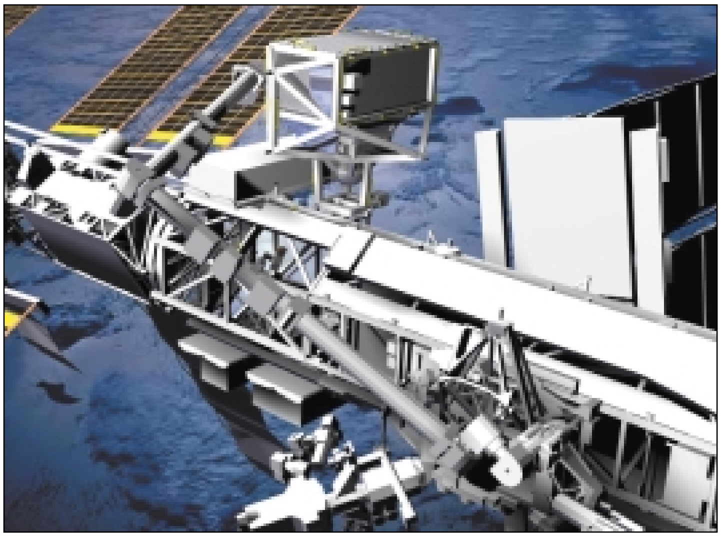
- The source of cosmic gamma ray bursts;
- The acceleration of ultra-high energy cosmic rays;
- Energetics of black holes; and
- Gravitational waves: whether they exist, and whether they travel at the speed of light.

in the universe. A pathfinder mission using one of two alternate technologies would provide much greater angular resolution than that of the Space Infrared Telescope Facility (SIRTF), as well as better sensitivity and signal-to-noise. This descendant of the HST, discussed further in connection with Objective Three, could be either a **space infrared interferometric telescope** or a **filled-aperture infrared telescope**. Technical requirements on the mirrors for such an instrument are challenging, but the necessary capabilities may evolve from earlier development for the NGST and the Terrestrial Planet Finder (Objective Four).

Measuring the **cosmic microwave background polarization** could provide an important test of the inflation theory, possibly detecting cosmological background gravitational waves produced when the universe was much less than a second old.

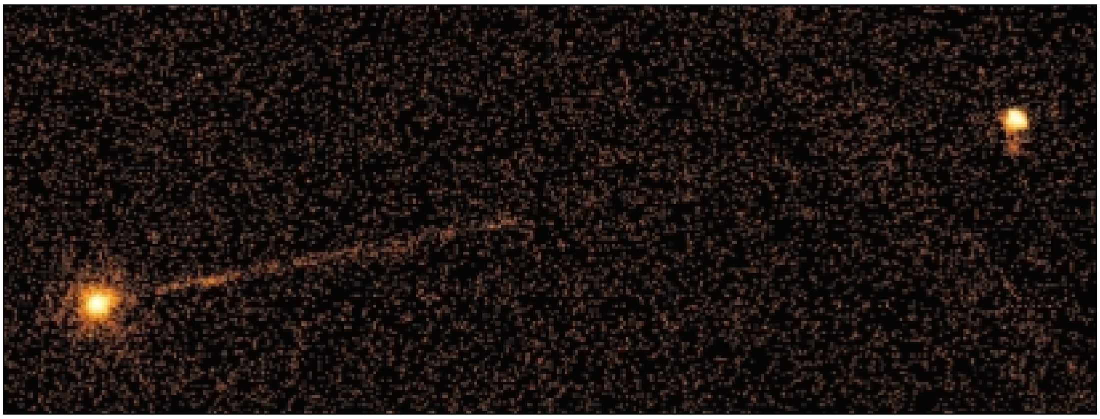
OBJECTIVE TWO: Explore the ultimate limits of gravity and energy in the universe

Cosmic rays, whose origin has long been a mystery, are important tracers of the dynamics and structure of our galaxy. The magnetic fields and shock structures with which cosmic rays interact along their journey are not directly visible to us, so we must study these fields and structures by detailed measurement of the arriving particles themselves. We currently believe that most cosmic rays are accelerated by the shock fronts produced by supernovae. The **Advanced Cosmic Ray Composition Experiment for the Space Station (ACCESS)** is being designed to explore this connection of cosmic rays with supernovae. ACCESS will have the sensitivity needed to study cosmic rays up to the highest energies believed achievable by supernova shock acceleration, and will enable us to analyze their composition and thus address the origin, acceleration, and ultimate fate of the individual nuclei, from hydrogen to iron and heavier ions. ACCESS will require a number of technological advances. For the charged particle detectors and calorimeter, silicon pixel detectors with a large dynamic range readout and good spatial resolution will be needed. Advances are also needed in readout electronics for gas-filled detector tubes used in the transition radiation detectors.



ACCESS instrument mounted on the International Space Station will explore the connection of cosmic rays with supernovae.

Do gravitational waves exist, and what is the structure of space-time near black holes? Complementing the ground-based gravitational wave detectors that will become operational within the next few



The Chandra x-ray image of Pictor A shows a spectacular jet that emanates from the center of the galaxy (left), probably a black hole, and extends across 360 thousand light-years toward a brilliant hot spot (right). The hot spot is thought to be the advancing head of the jet, which brightens where it plows into the tenuous gas of intergalactic space. By observing dramatic phenomena like this spectroscopically, Constellation-X will enable us to unravel their underlying physical causes.

years, the **Laser Interferometer Space Antenna (LISA)** will be able to observe low-frequency gravitational waves not detectable from the ground. A joint NASA-ESA undertaking, LISA will search for gravitational waves from massive objects, ranging from the very early universe before light could propagate, to super-massive black holes in the centers of galaxies, as well as short-period compact binary stars in the Milky Way. Three key technologies are needed to make LISA a reality. First, the experiment will require inertial sensors whose proof masses can be isolated from all forces other than gravitation. Micro-thrusters must keep each of LISA's three independent spacecraft centered on its proof mass. Then, to measure the motions of the isolated and widely separated proof masses, laser metrology to measure subpicometer changes between them is needed.

Constellation-X observations of broadened x-ray emission lines of iron in active galactic nuclei will measure black hole masses and spin, on the basis of relativistic effects that occur in the limit of very strong gravity fields.

For Possible Implementation After 2007

The key to understanding how condensed objects like quasars and pulsars work is to obtain more detailed observations of them. By using an orbiting telescope as part of a **space very long baseline interferometer (SVLBI)**, radio astronomy can achieve resolutions of about 25 microarcseconds. Such a mission could show us how matter is accreted onto black holes, how relativistic jets of matter are formed, and how gamma rays are produced near black holes. SVLBI can also investigate stellar evolution and the interstellar medium through observations of masers, pulsars, and close binary stellar systems. Among technical innovations in amplifiers and coolers, such a system would require very fast (gigabits per second) downlink communications to Earth.

Beyond this, the prize is to directly image a black hole, whose existence heretofore has been based on indirect evidence. This will require about

0.1 microarcsecond resolution, or almost ten million times better than CXO, which is itself about a factor of ten improvement over the earlier Einstein observatory. This is a technology leap that cannot be achieved in one step, so the plan is to focus on a mid-term mission as an intermediate step to this goal. The strawman configuration for a **microarcsecond x-ray imaging mission pathfinder** is a working interferometer with 100 microarcsecond resolution and about 100 cm^2 effective area. This would provide a substantial advance in scientific capability of its own, and allow us to detect and resolve an accretion disk around the massive black hole at the center of the Milky Way. It would also give us detailed images of jets, outflows, and broad-line regions in bright active galaxy nuclei, and to map the center of cooling flows in clusters of galaxies. The technology development for this investigation involves primarily matters of scale. The detectors would build upon both the Constellation-X micro-calorimeter and the CCD's designed for CXO, but with much larger arrays. Approaches to the technology for x-ray interferometry have been demonstrated in the laboratory.

A **high-resolution x-ray spectroscopy mission** (see Objective Three) would provide diagnostics of supernova mechanisms and a new view of accreting neutron stars and black holes in our galaxy, as well as the local group of galaxies.

The only full-sky survey we have in high energy x-rays dates from 1979. Observations of these hard x-ray emissions are key to studying accreting neutron stars, galactic black holes, active galaxies, and creation of the chemical elements. The needed x-ray observations in the 10-500 KeV range could be acquired by a proposed **energetic x-ray imaging survey telescope**.

As described in the previous section, an **orbiting wide-angle light collector** would enable us to observe the very highest energy cosmic rays. Observing these mysterious particles would be an investigation of the highest energy processes in the universe and a probe of the Big Bang within the framework of Grand Unified Theories of fundamental physics.

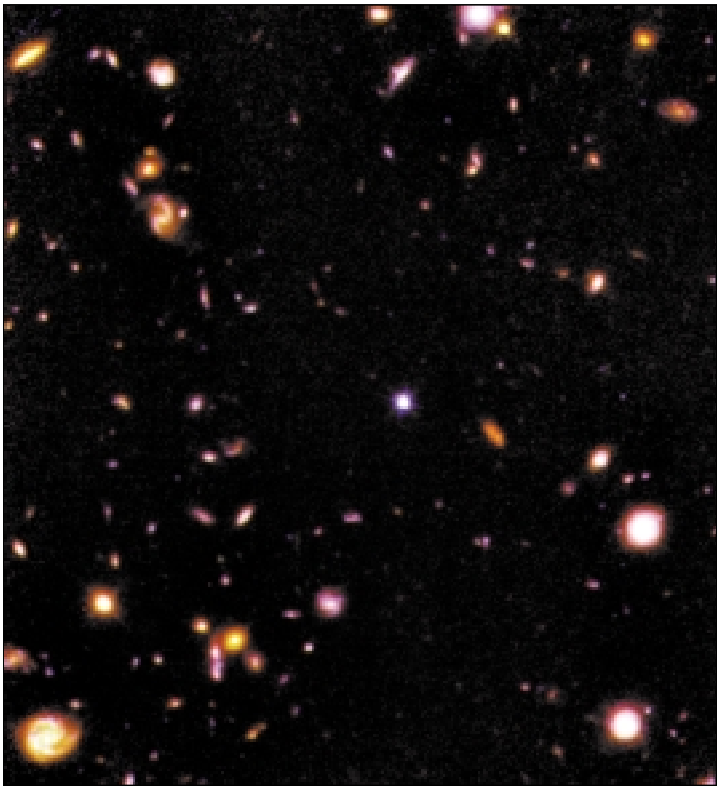
OBJECTIVE THREE: Understand how galaxies, stars, and planets form, interact, and evolve

One of our fundamental science goals is to understand how structure first arose in the extremely dense but featureless early uni-verse. Images that show that galaxies looked very different billions of years ago from our familiar modern universe are clues to the link between the first condensations of matter after the Big Bang and the galaxies and clusters of galaxies we see today. The HST has shown that after galaxies form, they can be observed colliding with one another or being badly disrupted. SIRTF will expand on these investigations by studying the evolution of the most energetic galaxies. But these important observations will not fully answer the core question of how galaxies—the fundamental building blocks of the universe —originated.

One possible concept for an NGST design, showing the telescope beneath a large Sun shade.

The HST's aperture is too small to gather enough faint light from the remote past to detect galaxies in the process of formation. To do so, we will need observations at near-infrared wavelengths from a telescope with a larger aperture (to provide sensitivity to faint objects) and superb angular resolution (to observe structure in distant objects)—the **Next Generation**

Space Telescope (NGST). First of the Origins Observatories, NGST will have about ten times the light-collecting area of HST and will be most sensitive at the infrared wavelengths where galaxies being born are expected to be brightest. Also, although the HST and ground-based observatories have revealed much about the formation of stars and their potential retinues of planets—and SIRTF and SOFIA will reveal much more—essential processes and events in the early lives of stars and planets are poorly known. Very young stars, as well as planets in the process of formation, will be important targets for NGST's powerful infrared instruments. When stars are first born, they are cocooned in the dusty gas clouds from which they formed. This dust very effectively absorbs visible light but emits copious infrared radiation. NGST will be able to peer into the clouds in which the youngest stars and planets are found, and will reveal their location, mass, chemical composition, and dynamics. (As an example of scientific synergy, Cassini's observations of Saturn's rings will help us interpret observations of these clouds by providing a close-up view of the behavior of dust, ice, and magnetic fields in a relatively nearby setting.) To achieve NGST's demanding scientific goals, we are developing very lightweight optical structures, new generations of infrared detectors, energy-efficient cooling techniques, and precision deployable structures.



An image of the darkest portion of the sky reveals the structure of young galaxies at cosmological distances, as shown by the near infrared camera (NICMOS) on the Hubble Space Telescope. Some of the reddest and faintest objects may be over 12 billion light-years away.

NGST observations will be complemented by data from the ESA/NASA Far Infrared and Submillimeter Telescope (FIRST). Observing at longer wavelengths where many galaxies emit most of their radiation, FIRST will be well suited to finding high redshift galaxies and studying the most luminous galaxies, complementing NGST's searches in the near-infrared. The ESA-led INTEGRAL gamma ray mission will be supplying information on stellar formation via both high-energy spectroscopy and imaging.

The **Space Interferometry Mission (SIM)** will serve important objectives in both technology and science. For technology, it will demonstrate precision metrology and aperture synthesis imaging, both vital for future optical space interferometer missions. Its science contributions stem from its anticipated tiny positional error circle for observed objects, only four micro-arcseconds; this is about 100 times better than the Hipparcos astrometry mission. This precision will make SIM a powerful tool for studying the distances, dynamics, and evolution of star clusters in our galaxy, helping us understand how stars and our galaxy were formed and will evolve. It will extend our census of nearby planetary systems into the range of small, rocky planets for the first time. SIM will also improve the calibration of luminosities of standard stellar distance indicators to enable us to more accurately measure distances in the universe.

The **Terrestrial Planet FInder (TPR)** (see Objective Four) will build on these missions to extend our understanding of planetary systems.

With a hundred-fold increase in sensitivity for high resolution spectroscopy over previous observatories, **Constellation-X** will look across a broad range of redshifts to date the formation of clusters of galaxies. Matter predicted by Big Bang creation and subsequent stellar processing seems to be missing, and Constellation-X will search for it in the hot, metal-enriched intergalactic medium. Constellation-X will also be able to analyze the chemical composition of stellar coronae, supernova remnants, and the interstellar medium by observing x-ray spectral lines.

For Possible Implementation After 2007

An exciting new approach to studying the origin of the chemical elements (nucleosynthesis) is embodied in a concept for a **high-resolution x-ray spectroscopy mission**, which would enable sensitive spectroscopic and imaging observations of emitted radiation related to nucleosynthesis. Many of these spectral features lie in the hard x-ray range. Observations of the spectra of young supernova remnants, and studies of the time-evolution of prompt emissions from recent explosions, would provide diagnostics on the production and distribution of heavy elements, and on the explosion mechanism itself. Such a mission would also provide sensitive spectral studies of active galaxies and measurements of magnetic field strengths in galaxy clusters. Technology development is needed for both the optics and the focal plane sensors. More complex multilayers will be needed to extend instrument response to the 200 KeV region. Germanium sensors will need the development of contact technologies and very large scale integration readout electronics operable at cryogenic temperatures.

An **x-ray interferometry pathfinder** system, such as the one described for Objective Two above, would add importantly to our knowledge of stellar structure, stellar plasma interactions, jets and outflows from active galactic nuclei, cooling flows in clusters of galaxies, as well as locate and resolve star formation regions.

Within our own galaxy, we are at the brink of understanding how planetary systems form. We have obtained spectacular images of stellar nurseries, and possibly of dust disks in the process of creating new planetary systems. We are beginning to peer more deeply into dusty clouds to identify the youngest members of new stellar clusters and probe the structure and basic physical properties of star forming regions. A **filled-aperture infrared telescope**, which would also serve Objective One above, would determine how planetary system-forming disks evolve. With its keen infrared vision, it would probe deeper into protostellar disks and jets to investigate the physical processes that govern their formation, evolution, and dissipation, as well as those that determine their temperature, density, and compositional structure. As outlined above, a competing concept with the same science goals would be a **space infrared interferometric telescope**, whose high sensitivity, spectral, and angular resolution would allow the far infrared background to be resolved almost completely into individual sources. Major technology development for both is needed in the areas of ultra-lightweight aperture technology, active sensing wavefront control, passive and active cooling, and enabling detector technologies. These technologies will build upon the ones developed for preceding missions such as NGST, SIRTF, and the Terrestrial Planet Finder.

Once the NGST has given us an understanding of the formation of the first galaxies in the early universe, we will be challenged to trace galaxy evolution back to the initial era of star formation, super-massive black holes, and metal element production in the present epoch. Capable of high resolution ultraviolet spectroscopy at a sensitivity a hundred times that of the HST, a follow-on **space ultraviolet optical telescope** would enable astronomers to follow the chemical evolution of the universe and determine its fate. Tracing the distribution of visible matter would make it possible to quantify the birth rate of galaxies and the energetics of quasars. It might also shed light on the distribution of the underlying dark matter.

Ultimately, we would like to make in situ measurements of matter and magnetic fields outside the bubble of space filled by the Sun's solar wind. An **interstellar probe** mission would explore the structure of the heliosphere and go on to sample matter and magnetic fields in the interstellar medium directly, for the first time. To travel this distance in just two decades will require a new approach to propulsion, perhaps solar sails.

Origins Observatories

The Origins Observatories are a series of astronomical telescopes in which each successive mission builds on the technological and scientific capabilities of previous ones. The vision is to observe the birth of the earliest galaxies in the universe, to detect all planetary systems in the solar neighborhood, and to find those planets that are capable of supporting life. To achieve this vision, the Origins Observatories line includes these components:

- A series of spectroscopic, imaging, interferometric missions, observing at visual and infrared wavelengths to answer the vision's fundamental scientific questions.
- A systematic technology development program in which technology enabling one mission leads naturally into the technology needed for the next one.
- Basic research to understand new observations.
- A comprehensive education and public outreach effort.

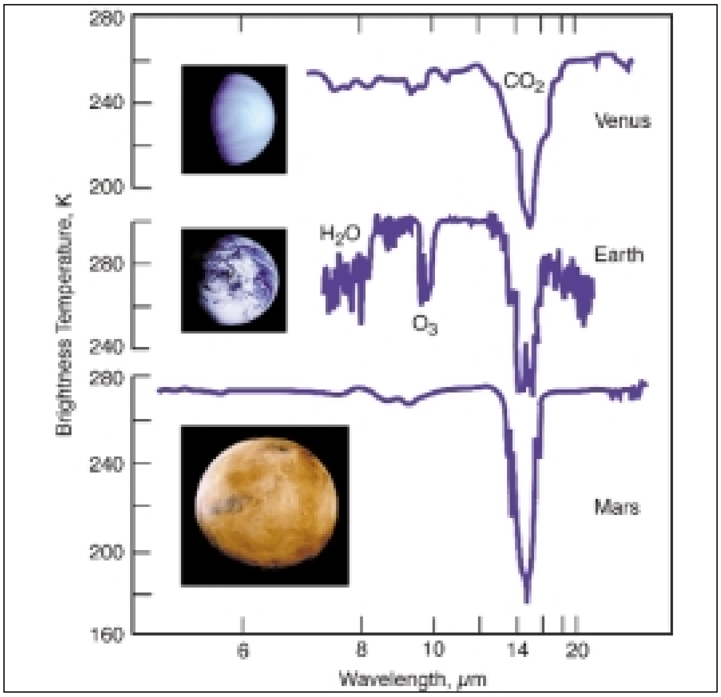
OBJECTIVE FOUR: Look for signs of life in other planetary systems

Determining whether habitable or life-bearing planets exist around nearby stars is a fundamental Enterprise goal. In addition, learning about other nearby planetary systems will provide precious context for research on the origin and evolution of our own Solar System. By measuring the velocity variation of a star's motion caused by the gravitational effect of unseen companions, ground-based observations have revealed dozens of circumstellar objects in the solar neighborhood that are much less massive than stars, but still far heavier than Earth. It is not certain, however, that the objects so far discovered are "planets" as we usually think of them, and new generations of missions will be required to discover orbiting objects that are more like Earth.

In 2003, several important projects that promise to detect planets substantially lower in mass than those known today will be nearing operation. These include the Keck Interferometer and the Full-sky Astrometric Mapping Explorer (FAME) mission.

While detecting the presence of Earth-mass planets is an important objective, determining their key characteristics—above all, the possibility of life—is much more difficult. **Astrobiology** research is developing a working catalogue of possible atmospheric signatures that would be indicative of life on a planetary scale. For example, today's Earth is recognizable as living primarily because of its oxygenated atmosphere, but this was not always the case. Astrobiology is seeking to discover what Earth's biosignature would have looked like at a time when free oxygen was negligible and other biogenic products would have been present in atmosphere.

Looking outside the Solar System, the discovery of numerous low-mass "non-stellar" bodies orbiting other stars is challenging our understanding of planet formation and implying that planetary systems may be commonplace. With our Solar System as a model for the propensity for



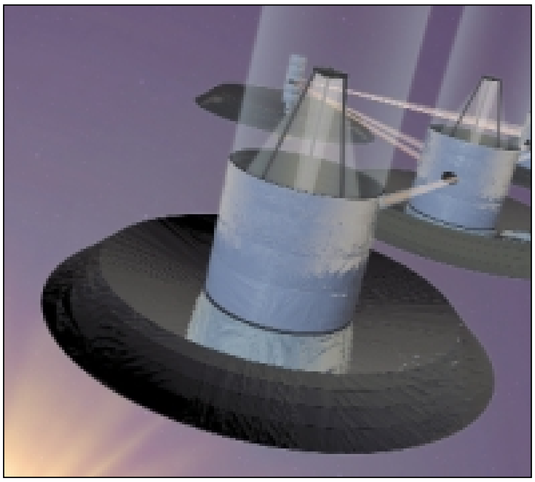
The atmospheric infrared spectra of Venus, Earth, and Mars all show a dominant carbon dioxide feature. In addition, Earth's spectrum exhibits water and ozone—the simultaneous presence of all three gases indicates a living planet.

life, we can conjecture that there are other worlds in our galactic neighborhood capable of supporting life. Our exploration of the diversity of planetary systems around other stars will emphasize systems that may have characteristics necessary for life. In additional to contributing to our knowledge of the structure and dynamics of our galaxy, **SIM**, described under Objective Three, will be the first observatory capable of indirectly detecting planetary bodies with only a few times the mass of Earth in orbit around other stars.

Continuing the Origins Observatories line, the **Terrestrial Planet Finder (TPF)** will extend the search for signatures of life beyond our Solar System. TPF will be an interferometric telescope array that will separate the infrared light of a planet from that of the star that it orbits in order to measure the spectrum of the planet. It will be able to search about 200 nearby stars for planets that possess warm atmospheres containing significant amounts of water or oxygen, which would indicate the possible presence of biological activity of some kind. To do so, the design for TPF will build upon large aperture, cryogenic optics, and infrared detector technologies also needed for the NGST, the beam control and nulling capabilities of the ground-based Keck Interferometer and SIM, and the precision free-flying demonstration of the **Space Technology-3 (ST-3)** mission.

For Possible Implementation After 2007

The first decade of the new millennium should have yielded tantalizing clues about the nature of the planets in the solar neighbor-



Left: The Space Technology-3 (ST-3) mission will test new technologies by flying two spacecraft in formation and using laser beams to keep the spacecraft aligned in precise positions relative to each other.

Right: By combining the high sensitivity of space telescopes with the high resolution of an interferometer, TPF will be able to reduce the glare of parent stars by a factor of more than one hundred-thousand to see planetary systems as far away as 50 light-years. TPF's spectroscopy will allow atmospheric chemists and biologists to analyze the relative amounts of gases like carbon dioxide, water vapor, ozone, and methane to ascertain whether a planet might support life.

hood, and about the presence—or absence—of life there. However, the TPF will be only the first step toward a detailed understanding of planetary systems in our neighborhood. The modest collecting area of the elements of TPF will permit only the first reconnaissance of these systems. The next step in studying other planetary systems will be observatories with significantly larger apertures and wider wavelength coverage.

The sensitivity of astronomical observatories depends strongly on the size of the light-collecting aperture, so that much larger successors to TPF would be able to observe far more target systems and search for rarer chemical species in planetary atmospheres. This will allow a less ambiguous interpretation of planetary spectra and permit a much wider range of planetary types to be observed. Two concepts on the horizon are a spectroscopic mission, a “**life finder**,” and later, a complementary “**planet imager**.” The prize from this new generation of observatories would be a truly comprehensive picture of planetary systems, including their physical characteristics and more conclusive signatures of life outside our Solar System. These missions to follow TPF will depend on even more ambitious optical systems, in particular, mirrors tens of meters in diameter. Since current space telescope technologies appear limited to smaller collecting areas, large optical systems technology will continue to have high priority for the Space Science Enterprise. Astronaut-assisted deployment or positioning approaches might be of great value in assembling and operating these future observatories, and advanced remotely-supervised robotic systems may also be available in that time frame.

OBJECTIVE FIVE: Understand the formation and evolution of the Solar System and Earth within it

Earth and all of the other bodies in the Solar System formed at about the same time from the same reservoir of material—a disk of gas and dust encircling the early Sun. These bodies have similarities, but also exhibit striking differences. For example, Jupiter and Saturn both have massive hydrogen-helium atmospheres apparently surrounding ice and rock cores, while Uranus and Neptune are mostly large ice and rock cores with much less surrounding gas. All of these outer planets, in turn, differ dramatically from Earth and the other “rocky” bodies that inhabit the inner Solar System. What were the differences in formation and evolution that led to these and other striking differences among the diverse bodies of the Solar System?

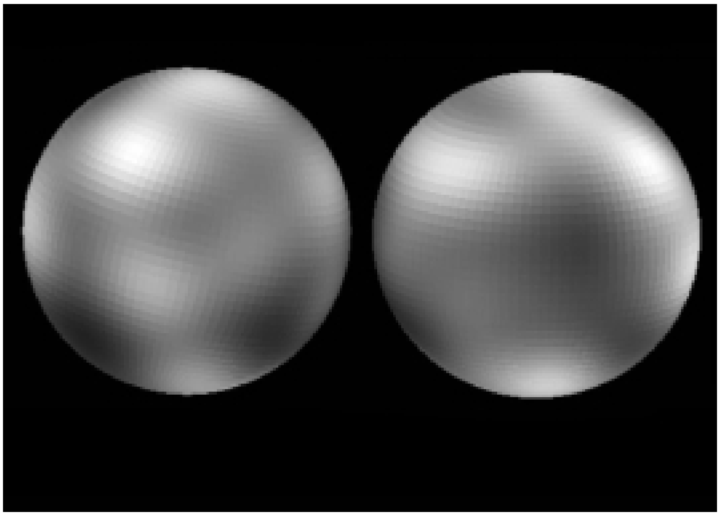
Looking more closely at the inner planets, we see that they are similar in size, but differ dramatically from one another in their atmospheres and surface properties. We believe that these rocky planets probably shared common origins but followed very different paths to the present. What evolutionary processes account for these differences? Are these processes still at work, and what do they imply about our future on Earth?

Superficially so different from Earth, Mars appears to have been much more Earthlike earlier in its history. One of the major objectives of the **Mars Exploration Program (MEP)** is to trace the evolutionary history of our neighbor planet. The Mars scientific community has adopted a "seek, in situ, sample" approach that employs surface and orbital reconnaissance to gain an understanding of the planet that will lead to multiple sample returns. To support this strategy, high-resolution orbital imaging will follow up on Mars Global Surveyor results that suggest the presence of near-surface water in recent times. Increasingly advanced landers will be interspersed with these orbital missions. One aspect of the program approach is to establish high bandwidth data return capabilities to support the “seek, in situ, sample” approach.

Key capabilities for near-term Mars missions include precision guidance and landing, surface hazard avoidance or tolerance, surface and atmospheric mobility, and aero-entry systems. Aerocapture would reduce propellant requirements. We need advances in systems for in situ analysis of materials that can help guide the selection of the small samples that we will be able to return. Sample return missions will also require development of high-specific thrust, compact ascent propulsion systems. A variety of advanced information system and communications technologies, including autonomy, inter-spacecraft communication systems, and optical communications, will be applied to future missions.

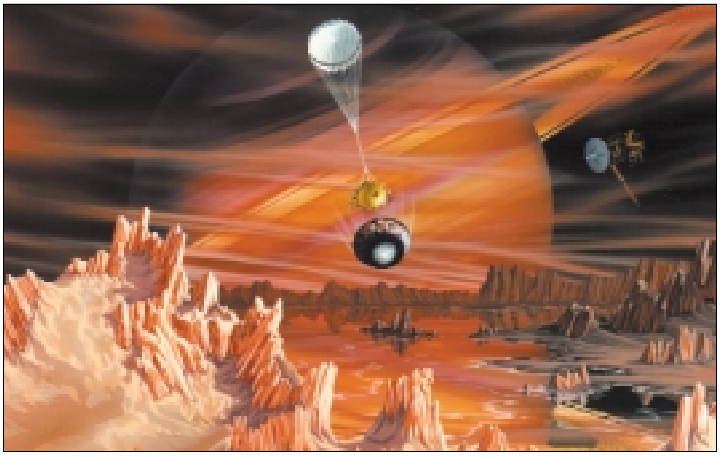
Valuable information about the early history of the Solar System resides at its boundaries. A **Pluto-Kuiper Express** mission would carry out the first reconnaissance of the last planet not visited by spacecraft and scout the inner edge of the Kuiper Belt. Pluto and its large satellite Charon represent a poorly understood class of remote and icy dwarf planets. The Kuiper Belt is a flattened disk of icy debris, believed to be in a primitive state, remaining from the processes that formed the major planets in our Solar System.

Other candidate missions in the **Outer Planets Program** to follow the Europa Orbiter include the **Titan Explorer** and **Europa Lander**. These missions would



Left: High-resolution images from the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) suggest that liquid water has seeped onto the surface in the geologically recent past.

Right: The surface of Pluto is resolved in these Hubble Space Telescope pictures. These images show that Pluto is an unusually complex object, with more large-scale contrast than any planet besides Earth. Variations across Pluto’s surface may be caused by topographic features such as basins or fresh impact craters. However, most of the surface features, including the northern polar cap, are likely produced by a distribution of frosts and chemical byproducts.



Artist's concept: The Cassini spacecraft flies by with its high gain antenna pointed at ESA's Huygens probe as it reaches the surface of Titan. Saturn is dimly visible in the background through Titan's thick atmosphere of methane, ethane, and (mostly) nitrogen. Cassini is a joint mission of NASA, the European Space Agency, and the Italian Space Agency.

build on the results from preceding missions to conduct in-depth analyses of these icy, organic-rich environments to determine whether they hold the possibility of life. Mission sequence decisions will be based on continuing scientific discoveries and the progress of our technology programs. For example, exciting results from the Cassini-Huygens mission arriving in the Saturn system in 2004 might advance the Titan Explorer ahead of other missions under study.

Highly capable, autonomous micro-avionics and very efficient on-board power subsystems are key to all future outer planetary missions. Multi-megarad radiation tolerance is a stringent requirement for all missions that operate in the Jovian environment. Avionics technologies projected for readiness in 2003 could support the Europa missions, while further advances will be required for the Titan Explorer. The Titan mission will rely on advanced solar electric propulsion and aerocapture. Special requirements for Europa Lander readiness include progress in bioload reduction and advanced chemical propulsion for landing on this massive airless body.

The so-called primitive bodies, comets and asteroids, contain important clues to the early history of the Solar System. It is hypothesized that comets and asteroids were the fundamental "building blocks" of planet formation and that most of these bodies that we see today are the debris left over from this process. Impacts on Earth by comets may have delivered the materials needed for the origin of life here: water, atmospheric gases, and perhaps organic chemicals. The Deep Impact mission, which will advance the

Outer Planets Program

Exploration of the outer Solar System has revealed that the outer planets and their moons are rich in organic material, that subsurface liquid water may exist in some places, and that prebiotic chemical processes occur in some of these environments. The Galileo spacecraft has returned fascinating information about the moon Europa. The Cassini-Huygens mission, now en route to Saturn, will extend this exploration through intensive investigations of the organic-rich atmosphere and surface of Saturn's giant moon, Titan.

Continuing this exploration thrust, the Outer Planets program will focus on prebiotic chemistry in likely places in the outer Solar System. Mission sequence decisions will be based on ongoing scientific discoveries and technological progress. Destinations for missions in this line include returns to Europa and Titan, reconnaissance of the Kuiper Belt, and a more comprehensive study of the Neptune system, including its moon Triton.

study of the composition of primitive bodies pioneered by earlier missions to Halley's comet, will be launched in mid-decade. To take the next step, a **Comet Nucleus Sample Return** is a high priority new implementation start to complement ongoing Solar System exploration programs. The goal of this mission, which could initiate a new "To Build a Planet" mission line, is to return a pristine sample of material from a comet nucleus for detailed chemical analysis. The Comet Nucleus Sample Return will depend on micro-avionics, advanced computing, and spacecraft autonomy technologies that are currently being developed. Advances in solar electric propulsion that focus on increased lifetime and reliability are needed. Other key capabilities include an Earth-entry system that can survive very large entry speeds into our atmosphere.

The composition and physical and chemical processes of comets are key to unlocking the secrets of the early Solar System. This dramatic pioneering image of the nucleus of Halley's Comet was obtained by the ESA Giotto spacecraft in March 1985.

For Possible Implementation After 2007

According to current planning, the Europa Orbiter, Pluto-Kuiper Express, Titan Explorer, and Europa Lander could be followed within the Outer Planets line by a **Neptune orbiter.** This mission is an important component of our investigation of the outer Solar System, including Neptune's moon, Triton, which may be an icy, organic-rich, captured Kuiper Belt object.

A number of other exciting opportunities are being considered for implementation as follow-ons in the "To Build a Planet" line after 2007. For example: so Earth-like in some respects, but so alien in others, Venus presents a genuine puzzle. Why did a planet with strikingly Earth-like size, composition, and geological activity develop a radically different surface and atmospheric environment? Understanding this evolutionary divergence has important implications for the study of life-sustaining environments as well as for our understanding of Earth's fragile, changing environment. A **Venus surface sample return** mission would help us to answer fundamental questions about the evolution of Earth-like planets.

Understanding the behavior of gas, dust, and radiation together is an important key to understanding the formation of the Solar System. In some ways, the rings of Saturn constitute a laboratory for the behavior of uncoalesced material in the primitive solar nebula. A **Saturn ring**

observer mission could perform detailed investigations of complex dynamic processes in Saturn's rings. In effect, we would be able to peer back in time to the epoch of planetary formation, when the material now contained in the planets was spread out in a disk encircling the Sun. It would also provide critical "ground truth" for a variety of observational and theoretical astrophysical studies. The Venus and Saturn ring missions would continue the "To Build a Planet" line.

The **Mars Exploration Program** will continue its search for evidence of water, the quintessential ingredient for life. A Mars synthetic aperture radar orbiter mission could detect buried water channels and help direct our search for ancient and modern water reservoirs. Advanced missions that could follow initial sample return missions could drill deeply (perhaps 10 to 100 meters) into the Martian cryosphere and hydrosphere to follow up results from earlier sample return missions. Surface, subsurface, orbiting, and airborne elements would extend our ability to carry out wide-area exploration and sampling in three dimensions. Far-term missions will require many of the technology advances that will be developed for the nearer-term, as well as further progress in the areas of thermal control, inflatables, aerobraking, precision landing, autonomy, advanced electric propulsion, advanced power systems, optical guidance, and control.

Other mission candidates for later implementation include a Jupiter polar orbiter for long-term detailed investigations of Jupiter's interior, atmosphere, and magnetosphere; giant planet deep probes to measure bulk composition, chemical processes, and atmospheric dynamics of the giant planets; a lunar giant basin sample return to collect samples from a very old impact basin far from previously sampled sites on the Moon; and a multiple asteroid mission/protoplanet explorer to investigate the relationship of main-belt asteroids to planetary evolution. As technological progress continues, some of these missions come within the scope of the Discovery program.

OBJECTIVE SIX:
Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our Solar System

NASA research on the origin, evolution, and distribution of life in the universe is focused on tracing the pathways of the biologically critical elements from the origin of the universe through the major epochs in the evolution of living

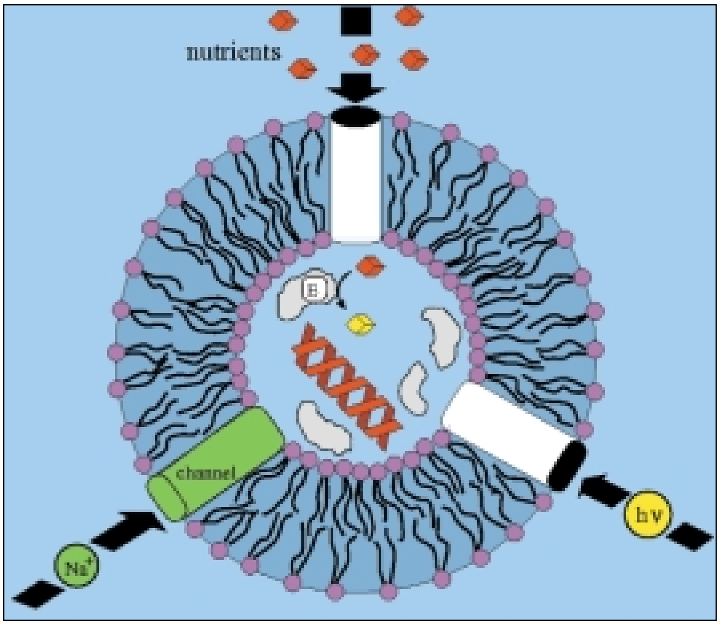
To Build a Planet

An understanding of the formation and development of planets and their environments is a crucial missing link in our understanding of the Solar System and the development of life. At this juncture, we have learned enough to frame this subject in terms of three fundamental questions:

- What are the building blocks of which planets are made?
- What dynamic processes are involved in the initial formation of planets and planetary systems?
- What determines the diverse outcomes of planetary formation and evolution?

Answers to these questions are accessible to us in present-day Solar System objects: comets and asteroids, planetary rings, and the planets themselves.

systems. To understand the possibilities for life, we need to study the only known example, life here on Earth. NASA has made major contributions to discoveries in this area, such as the recognition that life began very early in Earth's history (3.85 billion years ago) and that our earliest microbial ancestor may have been a heat-loving, hydrogen-utilizing microbe. Major changes in the evolution of life have been tied to biological and geological processes (for example, the oxygenation of our atmosphere) and to extraterrestrial events such as an asteroid impact 65 million years ago that ended the age of the dinosaurs. Stellar evolution models suggesting that the Sun was much fainter at the time life was arising on Earth have called attention to the influence of solar vari-



A computer-generated dynamic model of a primitive cell used to test theories about the formation and behavior of Earth's earliest life.

The Astrobiology Institute

The new science of astrobiology synthesizes many scientific disciplines—astronomy to biology, geology to ecology, chemistry to informatics. Scientists from these disciplines, working toward the common goal of discovering the thread of life in the universe, have developed an Astrobiology Roadmap with three fundamental questions, ten goals, and 17 specific program objectives (*http://astrobiology.arc.nasa.gov*).

To pursue these goals and objectives, NASA has adopted an innovative approach to integrating efforts in these disparate disciplines by establishing the NASA Astrobiology Institute. The Institute advances our knowledge by forming interdisciplinary teams of researchers to attack major questions across a broad scientific front. It is a "virtual institute," in that it is a collaborative activity rather than a physical location. The members of these teams are geographically dispersed, but synthesize expertise in diverse fields by coordinating research goals, by frequent personnel exchanges, and by ongoing series of workshops, seminars, and courses, supported by the Institute's electronic networks.

ability on both the emergence and persistence of life on Earth.

A new space science research and analysis initiative, the **Astrobiology Initiative**, will study life in the Universe to determine how life began and evolves, whether there is life elsewhere than on Earth, and what the future of life is, on Earth and possibly beyond it. Understood broadly, the new field of astrobiology encompasses not only fundamental biology, but also cosmochemistry, exobiology, evolutionary biology, gravitational biology, and even terrestrial environmental science and ecology. At NASA, some elements of this syncretic discipline fall into the purview of other enterprises. But the space science program addresses many of its most fundamental issues.

While not strictly a mission, the Astrobiology Initiative is comparable in scope and ambition to a major flight program. As a new research field, astrobiology intends to expand exobiology research and encompass areas of evolutionary biology to further our understanding of how life may persist and evolve to exert a global environmental influence. One objective of astrobiology is to reconstruct the conditions on early Earth that were required for the origin of life and to determine the nature of processes that govern the evolution of life. Two approaches to learn about life on early Earth are to investigate the geological record and to use the genetic record, contained in contemporary microorganisms, to

Goals of Astrobiology

Question: How does life begin and develop?

Goal 1: Understand how life arose on Earth.
Goal 2: Determine the general principles governing the organization of matter into living systems.
Goal 3: Explore how life evolves on the molecular, organism, and ecosystem levels.
Goal 4: Determine how the terrestrial biosphere has co-evolved with Earth.

Question: Does life exist elsewhere in the universe?

Goal 5: Establish limits for life in environments that provide analogues for conditions on other worlds.
Goal 6: Determine what makes a planet habitable and how common these worlds are in the universe.
Goal 7: Determine how to recognize the signature of life on other worlds.
Goal 8: Determine whether there is (or once was) life elsewhere in our Solar System, particularly on Mars and Europa.

Question: What is life's future on Earth and beyond?

Goal 9: Determine how ecosystems respond to environmental change on time-scales relevant to human life on Earth.
Goal 10: Understand the response of terrestrial life to conditions in space or on other planets.

characterize traits of our microbial ancestors. From an experimental approach, researchers will develop and test pathways by which the components of life assemble into replicating systems that can evolve. Current research is expanding our understanding of the possibilities for the earliest life, utilizing simpler molecules and systems that could have been the precursors to the protein/RNA/DNA system used by all life today. It is only recently that we have been able to measure the scope of biological diversity. We have found that life thrives on Earth across the widest range of environments, inhabiting hydrothermal vents, extreme cold-deserts, environments at the limits of pH and salinity, and rocks kilometers beneath Earth's surface. This information will give us clues to how life may have evolved and where it could persist elsewhere.

In order to develop a complete program, the Astrobiology Initiative is being complemented by new thrusts in advanced concepts and technology. Elements already identified are sample acquisition, preparation, processing, and quarantine; hyperspectral remote sensing and imaging; in situ detection of life and "smartlabs;" detection and analysis of non-equilibrium thermochemical states; extreme environment simulation chambers; biotechnology and bioinformatics; technologies to access planetary surfaces and subsurfaces; and next-generation planet imaging and analysis techniques. The intent is to identify specific areas in biotechnology, instrumentation, field studies, and missions where investment will significantly advance this new field.

Astrobiology is a major component of the **Research and Analysis Program** (R&A, described at greater length in section II-5). The R&A program also supports the analysis of primitive meteorites—and will extend this work to returned samples from asteroids and comets—to learn about the early Solar System and the biologic potential of planetary bodies.

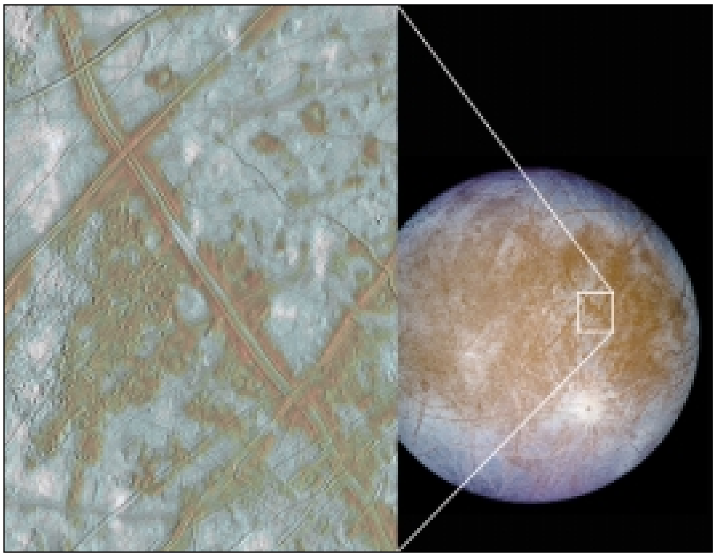
Studies of hot springs on Earth will help guide the search for life on other planetary bodies by showing life at its limits and fossilization processes.

Flight missions will also contribute directly to the search for life or its antecedents in the Solar System. **Cassini**, en route since 1997, will arrive at Saturn in 2004. Its **Huygens** probe (provided by the European Space Agency) will explore the organic-rich atmosphere of Titan, Saturn's largest moon, to broaden our understanding of organic chemistry in our Solar System, perhaps discovering an organic sea or a record of the satellite's organic history.

A number of flight programs that will go into implementation after 2003 will also contribute vitally to the search for life and its origins. For example, it is ironic that the ancient surface on Mars may contain the best record in the Solar System of the processes that have led to life on Earth. The **Mars Exploration Program** will expand our understanding of volatiles on the planet, study its atmospheric history, and determine the elemental composition and global characteristics of Mars' surface. Future missions will explore the ancient terrain and return samples, unveiling the Mars of over three billion years ago and, perhaps, also unveiling the precursors to life on ancient Earth. Part of the challenge will be to establish criteria to distinguish between materials of biological and non-biological origin both during sample selection and in subsequent detailed analysis of these samples on Earth. We will continue to search for and analyze Martian meteorites present on Earth to understand Mars and the exchange of materials between planets.

An understanding of Saturn's moon Titan could provide an important bridge between the study of life's chemical building blocks and the study of more evolved environments such as Mars and Earth. Follow-on to Huygens, **Titan Explorer** could investigate chemical conditions that might be similar to the early environment of Earth, and could offer a key to an ultimate understanding of the origin of life.

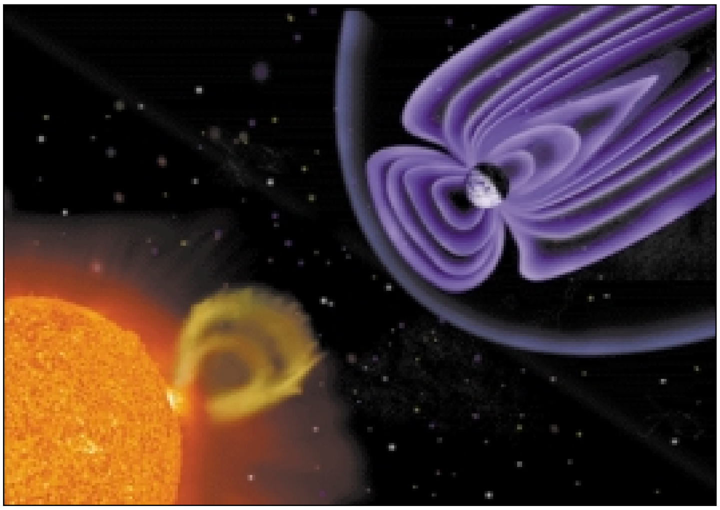
Images of Europa, an ice-covered moon of Jupiter, suggest existence of a sub-surface world of liquid water. We will pursue this suggestion of a second liquid water world in our Solar System with the Europa Orbiter, scheduled for launch in mid-decade. Actually, the presence of subsurface liquid water worlds now seems plausible in a number of satellites of the outer planets. These findings and our understanding of the early appearance and ubiquity of life on Earth reinforce the suspicion that life could exist elsewhere in the Solar System. By applying an understanding of the early evolution of life on Earth, as well as of its ability to thrive in extreme environments here, we can search for evidence of life elsewhere in our Solar System. A **Europa Lander** could be an important next step for this objective.



Images of Europa's surface indicate that water or slush may have oozed up through cracks in its icy crust. This suggests that a subsurface ocean has existed on this moon of Jupiter, and the discovery of a magnetic field around Europa indicates that a liquid ocean is still there beneath the ice.

For Possible Implementation After 2007

If a Europa Lander returns evidence of a subsurface water ocean, we could consider how to carry out more technologically difficult penetration of the frozen crust to hunt for life below by a **Europa subsurface explorer**. As we learn more about the potential for life in the universe, astrobiology research will suggest new targets for missions. For instance, already being contemplated as other potential water habitats are Callisto and the deep subsurface



Solar activity interacts with Earth and its magnetosphere in complex ways.

of Mars, which could also be targets of very advanced spacecraft.

OBJECTIVE SEVEN: Understand our changing Sun and its effects throughout the Solar System

The Sun has profound effects throughout the Solar System, both on the bodies that orbit our own star and on the space between them. To explain these effects, we need to understand both the inherent characteristics of the Sun and how its emissions interact with the rest of the Solar System. These interactions at Earth are particularly important because of their practical near-term effects (e.g., interference with satellite communications) and possible long-term implications (e.g., the effects of solar variability on climate). An understanding of the Sun and the consequences of its variation are also needed if we are to comprehend conditions at the dawn of life on Earth and predict our long-term future.

We are dramatically advancing our knowledge of how the Sun works through studies of solar interior dynamics. Using a growing fleet of spacecraft, we are making coordinated measurements of events that start at the Sun, propagate through interplanetary space, and ultimately impact Earth's magnetosphere and upper atmosphere. The next step is a first survey of the region where the terrestrial atmosphere transitions to space, opening a new view of the response of Earth's magnetosphere to the solar wind. We are also gaining important insights into the workings of extraterrestrial magnetospheres, exploring the most distant reaches of the Solar System, and completing the first exploration of the solar wind at the Sun's poles.

The **Solar Terrestrial Probe (STP)** program is a line of missions specifically designed to systematically study the Sun-Earth system. The STP program seeks an understanding of solar variability on time scales from a fraction of a second to many centuries. It will also determine cause (solar variability) and effect (planetary and heliospheric response) relations over vast spatial scales. Our first STP projects are the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission, NASA's contribution to the Japanese Solar-B mission, and the Solar Terrestrial Relations Observatory (STEREO); these will proceed into implementation before 2003. Planned follow-on STP missions focus on the responses of near-Earth space to solar input. **Magnetospheric Multiscale (MMS)** should help us quantitatively understand the fundamental plasma physics underlying the processes (including magnetic reconnection, plas-

Passing within three solar radii of the Sun, inside its outer atmosphere, Solar Probe will endure extreme conditions to provide unique data.

ma turbulence, and energetic particle acceleration) that control magnetospheric dynamics and thus clarify the impact of solar processes on the geospace system. The **Geospace Electrodynamic Connections (GEC)** mission will determine the spatial and temporal scales that govern the coupling between the magnetosphere and ionosphere, a major step toward understanding the connection between the solar wind, magnetosphere, and ionosphere. **Magnetotail Constellation (MagCon)** will employ a large number of very small satellites to map the structure of the magnetosphere. The availability of simultaneous multi-point measurements from missions such as MagCon will make it possible to construct the first high-fidelity "images" of the regional structure of the magnetosphere and to characterize in detail its response to variations in solar input.

Solar Probe will be our first voyage to a star, a mission to explore the near-environment of our Sun. Solar Probe will make a close flyby of the Sun, making the first in situ measurements deep within its outer atmosphere. In addition to providing data essential for understanding the source of the solar wind, these observations will allow us to relate remote observations of solar phenomena to the actual physical processes that occur in the solar atmosphere.

The Gamma Ray Large Aperture Space Telescope's (GLAST) greatly enhanced sensitivity relative to previous high energy gamma ray instruments will allow detailed studies of the physical mechanisms underlying the vast energy releases observed in solar flares.

Living with a Star (LWS), described under Objective Eight, is a special NASA initiative that directly addresses those aspects of the Sun-Earth system that affect life and society. Its program elements include a space weather research network; a theory, modeling, and data analysis program; and space environment test beds. The first LWS mission will be the **Solar Dynamics Observer**, which will focus on the solar interior with the goal of understanding the sub-surface roots of solar activity.

Community-formulated missions in the **Explorer Program** will take advantage of new scientific ideas and technologies to advance our knowledge of the Sun-Earth connection. In addition, missions undertaken within the **Discovery Program** will also contribute to our understanding of the terrestrial system. One example is information on Mercury's magnetosphere to be returned by the MESSENGER Discovery mission.

For Possible Implementation After 2007

Atmospheric waves link the troposphere and upper atmosphere and redistribute energy within the ionosphere-thermosphere-mesosphere (ITM) system. Clusters of satellites using high-resolution visible and infrared sensors could provide **ITM wave imaging**, enabling us to understand generation and loss mechanisms of these waves, their interactions, and their role in energy transport within the region. Significant improvement in infrared sensors will be required in order to enable this mission.

Understanding the heating and cooling of the solar corona by distinguishing between proposed heating mechanisms remains a challenge. Because much of the physics governing this activity occurs very rapidly and at very small spatial scales, this will require imaging and spectroscopic data able to resolve **microscale coronal features**. Implementation of such a mission will require significant developments in optics and detectors.

To fully understand the structure of the solar corona and to obtain a three-dimensional view of coronal mass ejections, we will need observations from above the Sun's poles to complement data obtained from the ecliptic plane. Viewing the Sun and inner heliosphere from a high-latitude perspective could be achieved by a **solar polar imager** in a Sun-centered orbit about one half the size of Earth's orbit, perpendicular to the ecliptic. Solar sail technology will be required to put a spacecraft in such an orbit in a reasonable time.

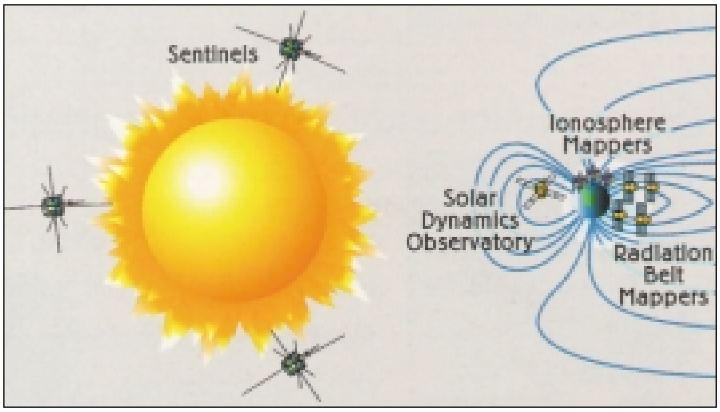
Future **LWS** missions will continue to contribute importantly to our scientific understanding of the underlying physical processes through which the Sun impacts Earth and society.

An **interstellar probe**, traveling more than 30 billion kilometers in 15 years or so, could directly study for the first time how a star, our Sun, interacts with the surrounding interstellar medium. On the way, it would investigate Solar System matter beyond Neptune, and then determine the structure and dynamics of the shock wave that separates our heliosphere from the space between the stars. Continuing on, it would explore the plasma, neutral atoms, dust, magnetic fields, and cosmic rays of the interstellar medium.

OBJECTIVE EIGHT: Chart our destiny in the Solar System

Evolutionary processes that have shaped Earth and other planets are still at work in the Solar System today. For example, there is strong evidence that large impacts caused biological mass extinctions on Earth in the past, altering the course of biological evolution. The impact of Comet Shoemaker-Levy 9 on Jupiter in 1994 vividly demonstrated that major impacts still occur and could alter the future human habitability of Earth. The Space Science Enterprise supports the search for near Earth objects (**NEOs**). We believe there are between 700 and 1100 NEOs larger than 1 km whose orbits traverse Earth's, and we have discovered less than 450 of them to date. The motions of these objects are clearly of interest as potential hazards. Many of them are also the easiest objects for a spacecraft rendezvous, and may contain water or even rich mineral deposits.

Hubble Space Telescope image of Jupiter in July 1994. The dark spots are scars left by multiple impacts of the fragments of Comet Shoemaker-Levy 9. Jupiter's diameter is approximately eleven times that of Earth, which would fit into the Great Red Spot (at left in the image).



Living With a Star is a new initiative to understand space weather and the effects of the Sun on Earth. Various LWS spacecraft will provide information about Earth's upper atmosphere, the heliosphere, and the Sun itself.

We know that solar activity can strongly affect daily life in today's technological civilization by causing power-grid failures, temporary communications interruptions, and even outright failure of communications and defense satellites. Particle radiation from the active Sun can endanger astronauts in space. Solar variability is also one of the natural drivers of global climate that must be better understood for accurate evaluation of the impact of human activities on global climate. An understanding of the evolution of the Sun and the consequences of its variations are critical if we are to properly understand the conditions at the dawn of life and to predict our long-term future.

Future **Solar Terrestrial Probe** missions and Sun-Earth connection-related **Explorers** will continue to improve our understanding of solar variability and how a habitable environment is maintained on Earth in spite of it.

Living with a Star (LWS) is a NASA initiative that directly addresses those aspects of the Sun-Earth system that affect life and society. It includes a space weather research network; theory, modeling, and data analysis programs; and space environment test beds. The flight component of LWS is a network of spacecraft that will provide coordinated measurements from a variety of vantage points distributed around the Sun and Earth. Analyzed together, these measurements will allow us to better understand and predict the effects of space weather events. The first planned LWS mission is the **Solar Dynamics Observatory (SDO)**, which will observe the Sun's outer layers to determine its interior dynamics and the activity of the solar corona, the source of sunspots and active regions, and origin of coronal mass ejections. A second LWS component is a constellation of **Sentinels** around the Sun to observe the movement and evolution of eruptions and flares from the dynamic Sun through the interplanetary medium to Earth's orbit. LWS geospace missions are the **Radiation Belt Mappers** and the **Ionospheric Mappers**. The Radiation Belt Mappers will characterize the origin and dynamics of terrestrial radiation belts and determine the evolution of penetrating radiation during magnetic storms. The LWS Ionospheric Mappers will gather knowledge of how Earth's ionosphere behaves as a system, linking incident solar energy with the top of Earth's atmosphere.

Beyond elucidating events and processes that might affect our destiny on Earth, missions to the Moon, Mars, and near-Earth asteroids will also contribute to our understanding of potential human destinations in the Solar System. Lunar Prospector returned evidence for hydrogen, possibly in the form of water ice, trapped in permanently shadowed regions near our Moon's north and south poles. Goals of the **Mars Exploration**

Program include investigating selected sites on that planet in detail and improving our understanding of how to ensure the safety and effectiveness of future human explorers, and perhaps eventually settlers. Future missions to Earth-approaching asteroids will assess the resource potential of these objects.

For Possible Implementation After 2007

Future elements of the **LWS** Initiative will provide coordinated measurements from an improved space weather research network, distributed around the Sun and Earth, to advance our ability to understand and predict space weather events and their effects. Future LWS components, such as a **solar-polar orbiter** and Earth **north and south "pole-sitters,"** are under study.

The **Mars Exploration Program** will continue and will build on the results of the nearer-term missions. From laboratory studies and space experimentation, astrobiology research may reveal whether life is limited to its planet of origin or can expand its evolutionary trajectory beyond. Outer Solar System missions to Europa and Titan would help clarify the larger context for life in our own family of planets and satellites.

Living With a Star

The Living With a Star Initiative is a set of missions and enhancements to our current program to augment our study of solar variability and its effects. Why do we care? The sphere of the human environment continues to expand above and beyond our planet. We have an increased dependence on space-based systems, a permanent presence of humans in Earth orbit, and eventually humans will voyage beyond Earth. Solar variability can affect space systems, human space flight, electric power grids, GPS signals, high frequency radio communications, long range radar, microelectronics and humans in high altitude aircraft, and Earth's climate. Prudence demands that we fully understand the space environment affecting these systems. In addition, given the enormous economic impact of even small changes in climate, we should fully understand both natural and anthropogenic causes of global climate change.

The Living With a Star Initiative includes:

- A space weather research network of spacecraft providing continuous observations of the Sun-Earth system for interlocking, dual use, scientific and applications research.
- A special data analysis and modeling program targeted at (1) improving knowledge of space environmental conditions and variations over the solar cycle, (2) developing techniques and models for predicting solar and geospace disturbances that affect human technology, and (3) assimilating data from networks of spacecraft.
- Space Environment Test beds for low cost validation of radiation-hardened and radiation-tolerant systems in high radiation orbits.
- Establishing and expanding partnerships for interdisciplinary science and applications with other NASA programs (Earth Science, Human Space Flight, Life Sciences), with other Federal agencies (e.g., via the interagency National Space Weather Program), with international collaborators, and with industry.

Section II-4

technology program

The next generation of spacecraft that will carry out our broad program of exploration must be more capable and more reliable while being more efficient in mass and power consumption. Some systems (telescopes, for example) will be much larger than today's; others (in situ probes for space physics, for example) will be much smaller. During the preparation of this Strategic Plan, the roadmap teams in the major Enterprise science areas that formulated science goals and collected and assessed mission concepts also analyzed the technical capabilities that would be needed to implement these concepts. These Enterprise technology needs were aggregated into ten *key capability* areas.

Key Capabilities

Advanced power and on-board propulsion are needed to support more capable instrumentation and telemetry, as well as to enable spacecraft to travel deeper and faster into space. Development in these areas will focus on power generation (solar and nuclear) and energy storage (battery technologies and flywheels); chemical, ion propulsion, and attitude control systems; solar sails; and micropropulsion systems and components.

Sensor and instrument component technology progress is needed to provide new observational capabilities for astrophysics, space physics, and planetary science remote sensing, as well as vehicle health awareness. Areas for future work include miniaturized in situ and advanced remote sensing instruments, and new sensing techniques using distributed spacecraft and bio-sensors for astrobiology. Of particular importance to space science is instrument capability to perform in harsh environments: vacuum, extreme temperatures, and intense radiation fields. New detector technologies will be based on fundamentally new measurement principles and techniques using new materials and architectures, as well as expanded use of different spectral regions.

> Of particular importance to space science is instrument capability to perform in harsh environments: vacuum, extreme temperatures, and intense radiation fields.

Many future mission concepts require constellations of platforms that act as a single mission spacecraft for coordinated observations or in situ measurements, or act as a single virtual instrument (for example, interferometry or distributed optical systems). Major areas for work in **distributed spacecraft control** are: advanced autonomous guidance, navigation, and control architectures; formation initialization and maintenance; fault detection and recovery; and inter-satellite communications.

High rate data delivery is essential to support virtual presence throughout the Solar System. We also want to minimize the mass and resource requirements of communications subsystems. Topics for advanced development in high rate data delivery include: information extraction and compression; low-cost, low-mass systems; optical communications; in situ communications for surface exploration; improved components for deep space communications; and high rate distributed information systems.

Very advanced space systems will be self-reliant, self-commanding, and even inquisitive. These **intelligent space systems** must be able to: plan and conduct measurements based on current or historical observations or inputs; recognize phenomena of interest and concentrate activities accordingly; and monitor and maintain desired status or configuration over long periods of time without frequent communication with ground.

Many science objectives benefit from more populous spacecraft constellations or more frequent flight opportunities at a fixed cost. The former category includes constellations of measurement platforms in flight as well as networks of landed spacecraft for in situ measurements. These **micro- or nano-sciencecraft** would have: smaller, more lightweight, more capable and resource-efficient spacecraft "bus" and "payload" components; efficiently integrated bus-payload spacecraft designs; high performance data compression technology; low power, high performance electronics; and micro-electromechanical systems (MEMS) technology.

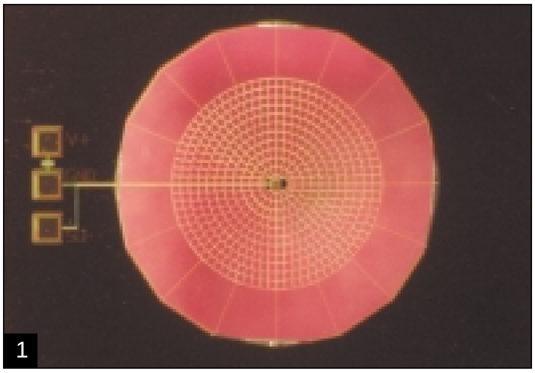
> Very advanced space systems will be self-reliant, self-commanding, and even inquisitive.

Advances in exploration of planetary surfaces will depend on **surface systems** technologies for safe, self-sufficient, and self-sustaining robotic and human presence independent from Earth for indefinite periods of time. Basic technology elements needed for surface and sub-surface sampling of planetary surfaces and small bodies will be teleoperated, along with autonomous robots and rovers with increased intelligence, speed, maneuverability, and dexterity. Specific capabilities would include drills, coring devices, and scoops, as well as sample handling, packaging, and return mechanisms.

Very large (km-scale) non-precision structures in space (e.g., sunshields, sails) and large (100m) precision structures (e.g., optical reflectors, antennas) levy new requirements for **ultra-lightweight space structures and observatories**. Progress is needed in: materials; inflatable and deployable structures, including control for precision deployment and maintenance; lightweight optics and optical structures, and thin-film materials; and radiation shielding, survivable spacecraft materials, and telescope technology.

Improved reliability and agility are needed for in-space docking and flight in planetary atmospheres. **Atmospheric systems and in-space operations** development will focus on aero-maneuvering (ascent, entry, and descent systems, and aero-shell and hazard avoidance systems), aerial systems (balloons, airplanes, rotorcrafts, and gliders), and operations (rendezvous, docking, and sample transfer systems).

To bring all of these advanced flight capabilities together in innovative mission designs, we will need a **next generation infrastructure** on the ground. This will include high performance computing and networking, support for collaborative work, advanced design tools, and distributed networks of computer resources. Tools will be developed to increase efficiency and speed of technology maturation and infusion.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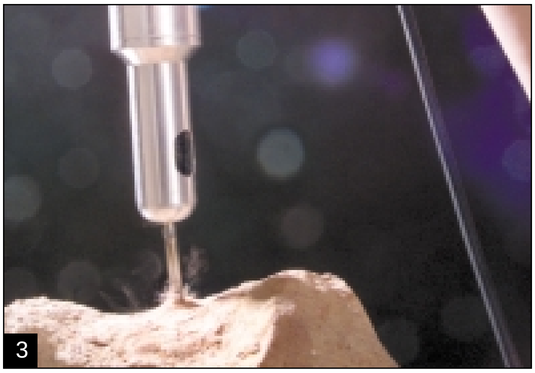
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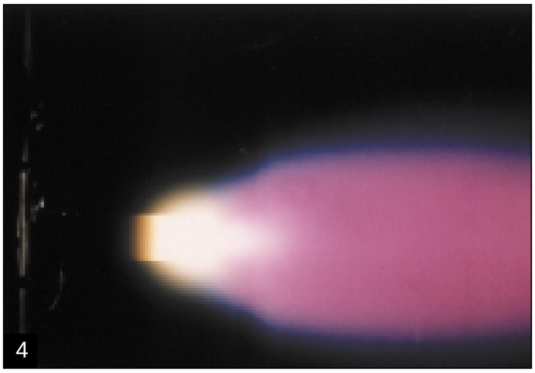
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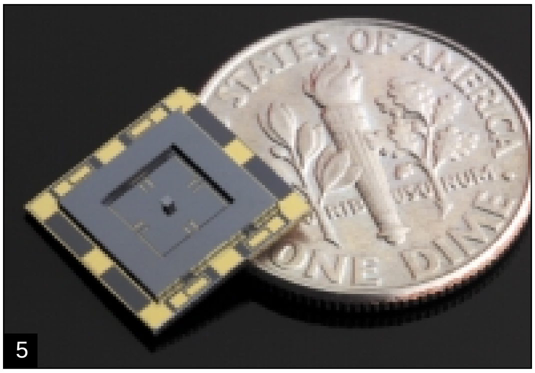
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1. The Boomerang micromesh bolometer, reminiscent of a spider's web, uses a free-standing micromachined mesh of silicon nitride to absorb millimeter-wave radiation from the cosmic microwave background. Millimeter-wave radiation is absorbed and measured as a minute temperature rise in the mesh by a tiny Germanium thermistor, cooled to three tenths of a degree above absolute zero. **2.** Aerogel, a low density material made from silicon dioxide, is protecting some crayons from the heat of the flame. Aerogels have primarily been used in scientific applications, most commonly as a particle detector in high energy physics. **3.** An ultrasonic driller/corer developed at NASA Jet Propulsion Laboratory is shown drilling sandstone while being held from its power cord. Relatively small vertical force is used in this application—a factor that will be useful when the drill is used in future space missions to drill and core for samples during planetary and asteroid explorations. **4.** A high power plasma thruster operates at a current level of 20,000 amperes and a peak power level of 10 megawatts. The technology may eventually be used to propel cargo or piloted vehicles to Mars and beyond. **5.** This new microgyroscope is lighter, cheaper, higher-performing, and less complex than its conventional counterparts while uniquely designed for continuous space operation. Its dimensions are 4 by 4 millimeters, smaller than a dime, and its weight is less than one gram. **6.** The Goldstone Deep Space Communications Complex, located in the Mojave Desert in California, provides radio communications for all of NASA's interplanetary spacecraft and is also utilized for radio astronomy and radar observations of the Solar System and the universe.

Key Enabling Technology Capabilities	Mission Lines								
	Origins Observatories	Solar Terrestrial Probes	Mars Surveyor	Outer Planets	Living with a Star	Cosmic Journeys	To Build a Planet	Astrobiology Initiative	Interstellar Probe
Advanced Power and On-Board Propulsion			■	■	■	■	■		■
Sensor and Instrument Component Technology	■	■	■	■	■	■	■	■	
Distributed Spacecraft Control	■	■			■	■			
High Rate Data Delivery		■	■	■	■		■		■
Intelligent Space System			■	■			■	■	■
Micro-/Nano-Sciencecraft		■	■	■	■		■	■	■
Surface Systems			■	■			■	■	
Ultra-Lightweight Space Structures and Observatories	■			■	■	■			■
Atmospheric Systems & In-Space Operations			■				■		
Next Generation Infrastructure	■	■	■	■	■	■	■	■	■

Space Science Technology Programs and Technology Readiness Levels

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

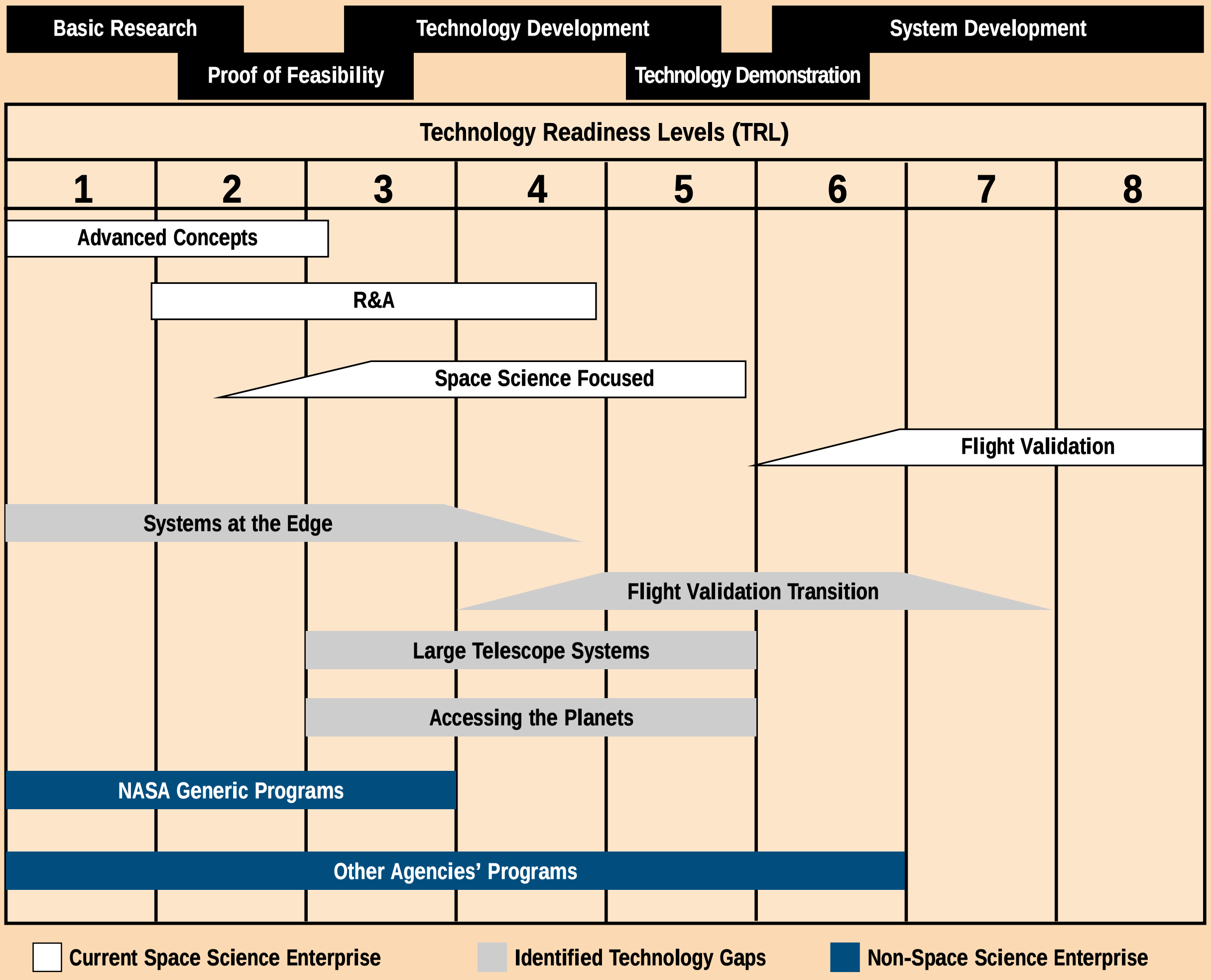
TRL 4 Component and/or breadboard validation in laboratory environment

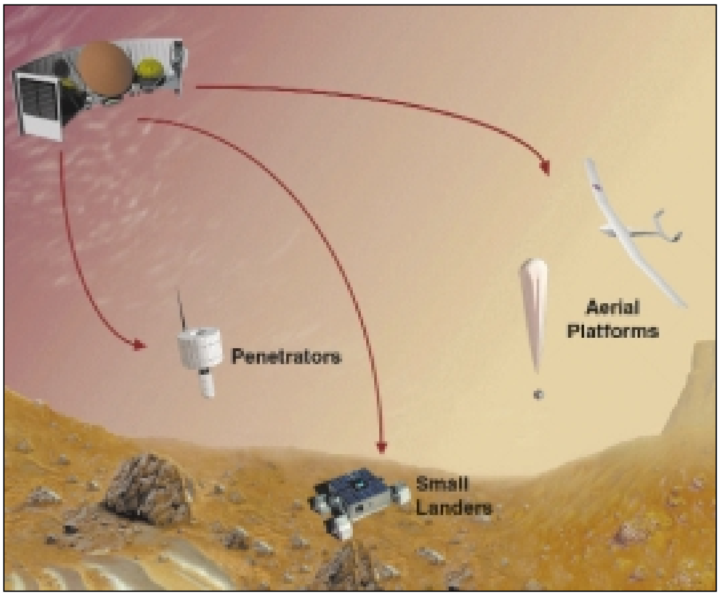
TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and "flight-qualified" through test and demonstration (ground or space)





A broad range of new technologies will be needed to carry out future space science missions. For planetary exploration, these include communications, instrumentation, descent systems, and intelligent mobile platforms.

The Technology Life Cycle

Taken with the Agency's Cross-Enterprise Technology Program that focuses on early stage technology research, Enterprise technology programs span the full spectrum of technology maturity, from fundamental seed ideas through flight validation. The concept of Technology Readiness Levels (TRLs) provides a systematic approach to technology management that supports maturity assessment and a consistent comparison of maturity between different types of technology. Technology products typically progress through the development cycle through multiple programs. For instance, after an advanced proof-of-concept is demonstrated, it may be transitioned into either the Enterprise focused program or into the cross-Enterprise program for continued development, depending on the breadth of its applicability. This would be followed by system-level development and flight validation in the focused or flight validation programs.

Enterprise Technology Program Components

The Space Science Enterprise technology program to advance the state-of-the-art in the ten focus areas is organized into three major elements: an advanced concepts program, a focused technology program, and the New Millennium flight validation program.

The **Advanced Concepts Program** conducts studies for far-term technology (10-25 years in the future) by eliciting long-range science ideas, developing relevant far-term system concepts, and then deriving technology requirements and innovative approaches to support them.

The **Focused Technology Program** addresses high-priority technology requirements that directly support missions in the Enterprise Strategic Plan. While activities within this program are driven by the needs of space science, other Enterprises often benefit from them.

The **New Millennium Program** completes the technology development life cycle by validating new technologies in space. In addition to dedicated technology missions, other flight validation platforms, including the Space Shuttle and International Space Station, balloons, sounding rockets, and piggyback spacecraft or launch vehicle opportunities are also used to validate technologies in the space environment. Demonstrations flown as secondary payloads on expendable launch vehicles flown by NASA, or co-manifested on other U.S. Government or commercial concerns' launches, offer still other opportunities. The possibility of cooperation within international partnerships for technology demonstration is also being explored.

In addition to these major Enterprise technology programs, the Enterprise provides requirements to, and benefits from, **Agencywide technology programs**: Cross-Enterprise Technology Development Program (CETDP), High Performance Computing Capability (HPCC), and NASA Institute for Advanced Concepts (NIAC). These programs support technology requirements for all NASA space Enterprises, focusing on early stages of the technology life cycle for multiple Enterprise users. They emphasize basic research into physical principles, formulation of applications concepts, and component-level performance evaluation.

The program analyses performed in conjunction with the preparation of this Plan have revealed gaps in the capability to meet the technology needs of the Space Science Enterprise and its future expansion. We are therefore taking steps to fill these gaps by proposing a **new technology initiative** that encompasses several programs. These include Systems at the Edge (focusing on low TRL research), Accessing the Planets (for in situ planetary exploration), Flight Validation Transition (promoting transition of new technologies to space demonstration), and a Large Space Telescope Initiative (for far-term space observatories).

> In addition to these major Enterprise technology programs, the Enterprise provides requirements to, and benefits from, Agencywide technology programs.

Technology Management

Management of the technology life cycle for **strategic, NASA-formulated missions** begins with the science theme roadmaps described in Section II-1. The Enterprise allocates resources in the Focused Technology Program and establishes priorities for the New Millennium Program and the Cross-Enterprise Program. The Research and Analysis program's yearly research solicitation also reflects the priorities established by the Science Board of Directors.

The technology programs are reviewed quarterly by Enterprise management. A Technology Steering Group, staffed by key program technologists at the NASA Centers, analyzes on a continuing basis the efficiency of resource allocations (gaps, overlaps, and redundancies) in the technology programs. The Steering Group reports periodically to Enterprise management. The Steering Group uses a variety of system analysis, risk analysis, and investment analysis tools and processes to determine the relative benefits and costs of alternative technologies, both those developed internally and those provided by university and industry partners.

Selected technology programs are periodically peer reviewed by external expert technologists on behalf of Center and Headquarters management. On the basis of these reviews and reports, reallocation of resources is considered by the Enterprise every year during the budget development process or whenever appropriate in response to deviations from planned performance or budgets.

Technology infusion into the **community-formulated Explorer and Discovery programs** occurs by a different path, since these missions are proposed as integrated packages by the research community and proceed directly to detailed definition without the benefit of a lead-in technology development program. For the Explorer program, an annual research solicitation offers a technology funding opportunity, primarily for instrument development. The Research and Analysis program offers a competitive program for funding of instrument development for planetary exploration. The selecting official has the option to allocate a small amount of funding for a proposal of unusual scientific merit that is not selectable because it is considered technically immature. Up-to-date information on technologies considered ready to fly is provided to proposers in the Explorer and Discovery programs, as well as to the proposal reviewers to ensure that a consistent standard for technical readiness is applied during the review process. Finally, technology developments supported under the Focused Technology Program for the NASA-formulated missions also become available to community proposers in the Explorer and Discovery programs.

Section II-5

research and data analy

Underpinning the space science flight programs are two programs of space science activities called Research and Analysis (R&A) and Data Analysis (DA)—collectively called Research and Data Analysis (R&DA). Broadly put, research supported under R&DA programs develops the theoretical tools and laboratory data needed to analyze flight data, makes possible new and better instruments to fly on future missions, and analyzes the data returned so that we can answer specific questions posed and fit them into the overall picture. Although priorities within both programs are established in accordance with the Enterprise strategic goals, the program types differ in scope. While DA programs are tied to specific missions, which are focused on the achievement of specific strategic objectives, the scope of R&A programs is generally wider

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because they must provide the new theories and instrumentation that enable the next generation of flight missions.

The alignment of R&A programs with Enterprise strategic goals is ensured through two mechanisms. First, NASA Research Announcements soliciting R&A proposals contain explicit prioritization criteria with respect to Enterprise objectives. Second, the entire R&A program is reviewed triennially to assess scientific quality and productivity of the major components and to adjust plans to best support Enterprise goals.

Data Analysis (DA) programs have traditionally been performed by mission instrument teams and interdisciplinary scientists competitively selected for an individual mission for the lifetime of that mission. For some missions or mission groups, periodic open and competitive solicitations enable DA participation by other investigators. As a matter of principle, the Enterprise has begun to add annual, open and competitive DA solicitations to all missions that can accommodate “guest investigations.”

Without a vigorous R&DA program it would not be possible to conduct a scientifically meaningful flight program. Examples of the contributions of the R&DA program abound across the whole frontier of space science.

Role of NASA’s Research and Data Analysis Programs

In a recent study (*Supporting Research and Data Analysis in NASA’s Science Programs: Engines for Innovation and Synthesis*, National Research Council, 1998), the Space Studies Board identified R&DA functions that are “integral elements of an effective research program strategy”:

- Theoretical investigations
- New instrument development
- Exploratory or supporting ground-based and suborbital research
- Interpretation of data from individual or multiple space missions
- Management of data
- Support of U.S. investigators who participate in international missions
- Education, outreach, and public information

Objectives of R&DA Programs

Theoretical, modeling, and laboratory work provide the tools to understand and integrate measurements made in space and on the ground, and can also directly impact future mission concepts. Numerical modeling of impacts and magnetohydrodynamics support both planning for future missions and understanding of data returned from past ones. Laboratory experiments, in turn, are used to validate these theoretical results. The R&A-supported laboratory work on meteorites underpins research on asteroids, as well as continuing analysis of fragments that are believed to have come to Earth from Mars. In a different vein, models for the atmosphere of Mars can be used to predict the performance of aerobraking systems for future spacecraft. The R&A Planetary Protection Program is developing methods to completely sterilize ice-penetrating probes so that we can one day confidently search for life on Europa without fear of a spurious detection due to contamination from Earth. And sample returns from Mars cannot be undertaken until the possibility of contamination of our own planet is fully understood and eliminated.

Exciting new revelations about the cosmos are not possible without the most **advanced detector and instrument systems** that can be built, most of which are developed through competitively-selected space science R&A programs. Many are given real-life testing in the sounding rocket and balloon programs before the decision is made to fly them on the much more expensive Earth-orbiting and deep space spacecraft. The new-generation detectors for the Hubble Space Telescope, the Chandra X-ray Observatory, Solar and Heliospheric Observatory, and the upcoming Space Infrared Telescope Facility were largely developed within the R&A program. Similarly, future generations of instruments slated for possible use on our planetary missions are being designed and built within the R&A program. As illustrated in the table “Examples of Flight Hardware with R&A Heritage” (p.89), instrument concepts developed through the R&A program have been the basis for flight instrumentation for every class of NASA flight mission, from the smallest to the Great Observatories.

Time exposure of a hypervelocity oblique impact, from the right of the frame. Low-angle impacts cause the projectile to fragment, and significant pieces survive to disperse downrange without much change in velocity. (NASA Ames Vertical Gun Range)

After we have obtained them, we must **analyze and interpret data** returned by NASA's space science missions to fully exploit them for addressing our strategic science objectives. R&A and DA support the necessary advanced modeling and theory. For example, recent computational modeling of the convective upwelling in Europa's ice shell has been used to interpret the "blisters" observed by the Galileo spacecraft to estimate the thickness of the shell and the depth of a possible liquid water ocean beneath it. Other Galileo data have been analyzed to reveal the physical state and major dynamical processes within Jupiter's turbulent atmosphere and on the surfaces of the giant planet's diverse satellites. Our understanding of the effects on Earth of the nearest star, the Sun, is progressing as a result of interpretation of data from such missions as the Solar and

Examples of Flight Hardware with R&A Heritage

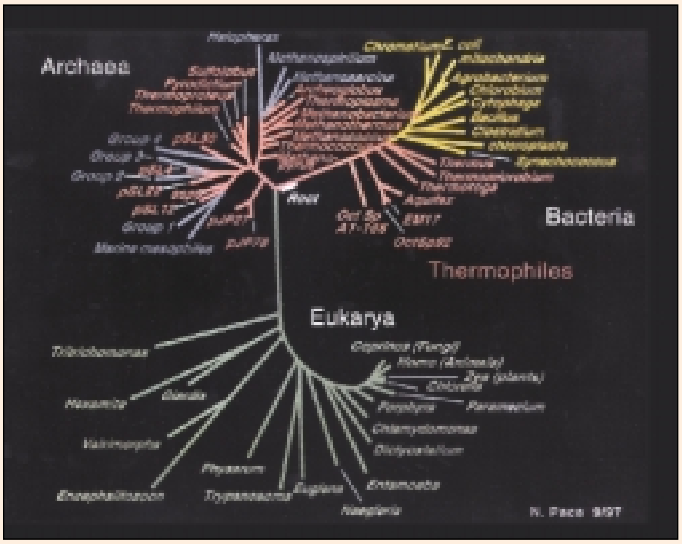
Chandra	Focal plane detectors
Cluster	Electron and ion analyzer predecessors
EUVE	Wedge and strip detectors
	Mirror
FAST	Wave-particle correlator
	Multiple-baseline electric field interferometer
FUSE	Holographic grating
	Delay-line detectors
	Mirror
Galileo	Ebert-Fastie spectrometer
Hubble Space Telescope	Multi-anode microchannel plate array detector
Lunar Prospector	Electron reflectometer
SNOE	X-ray photometer
SOHO	Ultraviolet spectrometer
	Delay-line detectors
	Multi-layer imaging
TIMED	Ultraviolet imager
TRACE	Normal incidence multilayer filters
Wind	Wave-particle correlator
	Electron and ion analyzer predecessors
Yohkoh	Glazing incidence x-ray optics

Heliospheric Observatory (SOHO) and the Transition Region and Coronal Explorer (TRACE). A very practical example is coronal mass ejections, which directly affect—in some cases permanently damage—Earth-orbiting communications satellites. A complete understanding of these ejections could have very significant benefits to our national security and to the space communications industry. In the more remote universe, R&DA supports investigations into one of the long-standing enigmas in astrophysics, the nature of gamma ray bursts. During brief flashes, these objects scattered over the sky are individually the brightest objects in the universe. A major advance was recently achieved when the visible counterpart to one of these bursters was observed simultaneously with its detection in gamma rays. Equally exciting, fine details of the fossil microwaves remaining from the Big Bang were revealed for the first time by one of a series of balloon-borne experiments from the Antarctic.

Vast amounts of data are returned from space science missions. The volume, richness and complexity of the data, as well as the need to integrate and correlate data from multiple missions into a larger context for analysis and understanding, present growing opportunities. Exploration and discovery using widely distributed, multi-terabyte datasets will challenge all

Looking at the World in New Ways

R&A supported work that revealed the existence of a distinct and perhaps ancient type of microorganism, first christened *archaeabacteria*. Further studies supported this initially controversial theory. When the genomic sequence of *Methanococcus jannischii* was published, our perception of the taxonomy of life on Earth was sweepingly revised to today's three domains: bacteria, eukarya, and archaea. NASA-supported researchers thus discovered a previously unrecognized branch of life on Earth, an advance with profound implications for the search for life elsewhere in the universe.



aspects of **data management** and rely heavily on the most advanced analysis and visualization tools. The design and implementation of the next generation of information systems will depend on close collaboration between space science and computer science and technology.

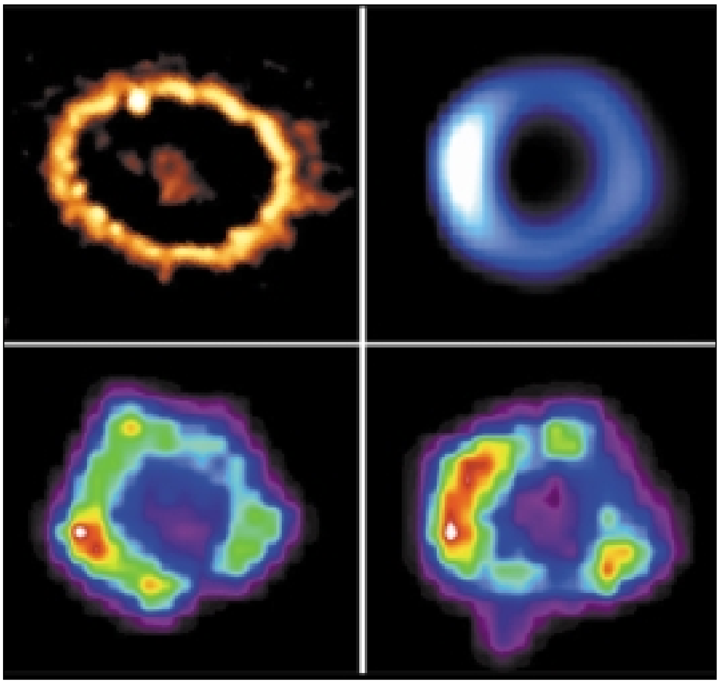
An example of such a collaboration is a National Virtual Observatory (NVO) initiative to collect most of the Nation's astronomical data, along with advanced visualization and statistical analysis tools. This will support "observations" and discovery via remote access to digital representations of the sky in all wavelengths. The NVO will provide multi-wavelength data for millions of objects, allowing discovery of significant patterns from the

Accelerating Scientific Progress

BOOMERANG was designed to image the Cosmic Microwave Background (CMB). Work on BOOMERANG began shortly after the first detection of anisotropy by the COBE spacecraft. Though COBE detected anisotropy in the CMB, it was not able to resolve it. The challenge was to construct an experiment that could image the CMB with *40 times the angular resolution and 100 times the instantaneous sensitivity of COBE.* This was achieved by the BOOMERANG instrument, which was launched on a 10-day Antarctic voyage in late 1998, carrying a detector that had not existed just four years before. The results offer the first strong confirmation of the idea that the universe underwent a period of violent “inflation” during the first nanosecond after the Big Bang.

The BOOMERANG Telescope being readied for launch near Mt. Erebus in Antarctica. The 28 million cubic foot balloon carried the BOOMERANG telescope to an altitude of 120,000 feet, above 99 percent of the atmosphere.

exploration and mining of the statistically rich and unbiased databases. Another example is the data management and computing challenge posed by the Living With a Star (LWS) initiative. Special challenges posed by LWS include high performance computational methods for theoretical modeling and simulation, complex data analysis and visualization tools, correlative data analysis and visualization capabilities across widely varying spatial and temporal scales, and assimilation of observational data into theoretical models.



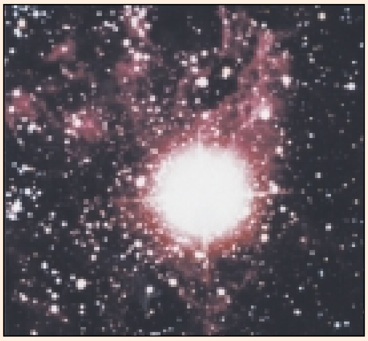
Images of the supernova SN1987A; combining information from several wavelengths helps unravel the mechanisms of astronomical phenomena. Clockwise from upper left: HST optical image; Australian Telescope Compact Array radio image; Chandra x-ray images from January 2000 and October 1999.

Setting the Stage for Future Missions

The Galileo mission has provided evidence that Europa has a liquid water ocean beneath its frozen crust, leading to speculation about possible sources of energy to support life in this ocean. Studies have indicated that without a ready supply of oxidized chemical species, the energy available for life would be minimal and any life on Europa would be very limited and difficult to detect. However, a recently developed alternative theory has revealed a novel pathway for chemical energy to be delivered to Europa. In this scenario, the intense radiation field surrounding Jupiter would produce oxidized and reduced carbon species that would be available to support life. This result is a vital consideration for the design of missions to search for life on Europa because it suggests searching the near-surface rather than penetrating kilometers of ice.

Responding to Unexpected Opportunities

On February 23, 1987, astronomers detected the first nearby supernova in 400 years. For the gamma ray measurements critical to understanding how new elements are formed in such a massive stellar explosion, NASA turned to its suborbital program as the only possible way to take advantage of this unprecedented but short-lived opportunity. A campaign of scientific balloon flights using gamma ray telescopes developed under the R&A program provided crucial evidence of how supernovae produce the heavy elements we see on Earth. Combined with observations from the ground and from space at other wavelengths, these gamma ray observations were key to developing a comprehensive picture of this stellar explosion.



Supernova SN1987A

Enabling a New Science

One of our most compelling questions is whether or not we are alone in the universe. If we are not, how does life emerge and evolve elsewhere in the universe? In fact, how did it appear on Earth? What is the future of life on Earth? These questions are the focus of the **astrobiology and exobiology** R&A program. Astrobiology has been at the forefront of an effort to break down discipline barriers to promote vigorous research at the boundaries between traditional scientific disciplines. Scientific debate on the potential for life on Europa, and even speculation on its possible nature, are recent examples of the resulting cross-disciplinary research that could motivate future missions.

To stimulate progress in astrobiology, the Space Science Enterprise recently created the Astrobiology Institute. The new Institute is an innovative virtual organization in which scientists throughout the country coordinate their research—and soon will be carrying out experiments—via high-speed computer links. It may be the most practical and efficient way to harness the highly diverse expertise of a geographically dispersed investigator population. The Astrobiology Institute will pioneer the technology that will enable teams of researchers and equipment scattered around the country, or even the world, to carry out front-line investigations.

Section II-6

education and public ou

Space Science Enterprise education and public outreach goals center on sharing the results of our missions and research programs with wide audiences and using space science discoveries as vehicles to improve teaching and learning at all levels. This is a deliberate expansion of the traditional role of the Enterprise in supporting graduate and postgraduate professional education, a central element of meeting our responsibility to help create the scientific workforce of the future. Our commitment to education now includes a special emphasis on pre-college education and on increasing the general public's understanding and appreciation of science, mathematics, and technology.

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Our policy for achieving our education and public outreach goals and objectives is to incorporate education and public outreach as an integral component of all of our activities, both flight missions and research programs. Contributing to education and outreach is the collective responsibility of all levels of Enterprise management and of all participants in the space science program. We focus on identifying and meeting the needs of educators and on emphasizing the unique contribution space science can make to education and the public understanding of science. Our approach facilitates the effective participation of space scientists in education and outreach activities. Enterprise efforts are a significant element of NASA's overall education program and are aligned with the Agency's efforts to ensure that participation in NASA missions and research programs is as broad as possible.

The two main elements of our education and public outreach program are support to education in the Nation's schools and informal education and public outreach that benefits both young people and adults.

With limited resources, high leverage is key to building a national pro-

Education and Outreach Implementation Approach

- Integrate education and outreach into Enterprise flight and research programs
- Encourage a wide variety of education and outreach activities
- Help space scientists participate in education and public outreach
- Optimize the use of limited resources by channeling individual efforts into highly leveraged opportunities
- Develop high quality education and outreach activities and materials having local, state, regional, and national impact
- Ensure that the results of our education programs and products are catalogued, archived, and widely disseminated
- Evaluate our activities for quality, effectiveness, and impact

Space science brings together inquiring minds of all ages.

gram that contributes both to improving teaching and learning at the pre-college level and to increasing the scientific literacy of the general public. The Enterprise achieves this leverage in **pre-college education** by building on existing programs, institutions, and infrastructure and by coordinating activities and encouraging partnerships with other ongoing education efforts. Such ongoing efforts include those inside NASA and within other Government agencies, and those being undertaken by non-governmental education organizations. We complement the very large investments in education being made by school districts, individual States, and other Federal agencies, particularly by the National Science Foundation and the Department of Education. This entails establishing alliances with education-oriented professional societies, state departments of education, urban school systems, education departments at colleges and universities, and organizations that produce science materials intended for national distribution. Our efforts support local, state, and national efforts toward standards-based systemic reform of science, mathematics, and technology education. We use existing dissemination networks and modern information technology to make information and education programs and materials easily accessible.

The other main element of our program, enhancing the general public's understanding of science, develops new connections with **informal education and public outreach organizations** of many different types across the country. Alliances have been established with science museums and planetariums, as well as producers of public radio and television programs.

We will continue to explore new possibilities for partnerships and to experiment with new ways to bring the results of the space science program to teachers, students, and the public. For example, we will expand current partnerships and create new alliances with organizations such as the Boys and Girls Clubs of America, Girl Scouts of America, 4-H Clubs, professional societies for scientists and educators, public libraries, and rural museums.

We have made significant progress in these areas since the previous Enterprise Strategic Plan was released in 1997. We have embedded funded education and public outreach programs in all of our mission and research programs, established dozens of local, regional, and national partnerships, and established a national support network of education and outreach forums and brokers-facilitators (fully described in a separate Enterprise education and public outreach implementation plan).

The Space Weather Center exhibit introduces visitors to space weather and how it affects everyday life. An interactive exhibit, it incorporates near real-time data from NASA missions currently studying the Sun and near-Earth space. (The exhibit is a partnership of the Space Science Institute and NASA Goddard Space Flight Center.)

New education and public outreach efforts will build on these activities and accomplishments. For example, we will:

- Emphasize collaborations with science museums and planetariums. Collectively, these institutions attract more than 100 million visitors per year. They have enormous experience in developing and presenting public education programs. They also have the resources for creating such programs and are playing an increasingly important role in working with the formal education system. We plan to build on strong mutual interests between the Space Science Enterprise and the museum and planetarium community.
- Take advantage of the high technology nature of much of the Space Science Enterprise's program to develop new materials and new programs in technology education. Many of the technologies being developed for our science program are also of great interest to the public, and we will explore ways to bring our technology as well as our science to the public.
- Develop, in collaboration with the NASA Office of Equal Opportunity Programs, new opportunities for underserved and underutilized groups to participate in space science missions, research, and education and outreach programs.
- Evaluate our education and outreach products and programs for quality and effectiveness. We must understand who our programs are reaching and what impact they are having, both on the formal education system and on the general public's understanding of science. We will continue to improve our efforts based on regular feedback.
- Be alert for special events and particularly promising opportunities in our scientific program to bring space science to the public and to use space science to improve science, mathematics, and technology education at all levels. For example, our planned long-term program of Mars exploration provides an opportunity to literally "bring the American public along for the ride" and become genuine participants in the adventure of exploring another planet.

The full variety and scope of the Enterprise's current and planned education and outreach activities are described in our 1996 report "Implementing the Office of Space Science Education/Public Outreach Strategy." Our systemic approach, based on a long-term commitment to partnership with existing education and public outreach institutions, is making a significant and durable contribution to education and public understanding of science, mathematics, and technology.

Section II-7

partnerships

NASA's space science program exists within a much larger research and technology context that spans the globe. In some areas space science leads the pace of innovation, and in others it benefits from efforts and investments of others. Our pace of discovery is quickened by contributions from other U.S. Government agencies, U.S. universities and industry, and scientific collaborators around the world.

Other NASA Enterprises

Partnerships with other NASA Enterprises are essential to the Space Science Enterprise strategy. For example, the Space Science Enterprise works with the Human Exploration and Development of Space (HEDS) Enterprise to provide information essential to future human exploration and development of the Solar System. This includes scientific information about likely human destinations such as the Moon and Mars, surveys and characterization of space resources, and evaluation of space radiation hazards. The partnership with HEDS also involves using Enterprise missions to test technologies for human exploration of space and planetary environments.

HEDS, in turn, provides the Space Science Enterprise opportunities to accomplish investigations that would otherwise be impractical. For example, the Space Shuttle flies science payloads such as telescopes to study the ultraviolet universe, sub-satellites to study the solar corona and the origin of solar wind, and cosmic dust collection experiments. The International Space Station will provide further opportunities for these and other types of investigations. Ultimately, some of the most important and complex science goals, such as understanding the possible origin and evolution of life on Mars, will be addressed by human explorers. Indeed, answering questions of this magnitude may prove to be a significant part of the rationale for human exploration. Moreover, ambitious future space observatories may depend on human assistance in assembly, maintenance, and upgrading; the history of the Hubble Space Telescope provides brilliant examples of this synergy.

Partnerships with other NASA Enterprises are essential to the Space Science Enterprise strategy.

The Space Science, Earth Science, and new Biological and Physical Research Enterprises are jointly developing a program in Astrobiology, a new multidisciplinary research field that studies the origin and distribution of life in the universe, the role of gravity in living systems, and Earth's atmosphere and ecosystems.

Our studies of the Sun, the near-Earth space environment, Earth's middle and upper atmosphere, and other planets are also of interest to the Earth science community. For example, variations in solar radiation and particle emission cause variations in Earth's atmosphere. The study of other planets, particularly Venus and Mars, is another avenue to understanding why Earth is capable of sustaining life, and how global change processes might operate in other planetary settings.

The Aerospace Technology Enterprise also makes important contributions to the Space Science Enterprise. For example, aeronautics expertise at Ames Research Center supports the SOFIA airborne observatory program.

Our education and outreach programs are carried out in close collaboration with the Office of Human Resources and Education and the Office of Equal Opportunity Programs to ensure that space science initiatives complement existing activities and support NASA's overall programs in these areas.

Other U.S. Government Agencies

The National Science Foundation (NSF) has many programs that support or enhance NASA space science missions. NSF-supported ground-based research on the Sun, the planets, and the universe contribute to the intellectual foundations of many NASA space science flight missions. NASA and NSF jointly fund planet search programs. NSF is also responsible for U.S. scientific activities in the Antarctic. NSF, the Smithsonian Institution, and NASA collaborate on the search for, collection, distribution, and curation of Antarctic meteorites. NASA and NSF have a joint program to use Antarctica as an analog for the space environment in developing long-range plans for Solar System exploration. NASA also uses Antarctica for a future generation of very long-duration balloon missions. There are close ties between NASA's astrobiology programs and NSF's Life in Extreme Environments (LEXEN) program.

The Department of Energy (DOE) similarly has a wide range of programs that support NASA space science activities. DOE has developed and supplied the radioisotope thermoelectric generators (RTGs) that have enabled a wide range of Solar System exploration missions—from Apollo to Viking to Voyager, as well as the Galileo and Cassini-Huygens missions to the outer planets. DOE has developed instruments and sensors for NASA's space science missions, particularly through its Los Alamos and Lawrence-Livermore Laboratories. DOE and NASA have jointly studied a mission to place high-energy particle detectors in space aboard satellites and the International Space Station, and the agencies are working together on the Gamma Ray Large Area Space Telescope (GLAST). Data from DOE missions also support the International Solar Terrestrial Physics program.

For its part, the Department of Defense (DOD) has been a major developer of high sensitivity, large-area infrared detector arrays needed for many space science missions. These and technology for large-area deployable optical systems are important for future large telescopes in space. Through its Naval Research Laboratory (NRL), DOD has contributed instruments to space science missions such as the Compton Gamma Ray Observatory (CGRO) and the Solar and Heliospheric Observatory (SOHO). In another area, NASA and DOD cooperated on the Clementine mission, a DOD-led joint mission that surveyed the Moon. Space science, in turn, contributes to some DOD objectives. For example, research on solar flares, coronal mass ejections, solar energetic particles, and the terrestrial middle/upper atmosphere and magnetosphere is important for DOD command, control, and communications systems. DOD and NASA have established a partnership for expanded cooperation on the space environment.

In addition, NASA cooperates with the National Oceanic and Atmospheric Administration (NOAA) and DOD by providing data used for forecasting and understanding the space environment. This effort is part of an interagency (NASA, NSF, NOAA, DOD, DOE, Department of the Interior [DOI]) national space weather program. NASA also works closely with the U.S. Geological Survey of the Department of the Interior and the National Institute of Standards and Technology (NIST, Department of Commerce).

The formation of technology development partnerships is an important goal of the Space Science Enterprise. DOE, DOD, and other agencies such as NOAA share many needs and capabilities with NASA, and NASA works closely with them to identify opportunities for synergistic technology development.

In the education area, NASA works with NSF and the Department of Education to use space science missions and programs to contribute to science, mathematics, and technology education and to share the excitement of space science discoveries with the public. For example, we worked closely with the Department of Education's Gateway to Educational Materials Consortium to develop an online resource directory for space science education products.

From the very beginning, universities and university scientists have played a central role in the planning and implementation of space science.

Universities

From NASA's very beginning, universities and university scientists have played a central role in the planning and implementation of space science. University scientists serve on NASA study teams and on key advisory committees that lay out long-range goals and objectives, strategies, and priorities for space science. University scientists develop new approaches for making critical measurements, serve as principal investigators for flight investigations, and carry out the laboratory, theoretical, and computational studies required to interpret data returned from space science missions.

Universities exist to create new knowledge and to transmit it. The intellectual environment of universities encourages innovation. Thus, university scientists carry out basic space science research and other long-term research needed to investigate underlying principles that form the foundations of new technology. Universities have the principal responsibility for ensuring the steady stream of highly trained and motivated people needed to assure the future vitality of the Space Science Enterprise. Space science programs are also significant contributors to the ongoing development of scientists and engineers to meet larger national needs. Support from NASA flight projects and research grants programs is an important contributor to maintaining the infrastructure that permits this university participation.

The trend towards smaller, more frequent, and lower cost missions, together with the advent of advanced communications and information systems technologies, has allowed universities to take on greater responsibility for the design, development, and operation of entire missions rather than just the development of individual instruments on larger NASA-developed missions. Easier electronic access to archived data and new policies that place science data in the public domain as soon as possible are helping scientists and students at a wide range of institutions, including colleges and smaller universities, to participate in the analysis of space science data.

For these reasons, the Space Science Enterprise is committed to a long-term partnership with our universities and their community of scientists and students.

Industry

Industry has made and will continue to make significant contributions to the planning, development and implementation of space science missions and research programs. Industry has played a critical role in the design, engineering, manufacture, construction, and testing of both large and small space missions; in the design, development, testing, and integration of advanced instruments; and in the development of advanced spacecraft, instrument, mission operations, and information system technologies. Many industry capabilities have been developed for commercial applications with DOD or NASA core technology support. The resulting extensive space industry infrastructure is available for use for space science purposes. The establishment of partnerships with industry allows space science to benefit from the experience and capabilities of the industrial sector.

> The Space Science Enterprise is committed to the long-term support of university research and to continuing to work closely with university scientists and students.

As noted earlier, universities are now partnering with industry to assume full responsibility for the design, development, and operation of entire missions. With the more frequent flight opportunities now being provided through the Explorer, Discovery, and New Millennium programs, such partnerships are likely to play an even more important role in the Space Science Enterprise in the future. The reliance on the identification, development, and utilization of advanced technology to dramatically lower instrument, spacecraft, and mission operations costs requires strong partnerships between industry and the Enterprise. Strong partnerships are also important for facilitating the transfer of NASA-developed technology to industry and thereby realizing the commercial potential of these technologies and contributing to the long-term capability and competitiveness of American industry.

Other Nations

The quest for knowledge does not recognize national boundaries. Scientific expertise and capabilities are today more than ever distributed among many nations. Common interests and limited resources virtually dictate that nations cooperate in the pursuit of common goals. Further, the Space Act specifically mandates a leadership role for NASA in promoting international cooperation in space research. For all of these reasons, international cooperation is a fundamental aspect of virtually all Space Science Enterprise programs.

In some cases, other agencies and nations contribute to NASA-led missions. Foreign collaborators can join with U.S. teams to propose on NASA's competitive announcements, and foreign agencies can negotiate to stake out roles in U.S. strategic missions outlined in this and future plans. To support participation of U.S. investigators on foreign missions, the missions-of-opportunity option in Explorer and Discovery solicitations allows U.S. researchers to compete for funding to provide instrumentation or other contributions to missions developed by other countries or agencies.

The Student-Tracked Atmospheric Research Satellite for Heuristic International Networking Experiment (STARSHINE) satellite leaves the cargo bay of the Space Shuttle *Discovery* near the completion of the STS-96 mission. The stowed Canadian-built remote manipulator system (RMS) arm is visible in the foreground.

International coordination of strategic planning poses a challenge, but one that merits continuing attention. Each agency, whether the European Space Agency or the numerous national agencies with which the Enterprise collaborates, has its own policies, planning cycles, funding processes, and scientific and technical priorities. The cooperative environment is characterized by a complex, but healthy, blend of competition and cooperation. But there is a general recognition, which NASA shares, that the opportunities for discovery outstrip the technical or financial resources of any individual player. As a result, we are continuing to work to better understand the goals and capabilities of our current and future partners, and we expect continuing progress in maximizing all parties' returns on space science investment through cooperative approaches to space research.

Section II-8

a vision of the future

Sometime in the new century, humanity will know its place in the universe . . . and will begin the challenge of writing its future in the history of the cosmos. Our telescopes will have revealed in detail the most fundamental structures in nature: the galaxies and the stars. Life-bearing planets—if they exist—will have been at least tentatively identified. The next major step after detailed spectroscopy of planetary atmospheres must be imaging of their surfaces: even a dozen or so pixels in one direction across the face of an Earth-like planet orbiting a neighbor star would reveal continents and weather patterns, as well as seasonal variations. The optical designs for such an ambitious undertaking are not complicated, but pose enormous engineering challenges.

If there are new fundamental forces in nature that await discovery, we will have searched for them within the gravitational maelstrom of massive black holes and in the earliest moments after the Big Bang. Our most powerful x-ray interferometers will have revealed the detailed structure at the edges of black holes, and submillimeter interferometers will study the nature of gravity itself within the fossil remnant of the primordial fireball. The life story of our Milky Way galaxy, as its stars, planets, and life are built up from primordial atoms, will be much better understood.

Our most sophisticated robots will have traveled to the dark outer reaches of the Solar System and plunged beneath the icy surfaces of Europa and Titan, to seek out signs of organic activity, and perhaps, the struggles of life to maintain a foothold even in these forbidding environments. Closer to home, Mars will have been surveyed in detail, with sur-

The two Mars 2003 rovers will extend the surface exploration begun by Viking and Pathfinder. These new rovers will be able to travel 100 meters per day, and will carry scientific instruments to determine the geological context of rocks and soil and measure their chemical composition and fine scale structure—even scraping the surface off rocks to expose their unweathered interiors.

face samples returned to Earth for detailed study. Programs to survey the Red Planet for hidden resources of water will be well underway, as well as an extended geological and meteorological reconnaissance.

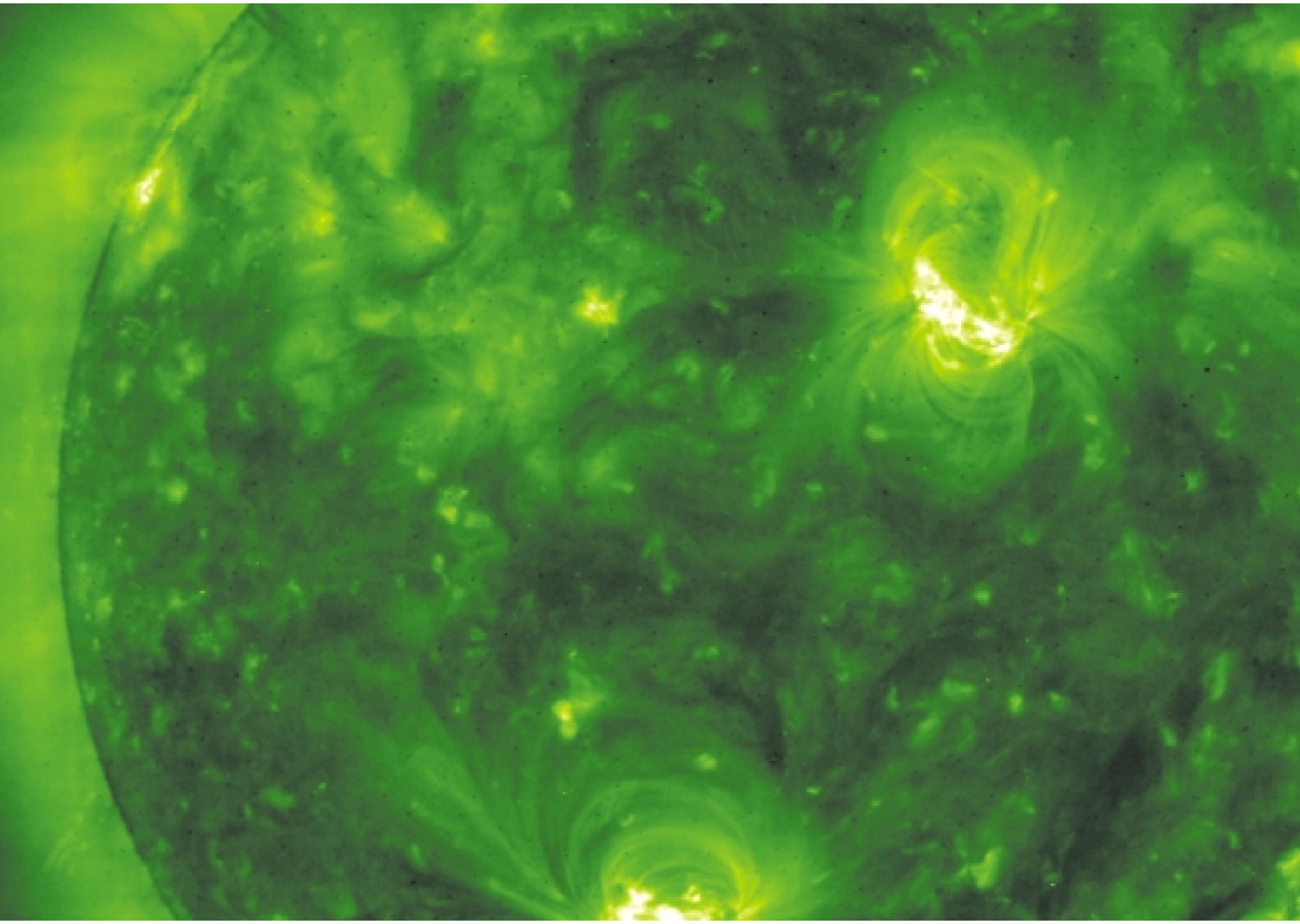
Our dynamic Sun and its surrounding planets will be understood as a system, including the effects of the Sun's life history on the origin and continuation of life in our Solar System. We will have gained the ability to predict and manage the effects of solar variability on Earth and on humans and machines in space. Our spacecraft will have ventured beyond the bubble of solar wind that surrounds the Solar System to take our first steps into interstellar space.

Thanks to technologies emerging today, Earthbound humanity will be able to participate actively in the great adventure of exploration. Our robotic emissaries to Mars and the other worlds in our Solar System will possess increasingly powerful capabilities for interaction with the home planet: virtual sight and sound, covering a broader spectrum of wavelengths and a far wider range of frequencies, will recreate on Earth the experience of exploring even the most forbidding environments in space. All our citizens will become space explorers.

The Hubble Space Telescope (HST) was designed to be a serviceable spacecraft. An astronaut uses the Power Ratchet Tool on an HST bay door while replacing the observatory's flight computer.

At the same time, a new generation of technology may permit more individuals, for a greater variety of reasons, to travel into space. It may be that future steps in understanding our place in the cosmos will be taken by a partnership between humans and machines in space. Complex optical systems, satellite subsystems, and instruments may be better updated, replaced, or repaired by human partners than by even very advanced remotely-operated robots. Trained geologists on Mars may one day amplify the capabilities of robotic collaborators used for large-area surveying and rapid reconnaissance by digging below the surface of dry riverbeds and along the shorelines of ancient oceans in search of the history of a biology—if any—beyond Earth.

One day, after our first planet-finding observatories have beamed back images of warm, wet worlds in orbit around neighboring stars, our descendants will begin to contemplate humanity's destiny of discovery beyond the Solar System.



The Solar and Heliospheric Observatory (SOHO) is a cooperative mission of ESA and NASA.

the space science enterprise

appendices

Table A

Science Objectives, Research Focus Areas, and New Near-Term Missions*

(Implementation Begins 2003-2007)

Science Objective	Research Focus Area	Mission Entering Implementation 2003–2007																	
		NGST	Con-X	ACCESS	LISA	SIM	TPF	MEP	Europa Lander	Pluto-Kuiper	Titan Explorer	CNSR	Astro-biology	Solar Probe	MMS	GEC	MagCon	SDO	NEO
Understand the structure of the universe, from its earliest beginnings to its ultimate fate	Identify dark matter and learn how it shapes galaxies and systems of galaxies	☐	☐																
	Determine the size, shape, age, and energy content of the universe		☐																
Explore the ultimate limits of gravity and energy in the universe	Discover the sources of gamma ray bursts and high energy cosmic rays			■															
	Test the general theory of relativity near black holes and in the early universe, and search for new physical laws using the universe as a laboratory		☐		■														
	Reveal the nature of cosmic jets and relativistic flows		☐																
Learn how galaxies, stars, and planets form, interact, and evolve	Observe the formation of galaxies and determine the role of gravity in this process	■	☐																
	Establish how the evolution of a galaxy and the life cycle of stars influence the chemical composition of material available for making stars, planets, and living organisms	☐	■																
	Observe the formation of planetary systems and characterize their properties	☐				☐	☐												
	Use the exotic space environments within our Solar System as natural science laboratories and cross the outer boundary of the Solar System to explore the nearby environment of our galaxy													☐	☐	☐	☐		
Look for signs of life in other planetary systems	Discover planetary systems of other stars and their physical characteristics					■	☐												
	Search for worlds that could or do harbor life					☐	■						☐						

Table A (continued)

Science Objective	Research Focus Area	Mission Entering Implementation 2003–2007																	
		NGST	Con-X	ACCESS	LISA	SIM	TPF	MEP	Europa Lander	Pluto-Kuiper	Titan Explorer	CNSR	Astro-biology	Solar Probe	MMS	GEC	MagCon	SDO	NEO
Understand the formation and evolution of the Solar System and Earth within it	Inventory and characterize the remnants of the original material from which the Solar System formed									■		■							
	Learn why the planets in our Solar System are so different from each other							❑		❑	❑								
	Learn how the Solar System evolves							❑	❑	❑	■	❑							
Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our Solar System	Investigate the origin and early evolution of life on Earth, and explore the limits of life in terrestrial environments that might provide analogues for conditions on other worlds												■						
	Determine the general principles governing the organization of matter into living systems and the conditions required for the emergence and maintenance of life												❑						
	Chart the distribution of life-sustaining environments within our Solar System and search for evidence of past and present life							■	■		❑		❑						
	Identify plausible signatures of life on other worlds												❑						
Understand our changing Sun and its effects throughout the Solar System	Understand the origins of long- and short-term solar variability													❑				■	
	Understand the effects of solar variability on the solar atmosphere and heliosphere													■				❑	
	Understand the space environment of Earth and other planets														■	■	■		
Chart our destiny in the Solar System	Understand forces and processes, such as impacts, that affect habitability of Earth																	❑	■
	Develop the capability to predict space weather														❑	❑	❑	❑	
	Find extraterrestrial resources and assess suitability of Solar System locales for future human exploration							❑											

*■=key (most important) research focus area addressed by a mission or program; ❑=other research focus areas addressed (a mission may have more than one).

Projects in the Discovery and Explorer programs of community-formulated missions that will proceed to implementation in the 2003–2007 period have not been proposed or selected yet, but are expected to make focused contributions in numerous areas.

Table B

Science Objectives and Representative Mission Concepts

(For Possible Implementation After 2007)

Representative Mission Concepts	Science Objectives							
	Understand the structure of the universe, from its earliest beginnings to its ultimate fate	Explore the limits of gravity and energy in the universe	Learn how galaxies, stars, and planets form, interact, and evolve	Look for signs of life in other planetary systems	Understand the formation and evolution of the Solar System and Earth within it	Probe the origin and evolution of life on Earth and determine if life exists elsewhere in the Solar System	Understand our changing Sun and its effects throughout the Solar System	Chart our destiny in the Solar System
Space infrared interferometric telescope	■		■					
Filled aperture infrared telescope	■		■					
Space VLBI		■	■					
X-ray interferometry pathfinder		■	■					
Orbiting wide-angle light collector	■	■						
Cosmic microwave background polarization	■							
Space ultraviolet optical telescope			■					
High resolution x-ray spectroscopy mission		■	■					
Energetic x-ray imaging survey telescope		■						
Interstellar probe			■				■	
Planet imager				■				
Life finder				■				
Future Mars Exploration					■	■		■
Neptune orbiter					■			
Venus surface sample return					■			
Saturn ring observer			■		■			
Europa subsurface explorer						■		
ITM wave imaging							■	
Solar polar imager							■	
Future Living With a Star							■	■

Section A-2

glossary of missions

Advanced Composition Explorer (ACE)—Measures energetic particles over a wide range of energy and mass, including the solar wind, solar particles, and the anomalous and galactic cosmic rays. The spacecraft measures the elemental and isotopic composition, from hydrogen to zinc, over the energy range of the cosmic rays from 100 eV to 500 MeV per nucleon for the charge range. ACE also provides realtime solar data from L1 for space weather applications.

Advanced Cosmic Ray Composition Experiment for the Space Station (ACCESS)—Attached payload for the International Space Station (ISS), it will measure the energy spectra from hydrogen to iron up to 10^{15} eV in order to test the supernova origin theory of cosmic rays.

Advanced Satellite for Cosmology and Astrophysics (ASCA)—Japanese x-ray imaging spectrometer mission. Launched in 1993, it served double its expected lifetime before suffering debilitating damage after an intense solar storm in July 2000.

Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG)—Balloon-borne instrument that measured tiny variations in the cosmic microwave background radiation in order to detect the earliest ancestors of today's galaxies and to obtain indications that the geometry of the universe is flat, not curved. Jointly supported in the U.S. by NASA and NSF, BOOMERANG's science team included members from Canada, Italy, and the United Kingdom.

Cassini-Huygens—International mission involving NASA, the European Space Agency (ESA), the Italian Space Agency (ASI), and several separate European academic and industrial partners. The spacecraft carries a sophisticated complement of scientific sensors supporting 27 different investigations to probe the mysteries of the Saturn system. The mission consists of a NASA orbiter and ESA's Huygens Titan probe.

Chandra X-ray Observatory (CXO)—High resolution imaging and spectroscopy mission to observe high-energy cosmic events such as pulsars, supernova remnants, and black holes.

Cluster-2—ESA-led mission to study plasma structures, boundary layers, and energy transfer in three dimensions both within Earth's magnetosphere and in the solar wind. The mission consists of four identical spacecraft, each carrying a full complement of fields and particles instrumentation, flying in tetrahedral formation.

Comet Nucleus Tour (CONTOUR)—Will study the aging processes of comets by examining diverse comet nuclei. Using an innovative trajectory design, this spacecraft will conduct close-up observations of two short period comets, Encke and Schwassmann-Wachmann 3, known from ground-based telescopic observations to have different properties. An encounter with a third short period comet may be possible if sufficient resources remain for an extended mission. This is the sixth Discovery mission.

Compton Gamma Ray Observatory (CGRO)—Simultaneously obtained gamma ray measurements in an energy range spanning six orders of magnitude from 30 KeV to 30 GeV. The mission made many fundamental discoveries, including the discovery that gamma ray bursts are not galactic phenomena as previously believed, and that active nuclei of distant galaxies are dynamic and prolific emitters of enormous amounts of energy in high-energy gamma rays. CGRO was deorbited in June 2000.

Constellation X (Con-X)—Mission to measure x-ray spectral lines in hot plasmas in order to determine the elemental composition, temperature, and velocity of the emitting matter. Objectives are to determine the flow of gas in accretion disks around black holes in active galactic nuclei and in binary x-ray sources, measure the abundances of newly created elements in supernova remnants, and detect the influence of dark matter on the hot intergalactic medium in clusters of galaxies.

Cosmic Background Explorer (COBE)—Made precise measurements of the diffuse radiation with wavelengths between one micrometer and one centimeter over the entire celestial sphere, providing the first major step forward in space-based cosmology. COBE verified beyond all reasonable doubt that the cosmic microwave background has a cosmological origin with tiny primordial perturbations from which large-scale structure in the present-day universe grew.

Cosmic Journeys—Proposed initiative to probe the most profound aspects of nature by using the universe as a laboratory. Within the Cosmic Journeys initiative, the Journey to a Black Hole probes more and more closely to these extreme states of gravity. The Journey to Dark Matter seeks to unravel the mysterious nature of the universe's "missing mass," matter that we cannot see but know is present due to its gravitational effect on the visible universe. And the Journey to the Beginning of Time explores the basic physics revealed in the first few instants of the universe, observing as far back as the first 10^{-32} seconds of time.

Deep Impact—Will determine the composition of pristine material in a comet nucleus. The spacecraft will send a 500 kilogram projectile into the nucleus of comet Temple 1 to excavate a crater deep enough to penetrate beneath the chemically-altered crust of the nucleus. Experiments on the spacecraft will then examine the properties of the ejected material and observe the structure of the crater. The eighth Discovery mission.

Deep Space-1 (DS-1)—Technology validation mission that successfully validated solar electric propulsion and a suite of eleven other high priority spacecraft technologies.

Discovery Program—Level-of-effort program offering the scientific community regular opportunities to propose low-cost deep space missions. Proposals are selected through competitive peer review, and selected teams have responsibility for implementation of the entire mission with minimal management oversight by NASA. Teaming arrangements among university, industry, and/or Government laboratories are encouraged. Discovery is the deep space counterpart of the Explorer program.

Europa Orbiter—Will orbit this icy moon of Jupiter to determine if there is an underlying ocean, determine the thickness of the ice, and image the complex features on its icy surface. To determine if there is an ocean, the orbiter may use radar sounding, high-resolution laser altimeters, and free-falling probes equipped with seismometers. As a possible liquid water habitat in our Solar System, Europa is a critical target in the search for life beyond Earth.

Explorer Program—Level-of-effort program to provide frequent, low-cost access to space for physics and astronomy investigations with small to mid-sized spacecraft. Investigations selected for Explorer projects are usually of a survey nature, or have specific objectives not requiring the capabilities of a major observatory.

Extreme Ultraviolet Explorer (EUVE)—Explorer mission to survey the entire sky in the extreme ultraviolet, discover the brightest sources in the sky, and perform detailed spectroscopic investigations of the EUV radiation from stars, nebulae, and galaxies. EUV radiation provides unique information concerning the physical and chemical properties of hot gas and plasma, and this information contributes to our knowledge of the matter and energy interactions between stars and the interstellar medium.

Far Infrared and Submillimeter Telescope (FIRST)—ESA-led mission to study objects that radiate a substantial portion of their luminosity in this band. This includes detecting dusty galaxies at cosmological distances when the universe was less than one billion years old, regular spiral galaxies out to intermediate redshifts, and dense molecular clouds in our galaxy where stars are currently being formed. This will allow a study of the dynamical and chemical evolution of galaxies and stars.

Far Ultraviolet Spectroscopic Explorer (FUSE)—Explorer mission conducting high-resolution spectroscopy of faint objects at wavelengths from 905 to 1,195 angstroms. FUSE is probing the interstellar medium and galactic halo to measure the amount of cold, warm, and hot plasma in objects ranging from planets to quasars, including primordial gas created in the Big Bang.

Fast Auroral Snapshot Explorer (FAST)—Small Explorer mission investigating the plasma physics of various auroral phenomena at extremely high time and spatial resolution. In polar orbit around Earth, the spacecraft carries fields and particle instrumentation and features fast data sampling and a large burst memory.

Full-sky Astrometric Mapping Explorer (FAME)—Explorer to determine accurate positions, distances, and motions of 40 million stars within our galactic neighborhood. FAME will measure stellar positions to less than 50 microarcseconds.

Galaxy Evolution Explorer (GALEX)—Explorer space ultraviolet mission to map the global history and causes of star formation over the redshift range $0<z<2$, 80 percent of the life of the universe. GALEX will also explore the period over which galaxies have evolved dramatically, and the time that most stars, elements, and galaxy disks had their origins.

Galileo Europa Mission (GEM)—Conducted the first comprehensive investigation of Jupiter, its magnetosphere, and its planet-size moons. On its arrival at Jupiter in December 1995, Galileo dropped an entry probe into the planet’s atmosphere that returned the first direct measurements of the physical properties and chemical composition of a gas giant planet. The orbiter discovered magnetic fields belonging to two of the satellites and has given us close-up views of their surfaces. The two-year Galileo Europa Mission, which focused primarily on the satellite Europa, followed the prime Galileo mission.

Gamma Ray Large Area Space Telescope (GLAST)—Mission to observe the gamma ray energy range from 20 MeV to 300 GeV. Fifty times more sensitive than the EGRET instrument on the Compton Gamma Ray Observatory, this instrument will observe thousands of active galactic nuclei (AGNs) and galactic sources, in addition to studying the more diffuse emissions from the Milky Way and other extended sources, including the diffuse all-sky background. A burst monitor will combine with the primary instrument to provide gamma ray burst observations over a wide energy range. Cooperative with the Department of Energy, Japan, and Europe.

Genesis—Mission to determine accurately the chemical composition of the Sun. The spacecraft will expose panels of ultra-pure materials to the solar wind for two years to collect samples of the material that continually streams off of the Sun. These samples will then be returned to Earth for detailed laboratory analysis. The fifth Discovery mission.

Geospace Electrodynamic Connections (GEC)—Near-term Solar Terrestrial Probe to help us understand how the interaction of Earth with the interplanetary medium is conditioned by the presence of Earth's atmosphere and its magnetic field. The mission will consist of four spacecraft following each other in the same orbit with variable spacing. The spacecraft generally fly in highly inclined elliptical parking orbits, but focused science campaigns will be conducted during satellite excursions down to 130 km or lower.

Geotail—ISAS-led mission to measure global energy flow and transformation in the magnetotail in order to increase our understanding of fundamental magnetospheric processes.

Global Geospace Science (GGS)—Consists of the Wind and Polar spacecraft and is part of the U.S. contribution to the International Solar Terrestrial Physics (ISTP) program. The objectives of GGS are to measure, model, and quantitatively assess geospace processes in the Sun-Earth interaction chain.

Gravity Probe B (GP-B)—Will test Einstein's general theory of relativity by measuring predicted dragging of space-time caused by the rotation of Earth. In order to make this measurement, GP-B will fly the world's most perfect sphere as a gyroscope. Also known as the Relativity Mission.

High Altitude Laboratory for Communications and Astrophysics (HALCA)—ISAS radio telescope in orbit that can be combined with large radio antennae on Earth to create a highly sensitive radio interferometric array. HALCA demonstrated the feasibility of space-Earth arrays and observation of fine structure in radio galaxies, jets from active galactic nuclei, and supernova remnants.

High Energy Solar Spectrographic Imager (HESSI)—Explorer mission to study the basic physics of the particle acceleration and explosive energy release in solar flares. HESSI will carry an x-ray and gamma ray imaging spectrometer with ultra-high temporal and spatial resolution in order to address the dynamic high-energy phenomena of the Sun.

High Energy Transient Explorer 2 (HETE 2)—Small mission to search for and detect the prompt x-ray and ultraviolet emission that may accompany gamma ray bursts, as well as measure their position and send the information to ground based optical telescopes fast enough to allow the prompt optical emission to be detected as well. Cooperative mission with Japan and France.

Hubble Space Telescope (HST)—Explores the universe in the visible, ultraviolet, and near-infrared regions of the electromagnetic spectrum. It is investigating the composition, physical characteristics, and dynamics of celestial bodies, examining the formation, structure, and evolution of stars and galaxies, studying the history and evolution of the universe, and providing a long-term space-based research facility for optical astronomy. Cooperative with ESA.

Imager for Magnetospheric to Aurora Global Exploration (IMAGE)—Explorer mission observing the response of Earth's magnetosphere to changes in the solar wind. The mission uses a combination of neutral atom, ultraviolet, and radio imaging techniques to provide global views of magnetospheric dynamics from a polar orbit.

Infrared Astronomical Satellite (IRAS)—Joint mission sponsored by the United Kingdom, the United States, and the Netherlands, that mapped the sky at infrared wavelengths. Mission ended in 1983.

Infrared Space Observatory (ISO)—ESA follow-on to IRAS, explored the "cool and hidden" universe through observations in the thermal infrared between 3 and 200 microns. Its objectives included studies of brown dwarfs in our galaxy, protoplanetary disks around nearby stars, and the evolution of galaxies.

International Gamma Ray Astrophysics Laboratory (INTEGRAL)—ESA-led gamma ray observatory dedicated to spectroscopy and imaging in the energy range 15 keV to 10 MeV. In addition to two gamma ray instruments it will have optical and x-ray monitors. This mission will study gamma ray lines from a range of astrophysical sources, giving us information on nucleosynthesis in supernovae, the supernova history of the Milky Way, active galactic nuclei, Seyfert galaxies, gamma ray bursts, and solar flare acceleration processes.

Keck Interferometer—Ground-based program to harness the twin 10-meter Keck telescopes together as a single instrument to search for planetary systems around other stars. This will complement and extend current ground-based planet detection capabilities and will serve as a prototype/test bed for future interferometers in space such as SIM and Terrestrial Planet Finder.

Laser Interferometer Space Antenna (LISA)—Joint NASA-ESA mission to detect and study in detail gravitational wave signals from massive black holes. This includes both transient signals from the terminal stages of binary coalescence, which we will call bursts, and binary signals that are continuous over the observation period.

Living With A Star (LWS)—Program to develop the scientific understanding of aspects of the connected Sun-Earth system that directly affect life and society, with specific emphasis on understanding the factors that affect human radiation exposure in space, the impacts of space weather on technical systems, and the effects of solar variability on the terrestrial climate. Program elements include the Solar Dynamics Observatory (SDO), Radiation Belt Mappers (RBM), Ionospheric Mappers (IM), and Sentinels missions; a program of space environmental test beds; and an associated theory, modeling, and data analysis program.

Lunar Prospector—Conducted the first global survey of minerals on the surface of the Moon. Of particular interest for future human exploration of the Moon, Lunar Prospector detected indications of water ice in the perpetually dark bottoms of craters near the north and south poles. The third Discovery mission.

Magnetospheric Multiscale (MMS)—Near-term Solar Terrestrial Probe to characterize the basic plasma processes that control the structure and dynamics of Earth's magnetosphere, with a special emphasis on meso- and micro-scale processes. The mission will consist of a constellation of five identical spacecraft, each carrying fields and particle instrumentation, flying in a variably spaced tetrahedron.

Magnetosphere Constellation (MagCon)—Solar Terrestrial Probe mission to understand the nonlinear dynamic responses and connections within Earth's magnetotail. It envisions placement of 50-100 autonomous micro-satellites, each carrying a minimum set of fields and particles instruments, into a variety of orbits.

Mars Exploration Program (MEP)—Program of successive Mars exploration missions to study: the solid planet, how it evolved, and what resources it provides for future exploration; the relationship to Earth's climate change process; and the potential for life there and elsewhere in the universe. The exploration series began with Mars Global Surveyor to orbit Mars and map the planet at infrared and visible wavelengths and observe selected areas at very high-resolution. MEP data will help us understand the geological and climatological history of the planet and lay the groundwork for choosing the sites for surface missions. The subsequent two missions, Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL), were lost in 1999. Two geologic exploration rovers will be launched in 2003. Additional orbiter and lander missions to follow are under study.

Mars Pathfinder—Paved the way for future low-cost, robotic missions to Mars. The mission deployed a micro-rover named Sojourner on the Martian surface and acquired geological and meteorological data to characterize the surface composition, geology, morphology, and atmospheric structure and conditions in Ares Valles. The second Discovery mission.

Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER)—Will conduct a comprehensive global survey of Mercury's interior structure, surface composition, geological processes, tenuous atmosphere, and magnetic field. The spacecraft will operate in orbit around Mercury for approximately one Earth year. The seventh Discovery mission.

Microwave Anisotropy Probe (MAP)—Follow-on to the successful COBE mission, MAP is a medium-class Explorer to measure the fluctuations in the cosmic microwave background with sufficient sensitivity to infer whether the first large structures in the universe after the Big Bang were galaxies or large clusters of galaxies. MAP's observations will also be sensitive enough to determine the total amount of dark matter in the early universe.

MUSES-C—ISAS-led mission to return a sample from an Earth-approaching asteroid. NASA will contribute a microrover to explore the asteroid's surface.

Near Earth Asteroid Rendezvous (NEAR)—In orbit around Earth-approaching asteroid Eros, NEAR is conducting the first comprehensive investigation of the physical properties and mineral characteristics of one of these small bodies. The first Discovery mission.

New Millennium Program (NMP)—Flight program to demonstrate new technologies in space.

Next Generation Space Telescope (NGST)—Follow-on observatory to HST to study the formation of galaxies at near infrared wavelengths. It will combine a collecting area 10 times larger than HST with spectrometers optimized for near infrared radiation.

Planck—ESA-led third generation mission for exploring the fluctuations and anisotropies in the cosmic microwave background. Planck will improve previous measurements of the background by a factor of five.

Pluto/Kuiper Express—Miniaturized spacecraft to fly past the Pluto/Charon system and conduct a reconnaissance of the only planet that has not been visited heretofore by a spacecraft. Following the Pluto/Charon encounter, the spacecraft may be redirected to survey a diverse collection of icy Kuiper Belt objects beyond the orbit of Neptune.

Polar—Measures the entry of plasma into the polar magnetosphere, determines the ionosphere plasma outflow, obtains auroral images, and determines the energy deposited into the ionosphere and upper atmosphere. Polar is the second spacecraft in the Global Geospace Science program; it carries in situ fields and particles instrumentation and a remote sensing imager.

Roentgen Satellite (ROSAT)—International collaborative mission to observe and map x-ray emissions from galactic sources. ROSAT studied coronal x-ray emissions from stars of all spectral types, detecting and mapping x-ray emissions from galactic supernova remnants, evaluating the overall spatial and source count distributions for various x-ray sources. Additionally, ROSAT performed detailed studies of various populations of active galaxy sources, conducting morphological studies of the x-ray emitting clusters of galaxies, and performing detailed mapping of the local interstellar medium. Cooperative with Germany and the United Kingdom.

Rossi X-ray Timing Explorer (RXTE)—Explorer mission to detect fluctuations in the x-ray intensity of cosmic sources that occur as rapidly as one millisecond or less. RXTE also studies the x-ray emission over a broad spectral band and a wide range of time scales in x-ray sources of all kinds. These capabilities enable astronomers to study accretion onto black holes in sources as different as x-ray binaries in our galaxy and the cores of active galaxies and quasars millions of light-years away.

Solar and Heliospheric Observatory (SOHO)—ESA-led mission, component of the International Solar Terrestrial Physics program, to study the internal structure of the Sun, its outer atmosphere, and the origin of the solar wind. The spacecraft carries instruments devoted to helioseismology, remote sensing of the solar atmosphere, and in situ measurement of solar wind disturbances.

Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX)—A small Explorer mission to investigate the origins and dynamics of solar energetic particles, heavy ions and electrons in the radiation belts, and anomalous cosmic rays. Its instruments observe the energy range from low energy solar particles to galactic cosmic rays.

Solar Dynamics Observer—First mission in the Living with a Star program, will observe the outer layers of the Sun to determine the Sun's interior dynamics and the origin of solar activity and coronal mass ejections.

Solar Probe—Will make the first measurements within the atmosphere of a star and will answer long-standing questions about how and where the corona is heated and how the solar wind is accelerated. The spacecraft, which will carry both imaging and in situ instrumentation, is targeted to pass within three solar radii of the Sun's surface.

Solar Terrestrial Probes (STP)—Program of successive missions to perform a systematic study of the Sun-Earth system. Its major goals are to provide an understanding of solar variability on time scales that range from a fraction of a second to many centuries and to determine planetary and heliospheric responses to this variability. The line begins with TIMED and is expected to continue near-term with Solar-B, STEREO, Magnetospheric Multiscale, Global Electrodynamic Connections, and Magnetospheric Constellation.

Solar Terrestrial Relations Observatory (STEREO)—Near-term Solar Terrestrial Probe to understand the origin and development of coronal mass ejections and trace the propagation and evolution of these disturbances from the Sun to Earth. The mission will consist of two identical spacecraft, one leading and the other lagging Earth in its orbit. Both spacecraft will carry instrumentation for solar imaging, for the tracking of solar ejection heading toward Earth, and for in situ sampling of the solar wind.

Solar-B—ISAS-led mission to reveal the mechanisms that give rise to solar variability and study the origins of space weather and global change. The spacecraft, which will be placed in polar Earth orbit, will make coordinated measurements at optical, EUV, and x-ray wavelengths, and will provide the first measurements of the full solar vector magnetic field on small scales.

Space Interferometry Mission (SIM)—First optical interferometer in space and a technological precursor to the Terrestrial Planet Finder. SIM will allow indirect detection of planets through observation of thousands of stars and investigate the structure of planetary disks with nulling imaging.

Stardust—Will fly through the coma of comet Temple-II, collect a sample of cometary dust, and return the sample to Earth for detailed laboratory analysis. A suite of remote-sensing instruments on the spacecraft will also investigate various physical and chemical properties of the comet. The fourth Discovery mission.

Stratospheric Observatory for Infrared Astronomy (SOFIA)—The next generation airborne observatory, SOFIA will provide astronomers routine access to the infrared and submillimeter part of the electromagnetic spectrum. It will observe a wide range of phenomena, from the formation of planets, stars, and galaxies, to the evolution of complex organic molecules in interstellar space. SOFIA will be ten times more sensitive than its predecessor, the Kuiper Airborne Observatory, enabling observations of fainter objects and measurements at higher spectral resolution. Cooperative with Germany.

Space Infrared Telescope Facility (SIRTF)—The fourth of NASA's Great Observatories and a follow-on to the Infrared Astronomical Satellite (IRAS). SIRTF will perform imaging and spectroscopy in the infrared of the formation of stars and planets and will investigate the evolution of luminous galaxies.

Submillimeter Wave Astronomy Explorer (SWAS)—Small Explorer mission to study water and other similar molecules throughout the galaxy. By measuring the density and distribution of these materials, the origin of ingredients necessary for life on Earth can be determined.

Swift Gamma Ray Burst Explorer—Explorer mission multiwavelength observatory for gamma ray burst astronomy. Swift has a complement of three co-aligned instruments. Two are an x-ray and a UV/optical focusing telescope that will produce arcsecond positions and multiwavelength light curves for gamma ray burst (GRB) afterglow. A third instrument is a wide field-of-view coded-aperture gamma ray imager that will produce arcminute GRB positions onboard within 10 seconds.

Terrestrial Planet Finder (TPF)—Currently envisioned as a long baseline infrared interferometer operating in the 7-20 micron wavelength range for direct detection of terrestrial planetary companions to other stars and of spectral signatures that might indicate a habitable planet.

Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED)—Solar Terrestrial Probe to understand the basic energetic and dynamics of the region where Earth's atmosphere transitions to space. The spacecraft, which will fly in a 600-km circular Earth orbit, carries remote sensing instrumentation that will be supplemented by significant collaborative investigations.

Titan Explorer—Mission to follow up on the scientific results at Titan expected from the Huygens probe and Cassini orbiter. Detailed study of the organic-rich environment of Titan may be of key importance to studies of pre-biotic chemistry.

Transition Region and Coronal Explorer (TRACE)—Small Explorer mission exploring the connection between fine-scale solar magnetic fields and the associated plasma structures. The spacecraft, which is in Sun-synchronous Earth orbit, carries a EUV/UV telescope for studies of fast-evolving dynamic phenomena on the Sun at one arc-second spatial resolution.

Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS)—An Explorer program-supported Mission of Opportunity payload with the goal of assessing the geo-response to solar wind input. This will be accomplished through analysis of the first stereo views of Earth's magnetosphere, which will be provided by the flight of a pair of energetic neutral atom imagers on spacecraft with complementary orbits.

Ulysses—ESA-led mission to explore the high-latitude regions of the Sun and inner heliosphere. The spacecraft passes over the Sun's poles at a distance of about 2 AU and carries a variety of fields and particles instruments.

Voyager Interstellar Mission (VIM)—Combines the capabilities of the Voyager 1 and 2 spacecraft to explore the region where the Solar System merges with the interstellar medium and to sample the local interstellar medium itself. These spacecraft are now both beyond the orbit of Pluto and are speeding toward the edge of the Solar System.

Wind—Part of the Global Geospace Science Program. The goals of Wind are to determine the characteristics of the solar wind upstream of Earth and to investigate basic plasma processes occurring in the near-Earth solar wind. It also carries two modest-sized gamma ray burst instruments for measuring the spectra and count rate time-history of gamma ray bursts.

X-ray Multiple-mirror Mission (XMM)—ESA-led x-ray spectroscopy mission to determine the abundance and density of iron, silicon, oxygen, and other heavy elements in stars and x-ray binaries. An understanding of the cycling of these elements between stars and the interstellar medium is necessary for studying the formation of planets.

Yohkoh—ISAS-led mission to better understand the birth and evolution of various forms of solar activity, especially solar flares. Because x-rays outline the magnetic structure of the Sun's outer atmosphere, the spacecraft carries instrumentation that combines hard and soft x-ray imaging and spectroscopy.

Section A-3 enterprise concurrence a

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Jupiter as seen in October 2000 by the Cassini spacecraft as it speeds by on its way to Saturn. Jupiter's moon Europa, seen as the bright point at the right, casts its shadow on the planet.

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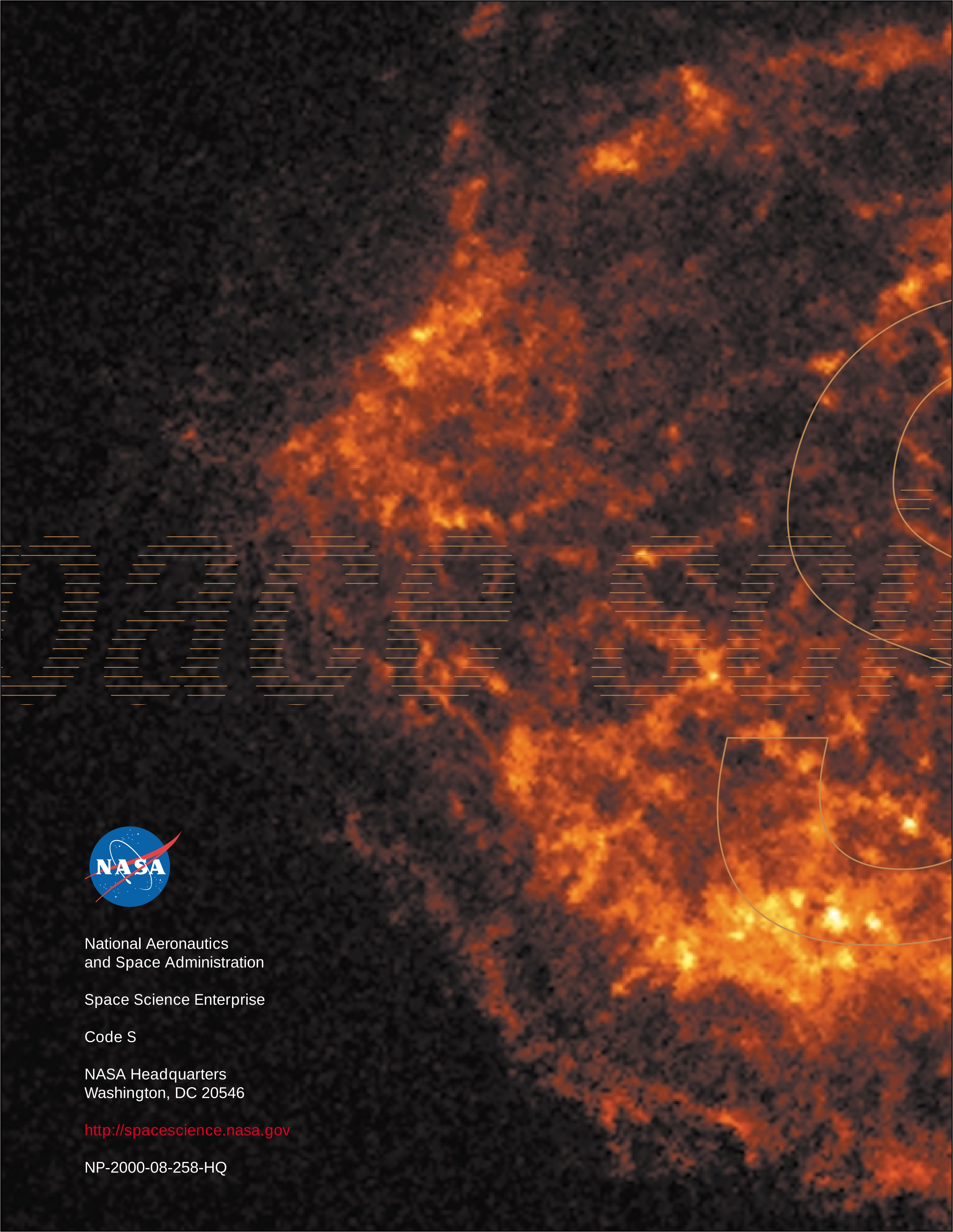

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