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

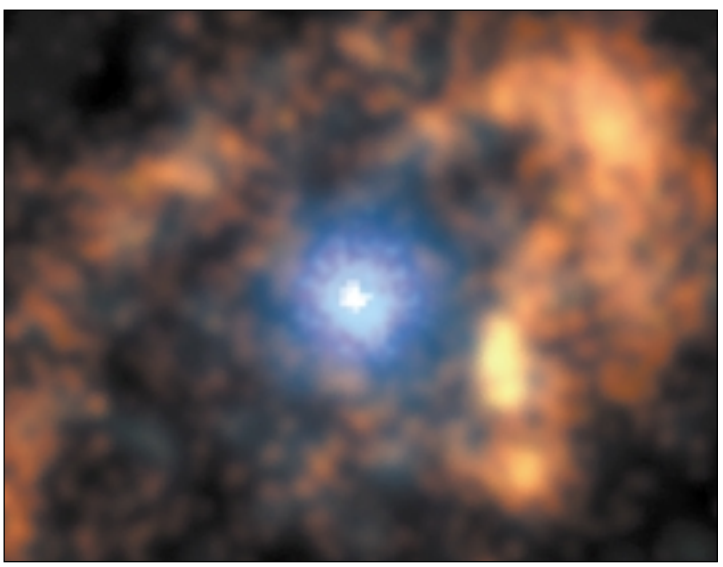
The Space Science Enterprise has made exciting advances in many goal areas during recent years. In this subsection, we briefly describe progress in astrophysics and cosmology, Solar System exploration, technology, and education and public outreach programs.

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.

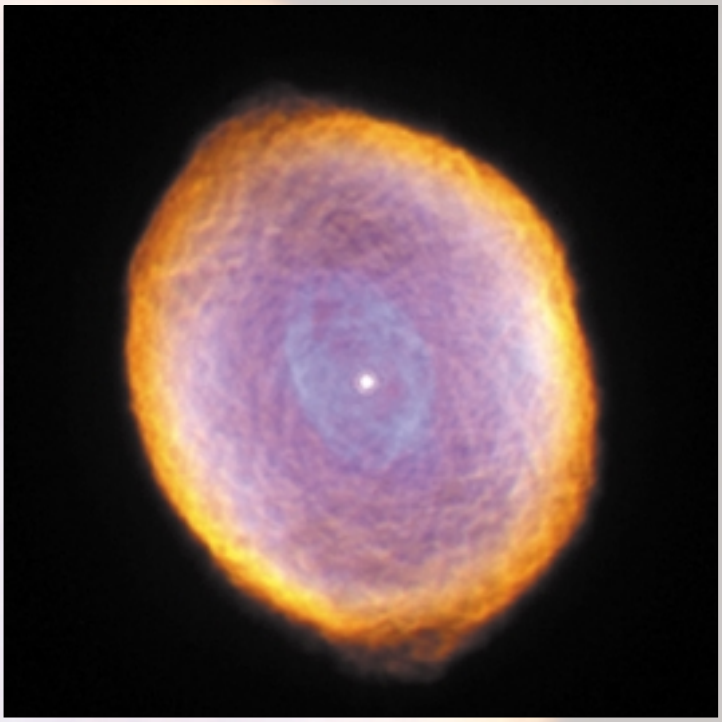
Two x-ray satellites, the **Rossi X-ray Timing Explorer (RXTE)** and the Japanese-U.S. **ASCA** mission, have helped us understand disks of accreting material in binary systems and provided evidence for spinning black holes in active galactic nuclei.

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.

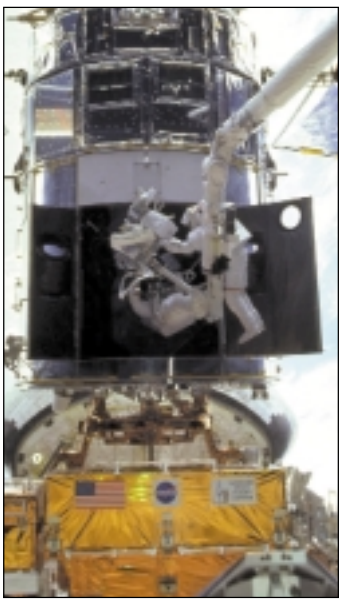


Glowing like a multi-faceted jewel, the planetary nebula IC 418 lies about 2,000 light-years from Earth in the constellation Lepus. The Hubble Space Telescope reveals some remarkable textures weaving through the nebula. Their origin is still uncertain.

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.

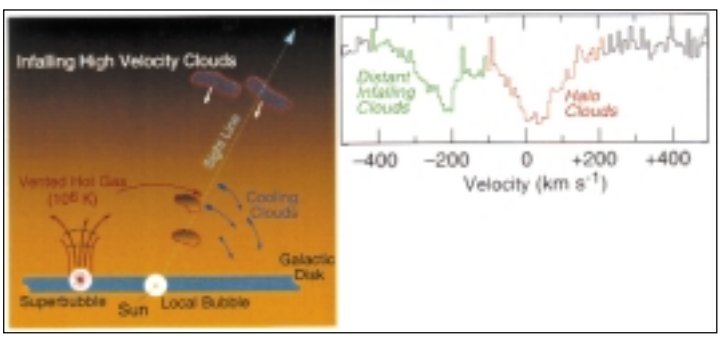
Another recent mission, the **Submillimeter Wave Astronomy Satellite (SWAS)** studies the processes of star formation by observations of water, molecular oxygen, isotopic carbon monoxide, and atomic carbon. Results of observations of dark interstellar clouds, evolved stars, external galaxies, and planetary 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.

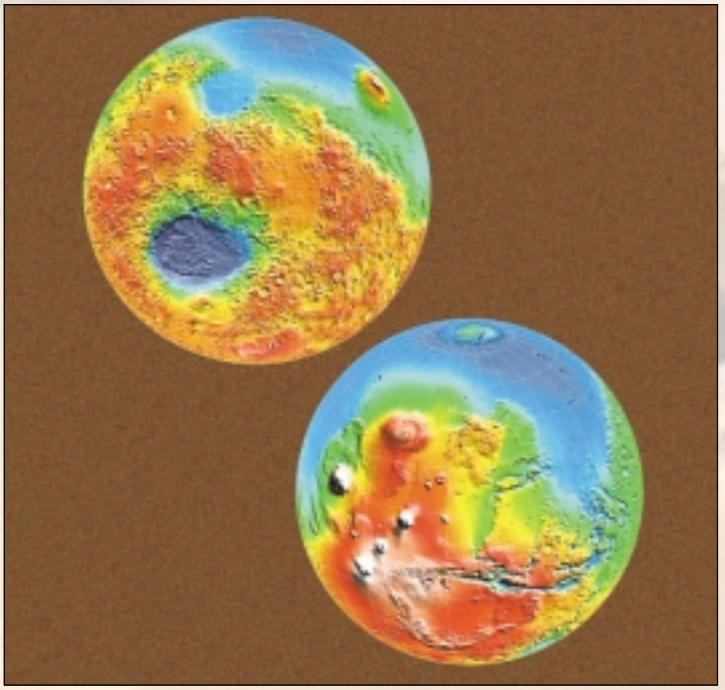
The **Far Ultraviolet Spectroscopic Explorer (FUSE)** is providing very high resolution ultraviolet spectra of the interstellar medium, giving information on the chemical content of material between stars and galaxies. The ultimate goal is to discover the conditions at the time of the Big Bang and how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

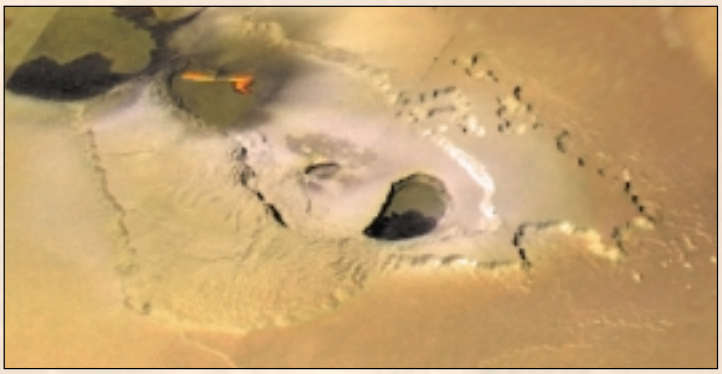
Over the past few years, NASA-supported ground-based research has discovered dozens of sub-stellar companions orbiting nearby stars.

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





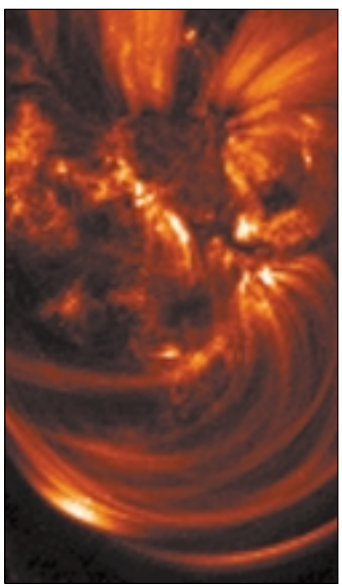
Top:
Global topographic map of Mars. The Mars Orbiter Laser Altimeter (MOLA) instrument on the Mars Global Surveyor spacecraft suggests what was once a vast ocean (blue indicates lower elevations).

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.

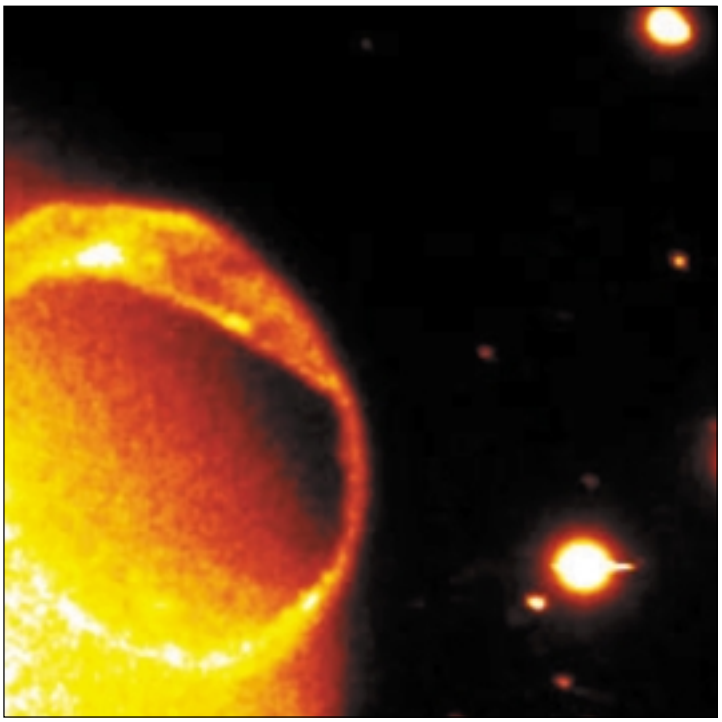


Left: This NEAR-Shoemaker image taken from an orbital altitude of 38 kilometers brings home the irregularity of the tiny world called Eros. Looking down the length of the asteroid, one sees near, middle, and far horizons. The whole scene is about one kilometer across.

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.

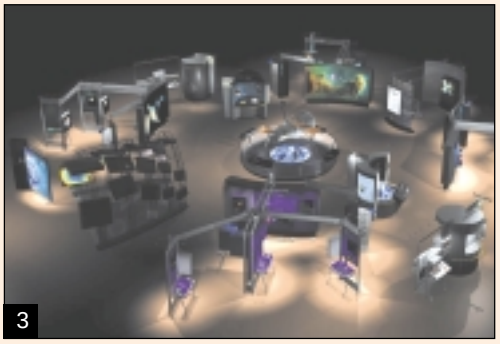
Examples of Education and Public Outreach Activities Underway

1

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.

2


3

4

5

Missions Currently Under Development

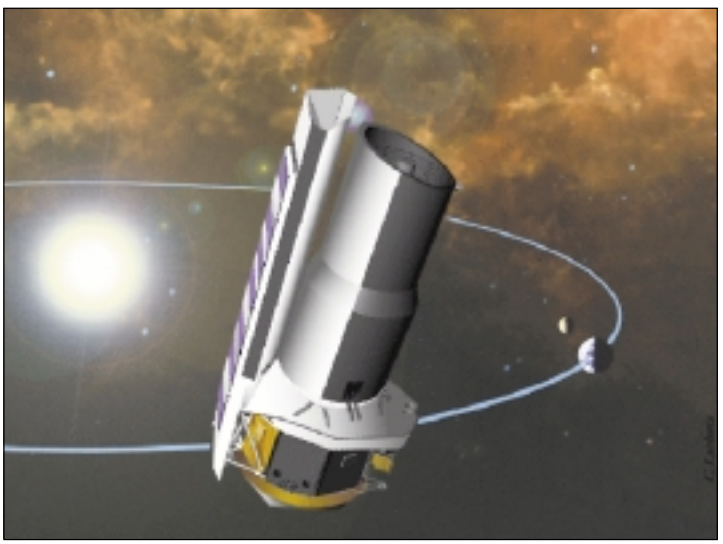
Building on the exciting results of missions completed or still operating, many missions that were only proposals in our 1997 plan are graduating from their study phases into development and will be launched within the next few years.

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. 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.

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

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.

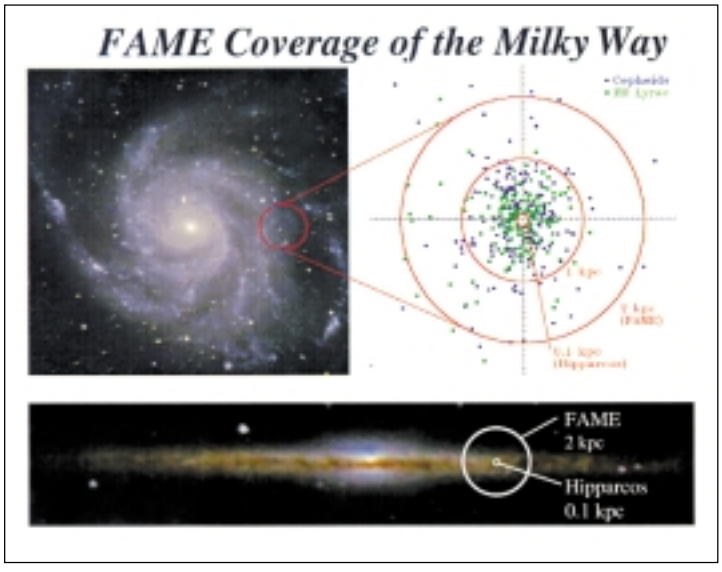
SOFIA will involve educators directly in its research programs by flying them on the observatory itself and centering its education and public outreach programs on these opportunities.

The 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.

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.

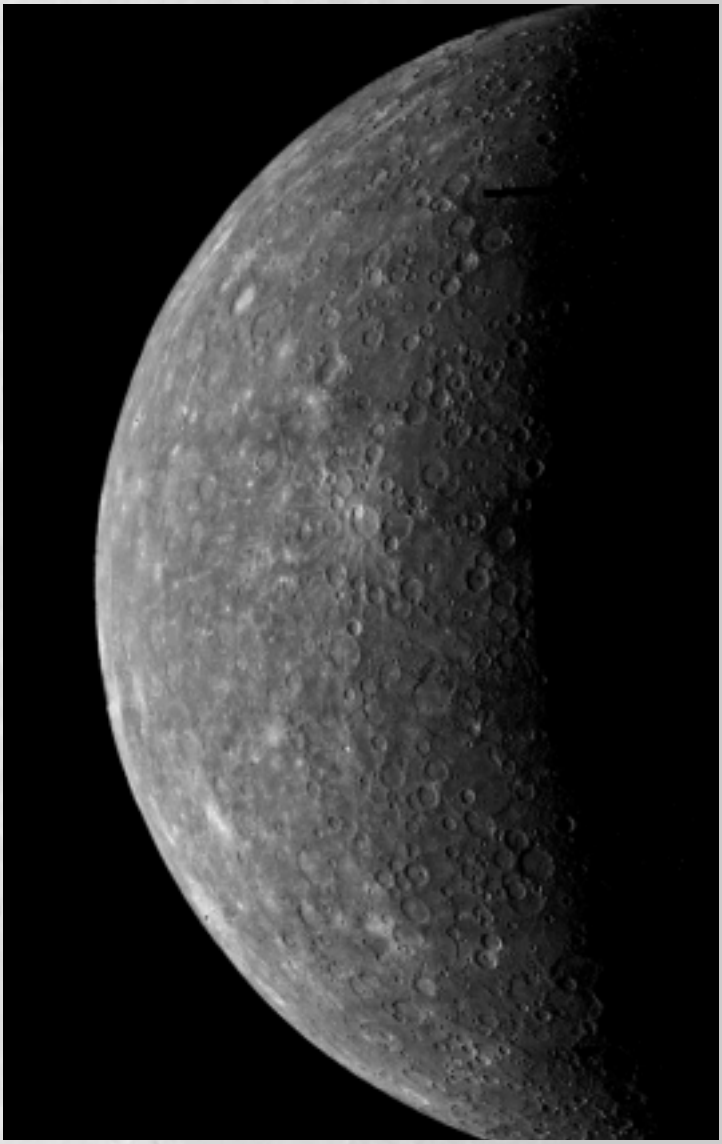
Planning and development continues for new missions in the **Mars Exploration Program (MEP)**. The losses of the Mars Climate Orbiter and Mars Polar Lander in 1999 were severe blows to the program, but scientific interest in Mars as a laboratory for comparative planetology and as a possible home for 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.

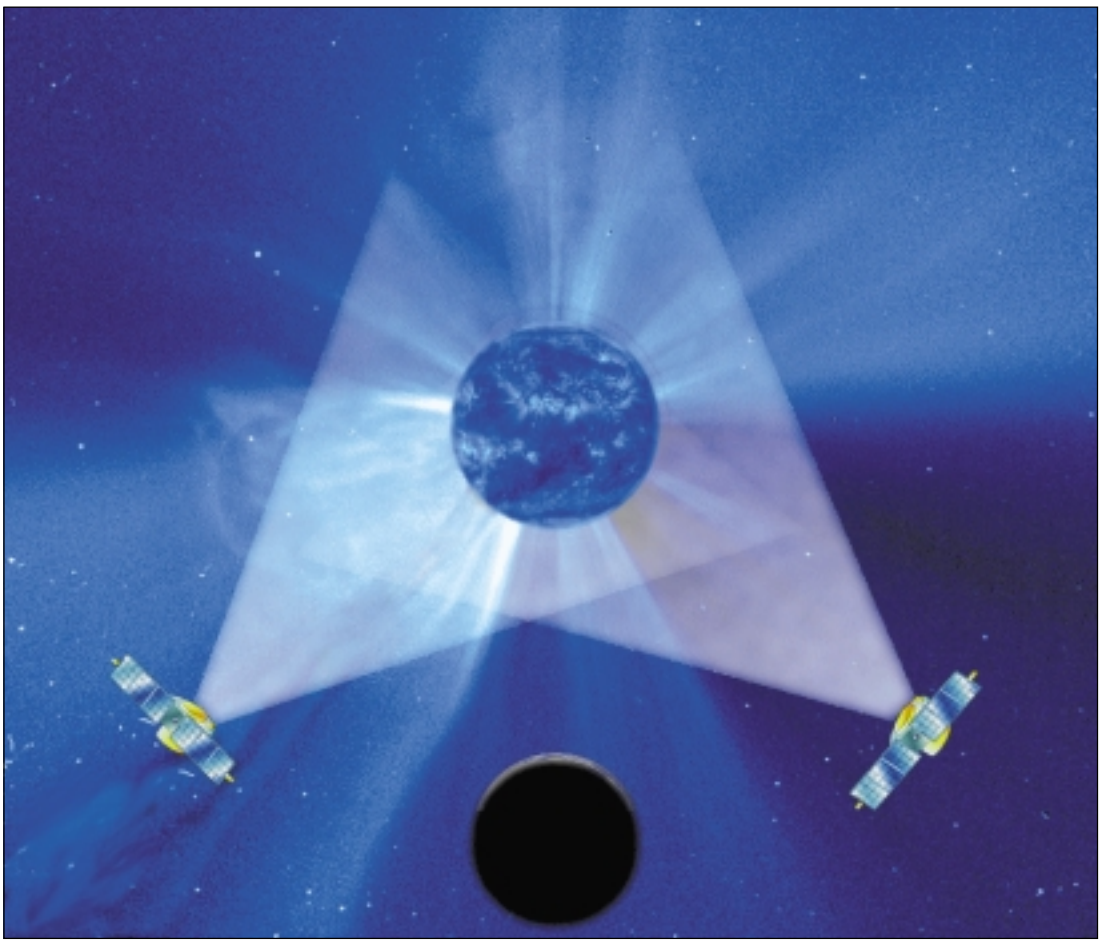
Geochemistry and Ranging (MESSENGER) mission, will study how the inner Solar System formed by analyzing the physical properties and chemical composition of the closest planet to the Sun. The planet Mercury will be the focus of an ambitious education and public outreach program aligned with National Science 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 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 Galileo Europa Mission's intensive study of Europa has yielded evidence for a global liquid water ocean beneath the icy crust.

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.