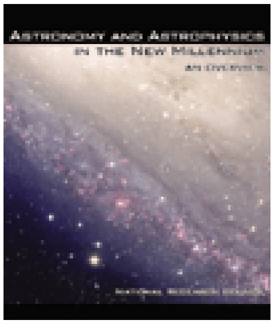
Astronomy and Astrophysics in the New Millennium: An Overview



Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, National Research Council

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Astronomy and Astrophysics in the New Millennium

An Overview

Astronomy and Astrophysics Survey Committee

Board on Physics and Astronomy

Space Studies Board

Division on Engineering and Physical Sciences

National Research Council

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Washington, D.C.

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Text drafted by Donald Goldsmith.

Layout and graphic design by Robert Sokol.

Additional contributions to the text from Alan Dressler, Christopher McKee, Donald Shapero, and Joel Parriott.

This report was reviewed in draft form by Gordon Baym, University of Illinois at Urbana-Champaign; Anita Cochran, University of Texas; Sharon Dunwoody, University of Wisconsin; Sandra Faber, University of California, Santa Cruz; John Huchra, Harvard-Smithsonian Center for Astrophysics; Richard McCray, University of Colorado; and J. Anthony Tyson, Bell Labs, Lucent Technologies. The review was overseen by Lewis Branscomb, Harvard University. Responsibility for the final content of this report rests entirely with the authors and the institution.

IMAGE CREDITS

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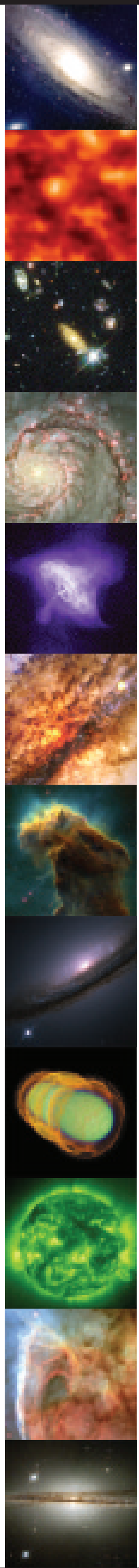


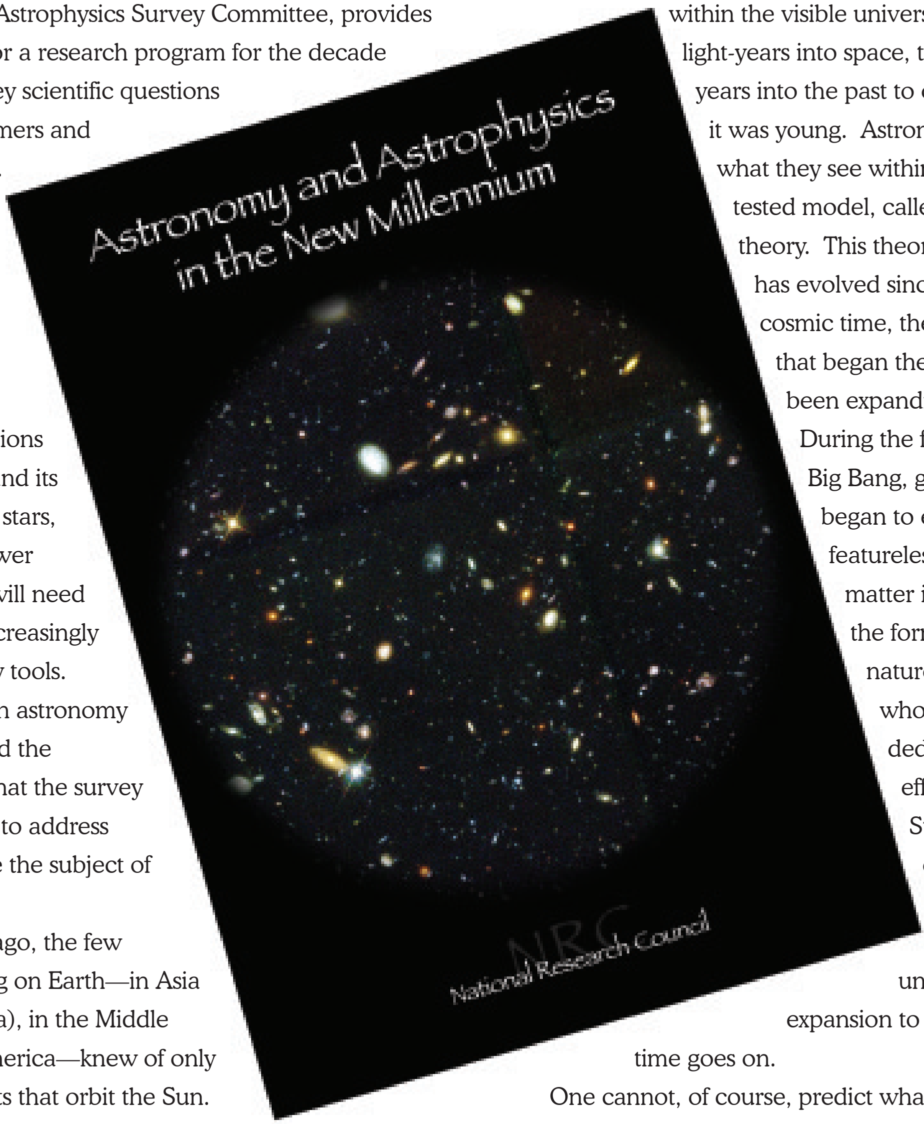
ASTRONOMERS EXPLORE THE UNIVERSE

ASTRONOMY and Astrophysics in the New Millennium is the most recent in a series of surveys of the field conducted once every 10 years by committees of leading astronomers. The current survey, authored by the Astronomy and Astrophysics Survey Committee, provides recommendations for a research program for the decade that addresses the key scientific questions confronting astronomers and astrophysicists today. The explosion of knowledge in recent years, made possible by current facilities, has in turn raised a wealth of intriguing new questions about the universe and its constituent galaxies, stars, and planets. To answer them, astronomers will need a diverse array of increasingly capable 21st-century tools. Current challenges in astronomy and astrophysics, and the research initiatives that the survey report recommends to address them (see p. 28), are the subject of this booklet.

One millennium ago, the few astronomers working on Earth—in Asia (particularly in China), in the Middle East, and in Mesoamerica—knew of only six of the nine planets that orbit the Sun. Although they studied the stars, they did not understand that these points of light were as mighty as our own Sun, nor could they imagine the vast distances that separate these stars from Earth. One millennium later humanity's astronomical horizons, enlarged by observations made from every part of our planet and above it, had expanded to include the entire universe.

Today we know that the Sun is but one of 300 billion stars in the Milky Way Galaxy, which itself is but one of trillions of galaxies within the visible universe. By peering billions of light-years into space, telescopes look billions of years into the past to observe the cosmos when it was young. Astronomers can now interpret what they see within the framework of a well-tested model, called the inflationary Big Bang theory. This theory describes how the cosmos has evolved since the first 10^{-36} second of cosmic time, the moment of the Big Bang that began the universe. The universe has been expanding ever since that moment. During the first billion years after the Big Bang, galaxies and galaxy clusters began to emerge from a relatively featureless cosmos. Most of the matter in the universe exists in the form of dark matter, whose nature remains a mystery but whose existence is convincingly deduced from its gravitational effect on visible matter. Startling new observational evidence points to an even more mysterious dark energy that pervades the universe, driving the expansion to ever-greater velocities as time goes on.

One cannot, of course, predict what astronomers will tell us in the year 3000 A.D., or even in 2100 A.D. For the foreseeable future of the next few decades, we can, however, summarize the defining issues for astronomy and astrophysics by posing five fundamental questions:



Cover of the current survey report.

- How did the universe begin, how did it evolve from a primordial soup of elementary particles into the complex structures we see today, and what fate lies in store for the cosmos?
- How do galaxies first arise and mature?
- How are stars born and how do they live and die?
- How do planets form and change as they age?
- Does life exist elsewhere in the universe?

Researchers have now begun to gather the fundamental observational data that will one day answer all of these questions. For only one do we already have a fairly complete answer: We know about the lives of stars. The development and observational validation of the theory of what astronomers call stellar evolution was arguably the greatest accomplishment of 20th-century astrophysics. For the new century, astronomers' long-term goal is to assemble a detailed picture of the formation, evolution, and destiny of the universe, and of its constituent galaxies, stars, and planets, which include the Milky Way, the Sun, and Earth.

FOURTEEN billion years of cosmic evolution since the Big Bang have spawned the mighty zoo of cosmic objects that populate the universe today. On one of these objects lives a species on the verge of fitting together the pieces of this puzzle of how the universe came to be the way it is. We humans are about to understand how we came to inhabit a small rocky planet in orbit around a rather average star in the outer arms of the spiral galaxy we call the Milky Way. That understanding will reveal to us the ultimate fate of the universe.

To achieve this goal, the Astronomy and Astrophysics Survey Committee believes that astronomers should carry out the following program of observational and theoretical research:

- Map the distribution of galaxies, gas, and dark matter in the universe, and survey the stars and planets in the Milky Way. Mapping the distant universe will help to reveal the formation of galaxies in the early universe and their maturation to the present, the evolution of primordial hydrogen and helium gas created in the Big Bang into gas enriched with almost all of the elements found in the periodic table, and the distribution and nature of the mysterious dark matter that constitutes most of the matter in the universe. Surveys within the Milky Way will help to reveal how stars and planets are created in collapsing clouds of gas and dust and the variety and abundance of planetary systems.
- Search for life beyond Earth, and, if it is found, determine its nature and its distribution in the Milky Way Galaxy. This goal is so challenging and of such importance that it could occupy astronomers for the foreseeable future. The search for evidence of life beyond Earth through remote observation is a major focus of the new interdisciplinary field of astrobiology.
- Use the universe as a unique laboratory to test the known laws of physics in regimes that are not accessible on Earth and to search for entirely new physics. It is remarkable that the laws of physics developed on Earth appear to be consistent with phenomena occurring billions of light-years away and under extreme conditions radically different from those under which the laws were derived and tested. Researchers have only begun to probe the conditions near the event horizons of black holes or in the very early universe. In these environments, the tests of the laws of physics will be much more stringent. New physical processes may be revealed that shed light on the unification of the forces and particles of nature.
- Develop a conceptual framework that accounts for the complete range of astronomical observations. As with all scientific theories, such a framework must be subject to continual checks by further observation.

For the new decade, astronomers are poised to make progress in five particular areas:

1. Determining the large-scale properties of the universe: its age, the types of matter and energy that it contains, and the history of its expansion;
2. Studying the dawn of the modern universe, when the first stars and galaxies formed;
3. Understanding the formation and growth of black holes of all sizes;
4. Studying the formation of stars and their planetary systems, including the birth and evolution of giant and terrestrial planets; and
5. Understanding the effects of the astronomical environment on Earth.

THE TELESCOPE AS A TIME MACHINE

ASTRONOMY is history. Because light takes time to travel from one place to another, we see objects not as they are now but as they were at the time when they released the light that has traveled across the universe to us. Astronomers can therefore look farther back through time by studying progressively more-distant objects.

The chief difficulty in employing this "time machine" to observe the cosmos during its past epochs arises from the fact that distant objects appear fainter than closer ones. We must therefore capture and analyze the light from progressively dimmer objects as we push farther back into the past. Specialized instruments are needed to study our nearest neighbor, the Andromeda Galaxy, which is 2 million light-years away. But this companion of the Milky Way shines a million times more brightly than a similar galaxy seen at a distance of 2 billion light-years! This comparison gives a sense of how difficult it will be to obtain images of objects formed close to the Big Bang era more than 10 billion years ago.

During the past few years, the Hubble Space Telescope has obtained long-exposure images that reveal the faintest objects ever detected. Some of these objects are galaxies seen during their early developmental stages when they were rich in young, hot, and very luminous stars. To peer still farther back through time, to reach the era when stars first began to shine, astronomers need a telescope that can detect extremely low intensities of infrared light. Astronomers need sensitivity in the infrared part of the spectrum because the light from these young stars in distant galaxies, even though emitted as visible light, has been stretched by the expansion of the universe to appear to us as infrared light.

The Hubble Space Telescope can observe the shortest-wavelength portion of the infrared domain, but its 2.4-meter mirror is too warm and too small to detect the faint glow from the most distant young galaxies. To observe galaxies in their earliest epochs, the survey report recommends a new, advanced-technology telescope designed to work best in the infrared part of the spectrum. In an orbit a million miles from Earth, this telescope will become so cold that its own infrared glow will be insignificant compared with the light from the distant galaxies, something an earthbound telescope could never achieve. Also, being above Earth's veil of air allows us to see radiation that cannot penetrate it, and guarantees the sharpest images the telescope can deliver, free from the turbulence in Earth's atmosphere that handicaps telescopes on the ground.

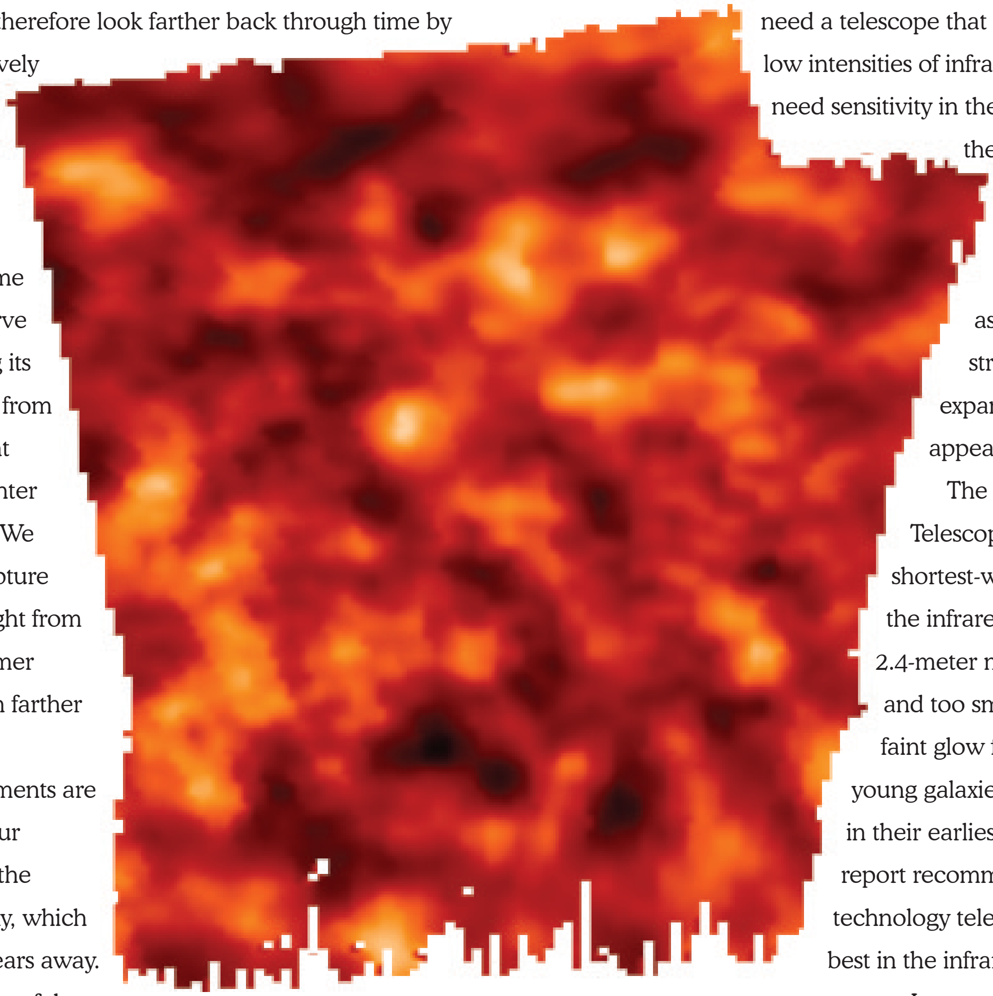


Image of tiny fluctuations in the universe's oldest light, only 300,000 years after the Big Bang. There is no way for astronomers to see farther back than this electromagnetic brick wall. Future tools for detecting gravitational radiation offer the promise of breaking through this wall to even earlier times.

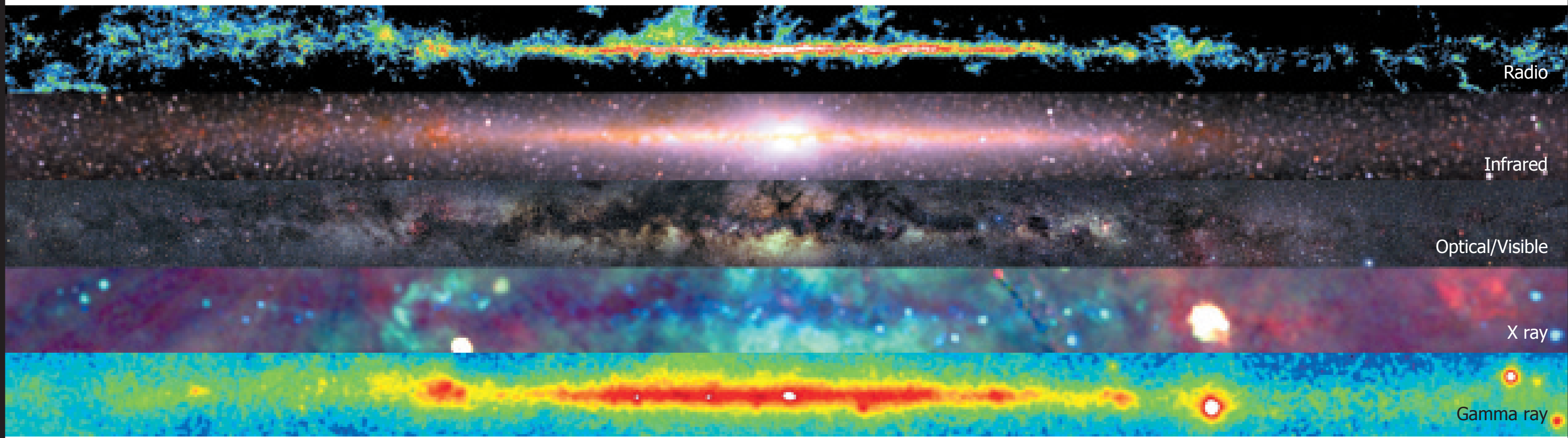
The Quest to Broaden Our Cosmic View

In their quest to improve our ability to observe the universe, astronomers have followed two lines of technological development. First, they have designed and constructed increasingly powerful telescopes and detectors, capable of observing progressively fainter sources with greater clarity. During the next decade, astronomers will construct telescopes with ever finer resolution, and will also link these instruments to create systems whose observational precision equals that of a single giant telescope as large as the maximum separation of the individual instruments. Second, as a more subtle but equally important way to widen our observational capabilities, astronomers have attempted to study different regions of the spectrum of electromagnetic radiation. This spectrum includes a variety of waves that differ in their wavelengths of vibration. Only a tiny part of the spectrum includes the waves that our eyes can detect. We call these waves "light," and our eyes and brains recognize the different wavelengths of light as different colors.

Every type of atom or molecule produces radiation, or blocks radiation from other sources, only at particular wavelengths. Observations over the total array of wavelengths therefore provide a "cosmic fingerprint" that reveals the different varieties and numbers of atoms and molecules in the objects whose radiation we can study in detail. By measuring this fingerprint from any cosmic source of radiation, astronomers can also determine the motions within the source, as well as the speed with which the source is approaching or receding from us.

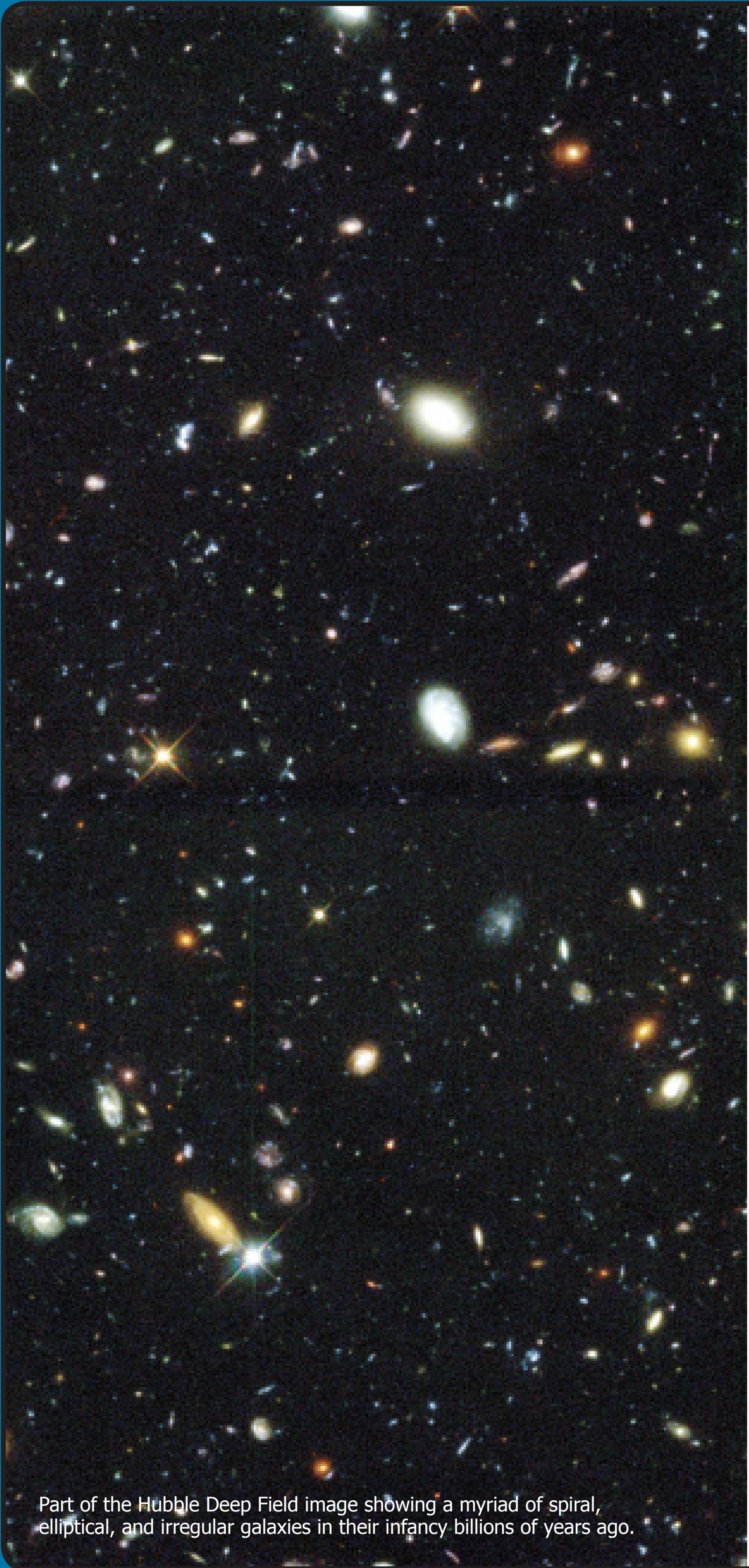
Visible light, however, can furnish only a small portion of this fingerprint. On either side of the spectral region that contains light waves, vast domains of the electromagnetic spectrum extend to shorter and longer wavelengths. Though human eyes cannot perceive this radiation, these domains are just as rich in information as the visible light with which we view our world. During past decades, astronomers have developed the tools to exploit most of these regions of the spectrum. Each new spectral domain opened by a new set of astronomical instruments not only has improved our understanding of objects already known, but also has revealed entire new classes of objects previously unsuspected. By studying cosmic sources of radio waves, for example, astronomers found totally unexpected phenomena such as pulsars, which produce rapid-fire bursts of radio emission; radio galaxies, in which explosive events accelerate charged particles to nearly the speed of light; and quasars, apparently the cores of young galaxies, where matter continuously spirals around and into a supermassive black hole.

Most radio waves, the longest-wavelength and lowest-frequency domain of the spectrum, can penetrate our atmosphere. But our atmospheric veil blocks most radiation outside the radio and visible-light domains, including gamma rays, x rays, ultraviolet light, and most infrared radiation. To improve our understanding of the cosmos, we require not only better ground-based observatories, which can detect visible light, radio waves, and some infrared radiation, but also space-borne observatories to study the cosmos in gamma rays, x rays, ultraviolet light, and those portions of the infrared spectrum that cannot penetrate Earth's atmosphere. By combining the results from these different instruments, we can understand sources of radiation far better than we could with observations made with any single telescope or within any particular domain of the spectrum.



Images of the central plane of the Milky Way at five different wavelengths.

The First Sources of Light in the Universe



Part of the Hubble Deep Field image showing a myriad of spiral, elliptical, and irregular galaxies in their infancy billions of years ago.

GALAXIES—enormous collections of hundreds of billions of stars—are the basic assemblages of structure in the universe. A crucial question in modern astronomy is, How did these objects begin to form?

The Big Bang set the stage for the birth of stars and galaxies. Observations with ground- and space-based radio telescopes have now shown that the universe began almost entirely smooth, as a rapidly expanding hot sea of particles and intense light that followed the Big Bang. Within this sea rolled subtle waves. These gentle undulations in matter and energy density grew slowly but steadily under the influence of gravity. A few hundred thousand years after the Big Bang, the strength of these ripples was only one-thousandth of a percent above the smooth background. Although this process occurred long ago, even today light continues to stream in from this ancient time, and the primeval waves, destined to grow into great superclusters of galaxies, are clearly seen by our most sophisticated instruments. Over the hundreds of millions of years that followed, gravity continued its work until giant clouds of cooling gas, the forerunners of today's galaxies, began to condense. Within these developed much smaller, denser clouds that gave birth to stars. The light from this first generation of stars, born some 12 to 13 billion years ago, brought the dawn of the modern universe with the birth of countless points of light that dot our night skies.

The Hubble Space Telescope has carried us back to within a few billion years of the Big Bang, allowing us to watch the growing up of young galaxies. But the actual birth of galaxies remains beyond our grasp. Within a billion years after the Big Bang, gravity had organized galaxy-sized clouds of gas, and stars condensed within these clouds and first ignited their nuclear furnaces. Looking back to that time is the primary goal of the Next Generation Space Telescope (NGST), the highest priority of the Astronomy and Astrophysics Survey Committee for the new decade. NGST will allow astronomers to peer into the distant past and see, for the first time, the birth of the modern universe.

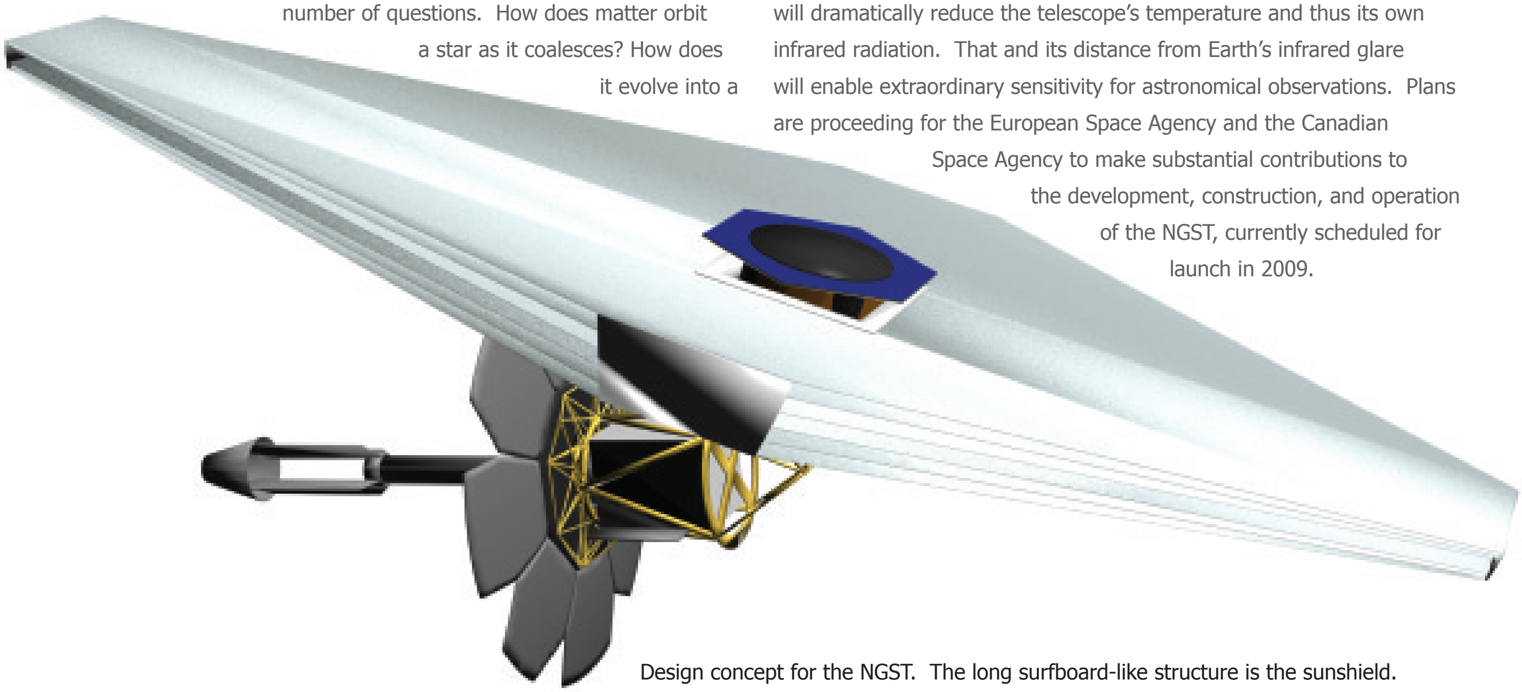
The Next Generation Space Telescope (NGST) will study the dawn of the modern universe

As currently conceived, the Next Generation Space Telescope will have a reflecting mirror 6 meters in diameter, with almost three times the diameter and seven times the collecting area of the mirror of the Hubble Space Telescope (HST). Equipped with detectors far more sensitive than those on the HST, the NGST will surpass by 10 times the HST's ability to detect radiation from faint sources. But even more important, the NGST will maintain itself at a temperature much colder than the HST's—only 50 degrees above absolute zero. By doing so, the NGST will observe the cosmos throughout large portions of the infrared spectral domain at sensitivities thousands of times that of any previous telescope. Redshift (the stretching of light by the expansion of the universe) moves the wavelengths of stars at a distance of 10 billion light-years from the visible into the high-sensitivity range of NGST. Thus NGST's capability to make super-sensitive infrared observations will enable it to see galaxies as they were 10 billion years ago in the first moments of their creation.

The NGST will also observe stars and planets as they form in the Milky Way—closer to home by a factor of 100 million. These protostars and protoplanets emit large amounts of infrared radiation but essentially no visible light. The NGST's ability to make high-resolution infrared observations of protostars and protoplanets will allow us to address a number of questions. How does matter orbit a star as it coalesces? How does it evolve into a disk and create planets? How does it disperse once the planet-formation process has ended? By combining observations of the early universe with those of the births of stars and galaxies, NGST will be the premier tool in the quest to understand our origins.

The assembly of a space-borne telescope with a mirror 6 meters (about 20 feet) in diameter poses challenges worthy of today's best astronomers and engineers. No rocket is available to launch a mirror of this size in a single piece. Instead, NGST must use a lightweight, segmented mirror that can be folded up into a compact package and that can deploy itself automatically once the package has been launched into space to its final destination. Because this mirror must maintain its surface to a perfection measured in millionths of an inch, its design, construction, and deployment all pose severe tests of skills in many different areas.

Telescopes for infrared observations have traditionally suffered from the deleterious effects of their own infrared radiation, which they produce simply because they are warm, and of the infrared radiation from Earth. Both sources of infrared radiation seriously interfere with our attempts to detect infrared radiation from the cosmos. Orbiting the Sun a million miles from Earth, the NGST will carry sunshields to allow its instruments to cool to temperatures hundreds of degrees lower than those of the HST. The HST, by contrast, is in a low orbit only a few hundred miles up, relatively close to Earth and its infrared emissions. The NGST's sunshields will dramatically reduce the telescope's temperature and thus its own infrared radiation. That and its distance from Earth's infrared glare will enable extraordinary sensitivity for astronomical observations. Plans are proceeding for the European Space Agency and the Canadian Space Agency to make substantial contributions to the development, construction, and operation of the NGST, currently scheduled for launch in 2009.



Design concept for the NGST. The long surfboard-like structure is the sunshield.

How Galaxies Took Shape

THE first clumps of matter to form in the universe began to pull themselves together within a few hundred million years after the Big Bang. Each of these giant clouds of gas and dust included an enormous amount of material, aggregating perhaps a trillion times the mass of our Sun. Within the first billion years or so after their formation, these newly formed galaxies had given birth to their first generation of stars. But even these youngest galaxies are sites of star death as well as star birth. Within a few million years after the first galaxies had formed, the most massive of the galaxies' earliest generation of stars had already burnt themselves out. These stars exploded as supernovas to seed their galaxies with the heavy elements synthesized within their nuclear-fusing cores.

To observe galaxies as they form and during their earliest youth requires infrared-detecting telescopes. Except for the most distant ones, young galaxies reveal themselves in the light from their newly formed blue stars. The expansion of the universe shifts all the light from young galaxies toward the red end of the spectrum, so that today we observe as red the light that their stars emitted as blue billions of years ago. These young galaxies, so distant that their light must travel billions of light-years to reach us, can be observed with a new generation of advanced telescopes on the ground and in space. Ground-based telescopes can observe the portions of the infrared domain closest to visible light, making highly detailed spectroscopic measurements using complex instruments too large and heavy to launch into orbit.

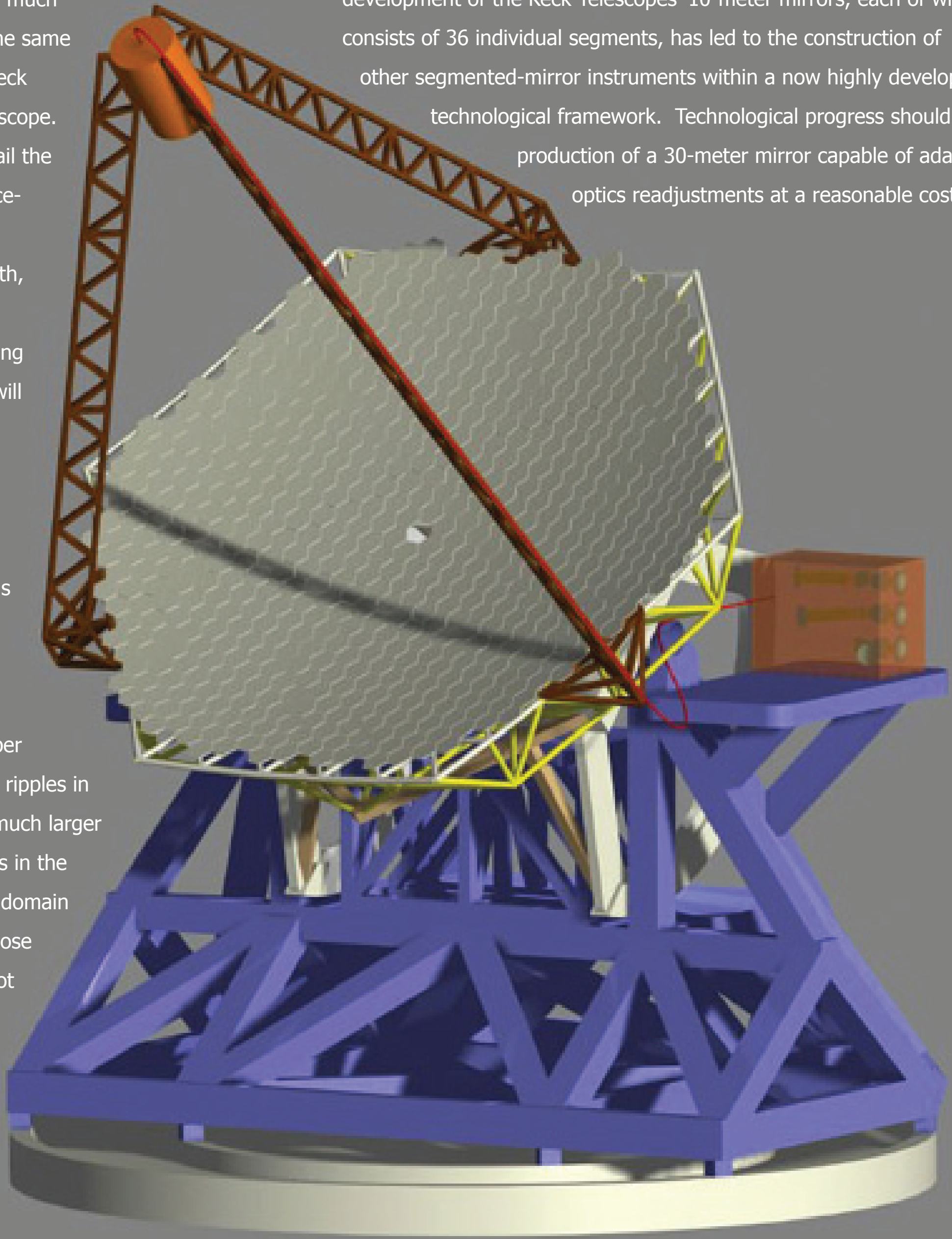
Optical image of the Whirlpool Galaxy—another spiral galaxy like the Milky Way. The individual reddish clumps scattered throughout the galaxy's spiral arms are huge nurseries of stellar newborns.

The Giant Segmented Mirror Telescope (GSMT)

THE Giant Segmented Mirror Telescope (GSMT), a ground-based telescope with a mirror approximately 30 meters in diameter, will provide a major advance in ground-based astronomy over the world's largest optical telescopes. The GSMT will have 10 times the light-collecting area of each of the twin Keck Telescopes in Hawaii, which now rank as the world's largest, and more than 20 times the collecting area of the NGST. With its much greater mirror size, the GSMT will play the same role with respect to the NGST that the Keck Telescopes do for the Hubble Space Telescope. The GSMT will investigate in greater detail the cosmic sources of radiation that the space-borne telescope discovers.

Because the GSMT will remain on Earth, it can profit from ongoing improvements in its complement of instruments, including marvelously precise spectrographs that will measure the amounts of radiation at different wavelengths. While it observes the cosmos in visible light and infrared radiation, the GSMT will employ an advanced system of adaptive optics. This system will continuously monitor the atmospheric fluctuations that would blur the telescope's vision, and it will then readjust the mirror surface many times per second in order to compensate for these ripples in the air. With this approach, and with a much larger mirror, the GSMT can obtain deep images in the short-wavelength portion of the infrared domain that are even crisper and deeper than those obtained by the NGST. Although it cannot observe galaxies as early in their history as the NGST can, the GSMT will have the infrared observing capability to follow the evolution of galaxies through all eras after the formation stage. It will be able to trace galactic history back to 10 billion years ago or earlier. In addition to galaxies, the GSMT will observe the closest planetary systems and star-forming regions within our Milky Way Galaxy.

The GSMT's great primary mirror will consist of individual segments, each as large as a good-sized astronomical telescope. The pioneering development of the Keck Telescopes' 10-meter mirrors, each of which consists of 36 individual segments, has led to the construction of other segmented-mirror instruments within a now highly developed technological framework. Technological progress should enable production of a 30-meter mirror capable of adaptive-optics readjustments at a reasonable cost.



Possible design concept for the GSMT. The mirror is roughly the same size as a baseball diamond.

Violent Events in the Cosmos

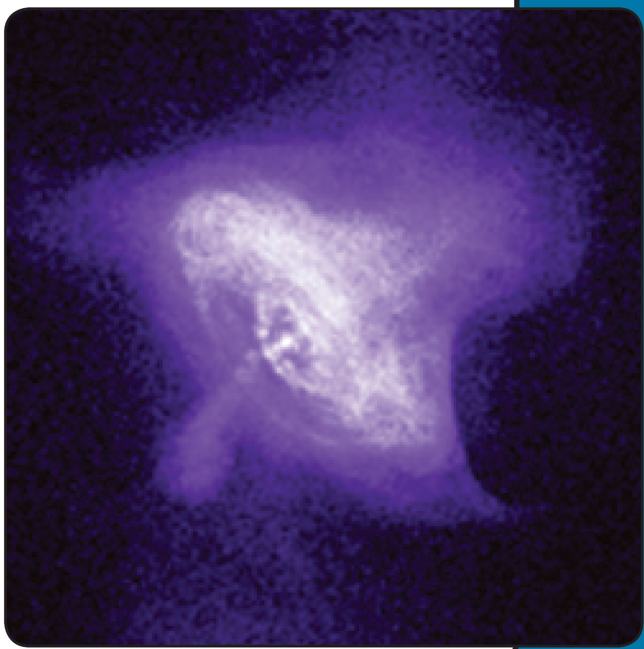
ASTRONOMERS once pictured the cosmos as an arena of calm, as planets moved serenely in their orbits around stars, stars orbited within galaxies, and galaxies moved through galaxy clusters. The past four decades, however, have revealed cosmic arenas of extreme violence. Crucial news about these violent locales reaches Earth in the form of high-energy x-ray and gamma-ray photons, typically created in enormous outbursts. Earth's atmosphere blocks all x rays and gamma rays, protecting life on Earth's surface but seriously restricting our ability to study the most violent cosmic phenomena.

The Chandra X-ray Observatory, launched in 1999, has yielded superbly detailed images of objects that generate copious amounts of x rays. In many cases, these images reveal the sites of tremendous outbursts such as supernovas, dying stars that blast hot gas into space at velocities of many thousands of miles per second. More sensitive x-ray observations will lead to understanding of the mechanisms through which these explosions occur. Among these mechanisms are the collapse of stellar cores, the sudden destruction of white dwarf stars, and the creation of neutron stars. Neutron stars are made entirely of neutrons and they pack into a region only a few miles across a mass equal to the Sun's.

X-ray-observing satellites have also found hot gas floating among the stars and galaxies. Observations of the spectrum of the x rays from this gas will make it possible to determine the temperature and relative amounts of its chemical elements. This information will provide crucial evidence for understanding the processes by which the elements were formed. It will help to establish the history of the creation of the elements throughout the universe. X rays also arise from high-temperature gas close to the surfaces of neutron stars, the collapsed remnant cores of exploded stars.

A new generation of x-ray satellites will be able to make superior observations of another class of objects: black holes. Supermassive black holes, each with millions of times the Sun's mass, appear at the centers of giant galaxies such as our Milky Way. Much closer to our solar system, black holes with masses similar to the Sun's have been created by dying stars. By studying the motions of matter close to these objects, astronomers have deduced the existence of these star-mass black holes within our galaxy. X-ray telescopes with high angular resolution and good spectral sensitivity can map the motions of the extremely hot, x-ray-emitting gas that swirls around and into the black holes. Such maps will verify that these black holes do exist and will test theories of how black holes bend nearby space.

Still greater mysteries arise from observations made in the highest-energy domain of the electromagnetic spectrum. During the past few years, astronomers have identified a new class of objects, gamma-ray bursts, that suddenly release enormous outflows of gamma rays. The nature and origin of these objects remain largely a mystery. We know that they lie far outside the Milky Way, but in all but a very few cases, astronomers have not yet been able to match the locations of these outbursts with any object visible in the sky. Because gamma-ray astronomy remains in relative infancy, we must look to the next generation of gamma-ray-detecting satellites to determine the nature of the gamma-ray bursts.

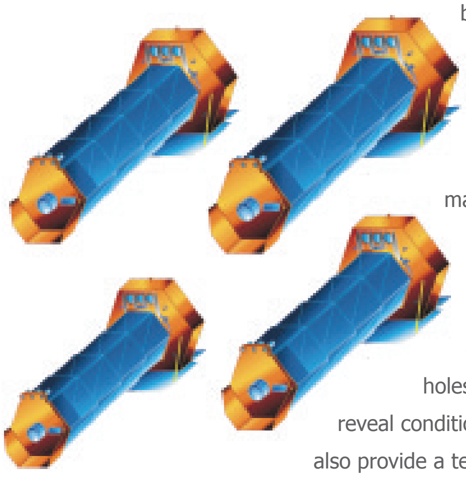


Optical (left) and x-ray (right) images of the Crab Nebula—the remnant of a supernova explosion in 1054 A.D.

New instruments for X-ray and Gamma-ray Astronomy

THE CONSTELLATION-X OBSERVATORY

The Constellation-X Observatory (Con-X) has the highest priority among the large initiatives recommended by the Astronomy and Astrophysics Survey Committee to study astronomical objects through their emission of high-energy radiation. Con-X will include four x-ray telescopes that orbit the Sun 2 million kilometers from Earth. By combining the signals from these four identical telescopes, Con-X will achieve a much greater sensitivity to x rays than that of previous x-ray satellites. And its angular resolution and ability to discriminate among x rays of different energies will far surpass the capabilities of its predecessors. Con-X's accurate observations of the matter between galaxies will enable measurement of the temperature and density of intergalactic material that has been heated to hundreds of thousands, and even millions, of degrees. This material may constitute most of the ordinary matter in the universe.



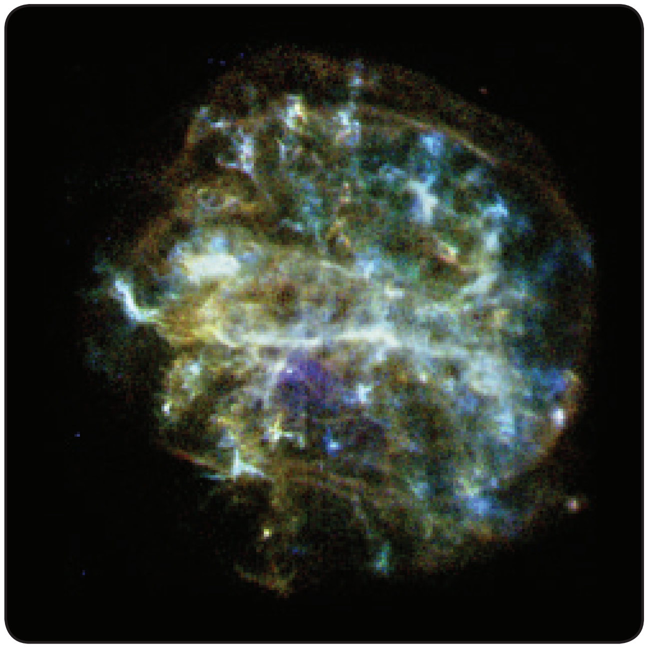
Con-X will also measure the motions of even hotter, highly magnetized gas swirling into black holes. These measurements will reveal conditions within this gas and will also provide a test of Einstein's general theory of relativity in the presence of gravitational fields far stronger than in any other astrophysical environment. Observations of the x rays generated near the surfaces of neutron stars will allow researchers to determine the masses and sizes of these remnants of supernova explosions. These determinations will, in turn, provide insights into the nature of the ultimate building blocks of matter: quarks and gluons. Precise measurements of the x rays of different energies emitted by matter both within and outside our Milky Way will shed light on the production of all the elements heavier than hydrogen and helium. Con-X should therefore improve our knowledge of the fundamental particles in the universe, of the nuclei made from them, and of the behavior of these nuclei in strong gravitational fields.

THE GAMMA-RAY LARGE AREA SPACE TELESCOPE (GLAST)

To observe photons with energies higher than those of x rays, researchers await the launch of the Gamma-ray Large Area Space Telescope (GLAST). Orbiting outside Earth's atmosphere, GLAST will detect gamma rays with energies in the middle of the gamma-ray domain. GLAST will have a far greater sensitivity and ability to pinpoint the locations of sources than its predecessor, the Compton Gamma-Ray Observatory. With its ability to point to a precise location in space, GLAST will be able to study gamma-ray bursts.

OTHER HIGH-ENERGY INSTRUMENTS

The Energetic X-ray Imaging Survey Telescope (EXIST) will survey sources of relatively high energy x rays. EXIST will study the numerous x-ray sources that flash on and off on time scales of minutes and hours. Its ability to observe low-energy gamma rays will allow it to detect low-energy bursts of gamma rays associated with some supernova explosions. To detect the highest-energy gamma rays produced in the cosmos (which GLAST cannot do), specialized arrays of detectors are required that can record the bursts of photons triggered by a single high-energy photon. The ground-based Very Energetic Radiation Imaging Telescope Array System (VERITAS) will be able to detect the highest-energy radiation of these three instruments.



Above: Design concept for Con-X.
Right: X-ray image of the young supernova remnant G292.0+1.8.

What Happens at the Heart of a Galaxy

DURING the past three decades, astronomers have found that the centers of giant galaxies are often locales of immense violence, from which enormous bursts of energy flood outward. In many cases, this energy is in the form of synchrotron radiation, produced by a process first observed in particle accelerators called synchrotrons. This process occurs when charged particles move at nearly the speed of light through strong magnetic fields. Therefore, wherever radiation is produced by the synchrotron process, we can infer that violent events have recently accelerated particles there to velocities very close to the speed of light (300,000 kilometers per second). The synchrotron process can produce all types of radiation, from high-energy gamma and x rays down to low-energy radio waves. Consequently, it can be studied with a host of different instruments, each capable of gaining a different perspective on the objects that produce this radiation.

The most intense outflows of radiation at the centers of some galaxies apparently arise from the effects produced by supermassive black holes. Such objects, no larger than our solar system, contain a mass hundreds of millions of times greater than the Sun's. A supermassive black hole bends the space nearby, attracting matter that spirals at ever-increasing speed before disappearing within the event horizon, at a distance from the black hole's center that marks a point of no return. Surrounding its event horizon, a supermassive black hole develops an accretion disk of orbiting matter, within which particle collisions occur at enormous velocities. From such an accretion disk, the central region of a large galaxy can produce more energy per second than the entire output of an ordinary large galaxy!

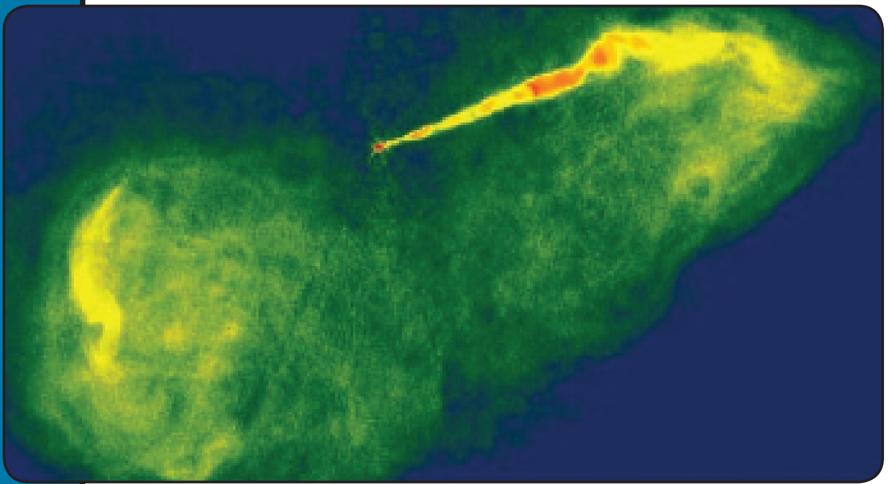
In most cases, the accretion disk diverts some of the matter spiraling inward, producing twin jets that eject matter at enormous velocity in opposite directions above and below the disk. When we have a side view of these jets, we see large amounts of radiation. But when we happen to look directly down one of them, along the fire hose of emission from the vicinity of the black hole, we receive a truly enormous blast of radiation, fortunately dimmed because the jets are so far away from us.

During the coming decade, with advanced instruments, we will be able to make better observations of the accretion disk that surrounds the supermassive black hole at a giant galaxy's center. These observations will allow us to improve our currently modest understanding of how the disk diverts the material to produce jets of outflowing matter in opposite directions. Detailed studies of how particles move close to these black holes will allow us to test the predictions of Einstein's general theory of relativity. This test will go beyond the "weak limit" that describes most objects in the cosmos to probe phenomena in gravitational fields sufficiently strong to create huge warps in space.

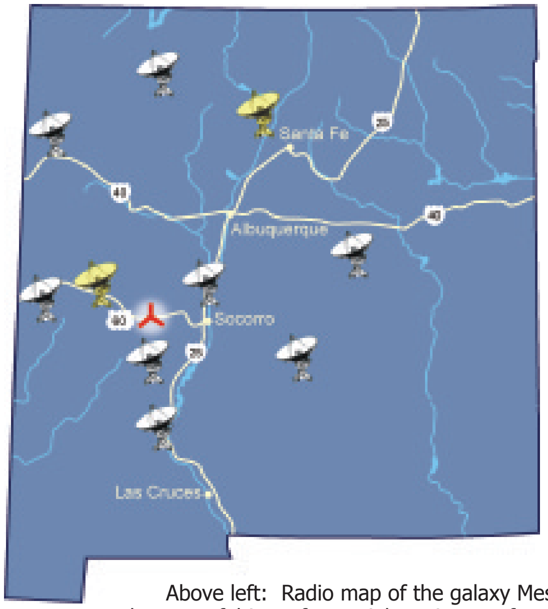
Optical image of the central part of the Centaurus A Galaxy where a supermassive black hole hides.

Radio Waves Can Probe the Centers of Violent Galaxies

RADIO astronomers have pioneered systems for interferometry. This technique combines the signals from several instruments in a manner that allows them to act as a single "virtual telescope," one with a huge effective diameter equaling the distance between the most widely separated telescopes. The greater the diameter of a telescope, the more detail it can see. An example is the Very Large Array (VLA) of movable radio telescopes near Socorro, New Mexico, with an effective diameter of up to 27 kilometers. Building on the VLA's success, the Expanded Very Large Array (EVLA) will create an array of radio dishes with 10 times the VLA's sensitivity and angular resolution. The EVLA will have a thousand times the VLA's capability for making spectroscopic observations at different radio wavelengths. The expansion will involve replacement of the current detectors, computers, and software to improve sensitivity. In a second stage of the expansion, as many as eight new antennas will be built. Interconnected by fiber-optic links, the new and old dishes will allow the EVLA to study the cosmos with an angular resolution comparable to that of the Next Generation Space Telescope (NGST) and of the Atacama Large Millimeter Array (ALMA). These three instruments will complement one another by providing high-resolution views of the cosmos in the spectral domains of radio, millimeter (radio waves with the shortest wavelengths), and infrared wavelengths.



Still finer angular resolution will come from the Advanced Radio Interferometry between Space and Earth (ARISE) initiative. ARISE combines a radio telescope 25 meters in diameter, orbiting in space, with the existing Very Long Baseline Array (VLBA) of radio telescopes. ARISE will enable the study of explosive events, such as the jets ejected from the matter orbiting a supermassive black hole. It will have a precision that may be good enough to explain how and why these ejections occur. And it may be able to reveal how the ejection of matter leads to the production of an enormous quantity of radio emissions. But a system with even the finest angular resolution cannot observe faint sources unless it can collect sufficient amounts of radiation. To observe the faintest radio sources in the cosmos, radio astronomers from around the world are planning the Square Kilometer Array (SKA) of radio telescopes, which will cover a total area of one square kilometer. The SKA will have hardware and software capable of simultaneously analyzing the signals detected in each of the huge number of telescopes in the array. The SKA will effectively function as a single radio dish even larger than 1 kilometer in diameter, possessing 10 times the collecting area of the 300-meter radio telescope near Arecibo, Puerto Rico. The SKA will be able to observe the clouds of gas that formed the precursors of galaxies 12 to 14 billion years ago, as well as gas within distant galaxies. The Astronomy and Astrophysics Survey Committee recommends that, during this decade, resources be provided for the U.S. contribution to the technology development required for the SKA, which will be by far the most sensitive radio instrument ever built.



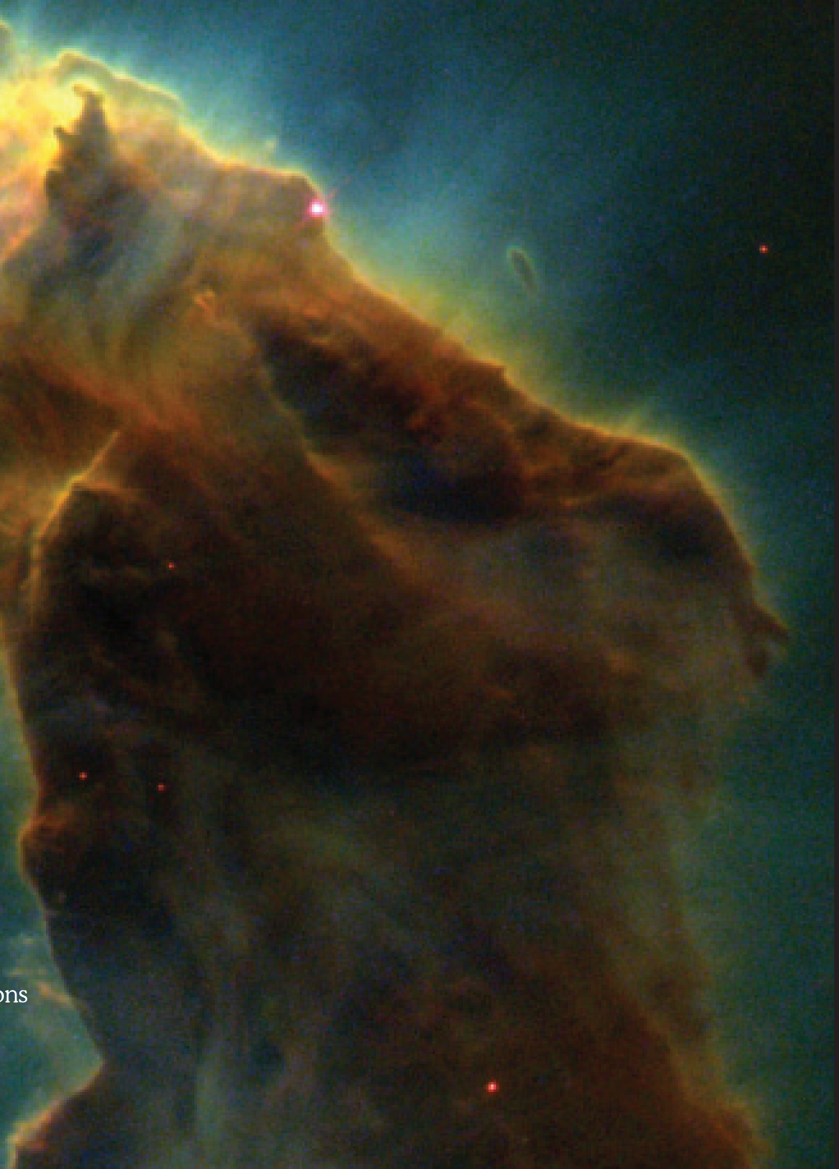
Above left: Radio map of the galaxy Messier 87 and the powerful jets of material coming out from the central black hole. Above right: Location of VLA (shown in red) and the additional antennas constituting the EVLA.

The Origins of Stars and Planets

LIKE the giant galaxies in which they appear, stars and their planets form when clumps of gas and dust contract to much smaller sizes. During the first phases of star formation, each of these contracting clumps was too cool to produce visible light. Within these clumps, the attraction of each part for all the other parts caused the clumps to shrink steadily, squeezing their material into ever-smaller volumes. As the clumps continued to contract, the resulting increase in density caused a corresponding rise in temperature at the clumps' center. Eventually, as this central temperature rose above 10 million degrees, atomic nuclei began to fuse. The onset of nuclear fusion, which marks the birth of a new star, occurred nearly 5 billion years ago in the case of our Sun. In the case of the oldest stars that shine, this onset of nuclear fusion began 10 to 14 billion years ago.

During the later stages of the contraction process, a rotating disk of gas and dust formed around the central mass that would become a star. To detect these protoplanetary disks, the precursors of planetary systems around stars that are in the process of formation, requires telescopes with an improved angular resolution, sufficient to reveal more than the disks' bare outlines. We now know that other stars have planets, as revealed by recent astronomical measurements that detected the pull exerted on their stars by large, Jupiter-like planets.

Many of the initiatives recommended by the Astronomy and Astrophysics Survey Committee will address the origins of stars and planets. NGST and GSMT will probe the dusty environments of star-forming regions with unprecedented sensitivity and angular resolution. Existing ground-based telescopes will be made much more powerful through new instruments provided by the Telescope System Instrumentation Program. Protoplanetary disks are much cooler than stars and emit most of their radiation in the infrared region of the spectrum. To permit observations in the far infrared, the committee recommends the development of the Single Aperture Far Infrared Observatory (SAFIR). Observations at millimeter and different infrared wavelengths will enable astronomers to measure the concentrations of different species of atoms and molecules in the disk. It will also be possible to determine the speeds at which these particles are moving and the temperatures to which they have been heated.



Optical image of one of the pillars of the Eagle Nebula. New stars are embedded inside the finger-like structures extending from the tip of the pillar.

The Telescope System Instrumentation Program (TSIP) will leverage non-federal investment in large new ground-based telescopes

THE AASC's highest-priority recommendation in the moderate cost category for both space- and ground-based initiatives promotes not an instrument but a program, one that will fund instruments for the new generation of large telescopes that are being constructed at university and independent observatories. The Telescope System Instrumentation Program (TSIP) will leverage these investments by markedly improving the equipment that detects and analyzes the radiation reaching these telescopes. In particular, TSIP will assist the development of systems for adaptive optics, which continuously readjust the reflecting surface of a telescope, canceling the blurring effects of the atmosphere. Adaptive optics will allow a manyfold increase in the angular resolving power of all large telescopes. This improvement will give these telescopes an increased ability to study a host of phenomena. Among these are the atmospheres of the other planets in the solar system, the structure of protoplanetary disks around other stars, the behavior of matter in active galactic nuclei, the history of star formation in young galaxies, and the nature of the objects that produce mysterious bursts of gamma rays.

The Single Aperture Far Infrared Observatory (SAFIR) will provide our most sensitive eye on the far-infrared frontier

The Next Generation Space Telescope (NGST) will enable infrared observations with about three times the angular resolution and 100 times the sensitivity of the HST. However, the NGST cannot observe infrared radiation with the longest wavelengths—the far-infrared domain of the spectrum. This spectral region is rich in information about stars and galaxies in the process of forming; brown dwarfs ("failed stars" that have too little mass to begin nuclear fusion); and ultraluminous, infrared-radiating galaxies. Although significant improvements in observations of the far-infrared domain will occur with the coming deployment of the Space Infrared Telescope Facility, the airborne Stratospheric Observatory for Infrared Astronomy, and the European Space Agency's Herschel Space Observatory, longer-wavelength observations with greater sensitivity are needed. The recommended next step for observing the cosmos at far-infrared wavelengths is the space-borne Single Aperture Far Infrared (SAFIR) Observatory. SAFIR will include both a telescope with a mirror at least as large as that of the NGST and a set of cooled instruments. Its size and temperature will give it an angular precision and an ability to detect faint sources that will make it roughly a million times superior to existing instruments that observe the far-infrared spectral domain. Because the NGST will pioneer cost-effective development of space-borne telescopes with mirrors larger than the HST's, SAFIR can be designed and built more cheaply than the NGST.

Other longer-wavelength tools

The Combined Array for Research in Millimeter-wave Astronomy and the South Pole Submillimeter-wave Telescope will be powerful tools for studying star-forming molecular clouds and other dusty parts of the universe, as well as clusters of galaxies.

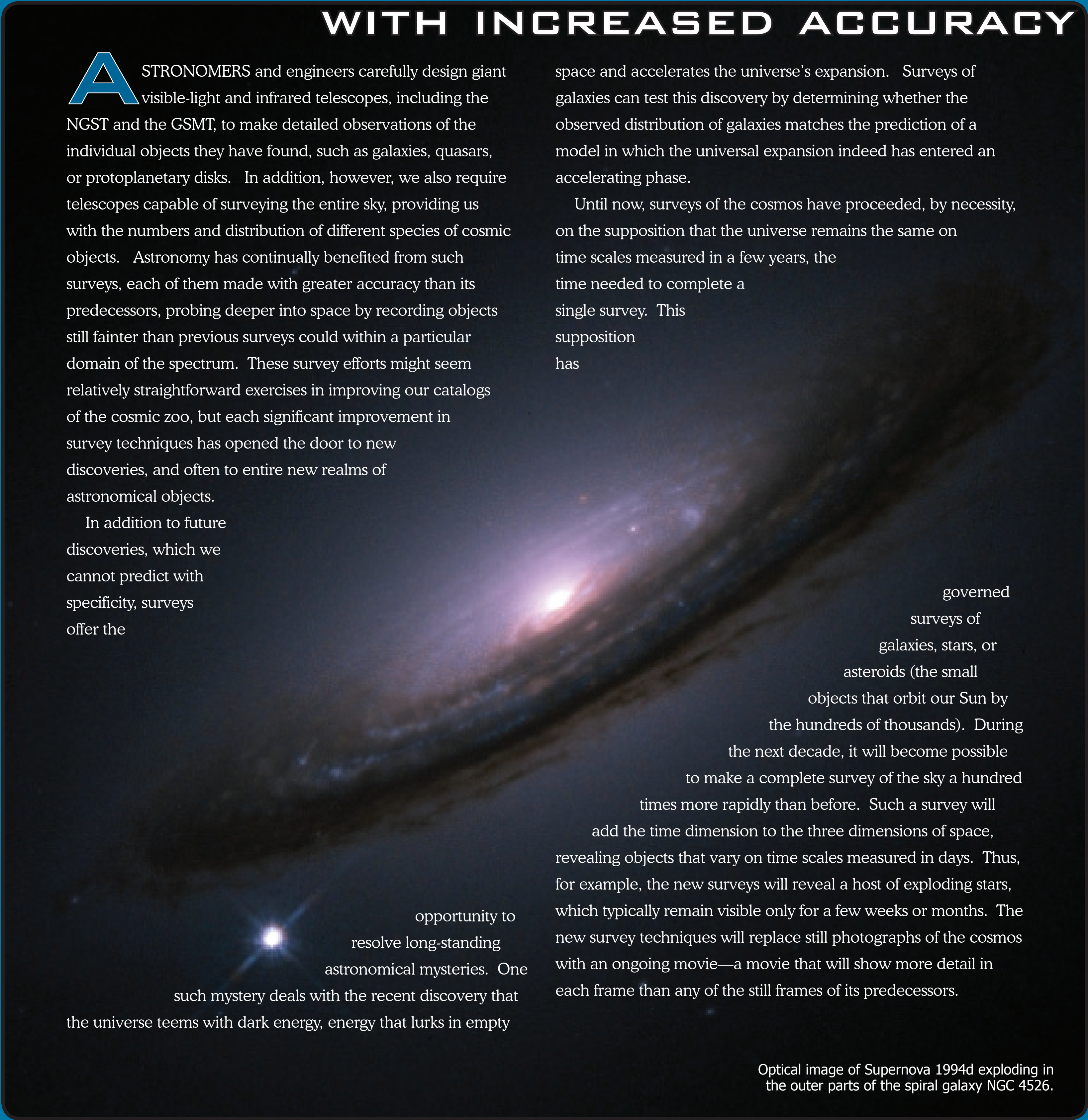
Optical image of the Orion Nebula star-forming region.

Surveying the Universe
with Increased Accuracy

ASTRONOMERS and engineers carefully design giant visible-light and infrared telescopes, including the NGST and the GSMT, to make detailed observations of the individual objects they have found, such as galaxies, quasars, or protoplanetary disks. In addition, however, we also require telescopes capable of surveying the entire sky, providing us with the numbers and distribution of different species of cosmic objects. Astronomy has continually benefited from such surveys, each of them made with greater accuracy than its predecessors, probing deeper into space by recording objects still fainter than previous surveys could within a particular domain of the spectrum. These survey efforts might seem relatively straightforward exercises in improving our catalogs of the cosmic zoo, but each significant improvement in survey techniques has opened the door to new discoveries, and often to entire new realms of astronomical objects.

In addition to future discoveries, which we cannot predict with specificity, surveys offer the opportunity to resolve long-standing astronomical mysteries. One such mystery deals with the recent discovery that the universe teems with dark energy, energy that lurks in empty space and accelerates the universe's expansion. Surveys of galaxies can test this discovery by determining whether the observed distribution of galaxies matches the prediction of a model in which the universal expansion indeed has entered an accelerating phase.

Until now, surveys of the cosmos have proceeded, by necessity, on the supposition that the universe remains the same on time scales measured in a few years, the time needed to complete a single survey. This supposition has governed surveys of galaxies, stars, or asteroids (the small objects that orbit our Sun by the hundreds of thousands). During the next decade, it will become possible to make a complete survey of the sky a hundred times more rapidly than before. Such a survey will add the time dimension to the three dimensions of space, revealing objects that vary on time scales measured in days. Thus, for example, the new surveys will reveal a host of exploding stars, which typically remain visible only for a few weeks or months. The new survey techniques will replace still photographs of the cosmos with an ongoing movie—a movie that will show more detail in each frame than any of the still frames of its predecessors.



Optical image of Supernova 1994d exploding in the outer parts of the spiral galaxy NGC 4526.

The Large-aperture Synoptic Survey Telescope (LSST) will survey the changing universe from exploding stars to earth-threatening asteroids

EVERY week, the Large-aperture Synoptic Survey Telescope (LSST), whose 6.5-meter mirror has been shaped to provide a much wider field of vision than that of other telescopes, will survey the entire sky, producing an almost real-time movie of the night sky.

These surveys will be produced in digitized format and distributed immediately to astronomers and the public over the Web. They will yield a wealth of data that will open our eyes in new ways to cosmic objects that vary in brightness on time scales of days, weeks, months, or years, and range in distance all the way from the outer reaches of the visible universe down to the dangerously close. LSST will discover approximately 100,000 supernovas each year, located in galaxies many millions or even billions of light-years from the Milky Way, some of which can be studied in detail with the GSMT. Another benefit of LSST's deep-space survey will accrue from its ability to find places in the night sky where a massive object happens to lie almost directly between Earth and a still more distant object. Under these circumstances, the massive object magnifies the light from the more distant object by bending nearby space. LSST's measurements of these magnification effects will allow us to map the distribution of dark matter in space. This map will test, on the largest attainable distance scales, evidence of the acceleration of the expansion of the universe, theorized to be due to the presence of so-called dark energy.

Much closer to Earth, LSST will find 90 percent of all the near-Earth objects—asteroids moving on orbits that pass close to our own—with diameters that exceed 300 meters. Each of these asteroids represents a potential threat worth identifying and assessing, since a collision of such an asteroid with our planet could produce localized, if not planet-wide, disaster.

LSST will also study comets and their close cousins, the members of the Kuiper Belt. Most of the comets that we see probably originate in the Kuiper Belt, a collection of minor planets orbiting beyond Neptune. The Kuiper Belt is the remnant of the protoplanetary disk of material that once orbited the Sun and produced the planets and their large satellites nearly 5 billion years ago. These remnants incorporate the nearly pristine record of the composition and dynamics of the Sun's protoplanetary disk. Astronomers have now discovered more than 500 separate objects in the Kuiper Belt, most with diameters between 100 and 800 kilometers. Deeper surveys made with the LSST should reveal many more of these objects, which are believed to number nearly 100,000, with diameters larger than 100 kilometers. Astronomers suspect that among them may be perhaps as many as 10 objects as large as Pluto (2,000 kilometers across), but several times farther from the Sun.

LSST should generate the largest nonproprietary database and data-mining system in the world, adding the dimension of time to the three spatial dimensions in our knowledge of the cosmos. The classification, analysis, and distribution of an anticipated trillion bits of data collected each day represent an enormous challenge.

Left: Image showing the gravitational "fish-eye lens" effect. The dark matter in the massive cluster of yellowish galaxies curves space-time to such a degree that the light from a more distant blue galaxy behind the cluster is focused toward Earth and appears as the distorted blue arcs around the edge of the "lens." Right: Optical image of the asteroid Ida (more than 50 kilometers long) and its moon Dactyl taken by the passing Galileo spacecraft.

The National Virtual Observatory (NVO) will provide user-friendly access to the nation's large astronomical databases

The National Virtual Observatory (NVO), the highest priority among the recommended small initiatives, will link all major space- and ground-based astronomical data banks into a virtual Web-based system. The NVO is intended for users from grade-school children to professional astronomers, and it will allow automated searches among all the objects and the wide range of wavelengths contained in the vast array of observations made by LSST and other planned and currently operational facilities. Collaborations with international partners should lead to a future global virtual observatory.

Gravitational Radiation

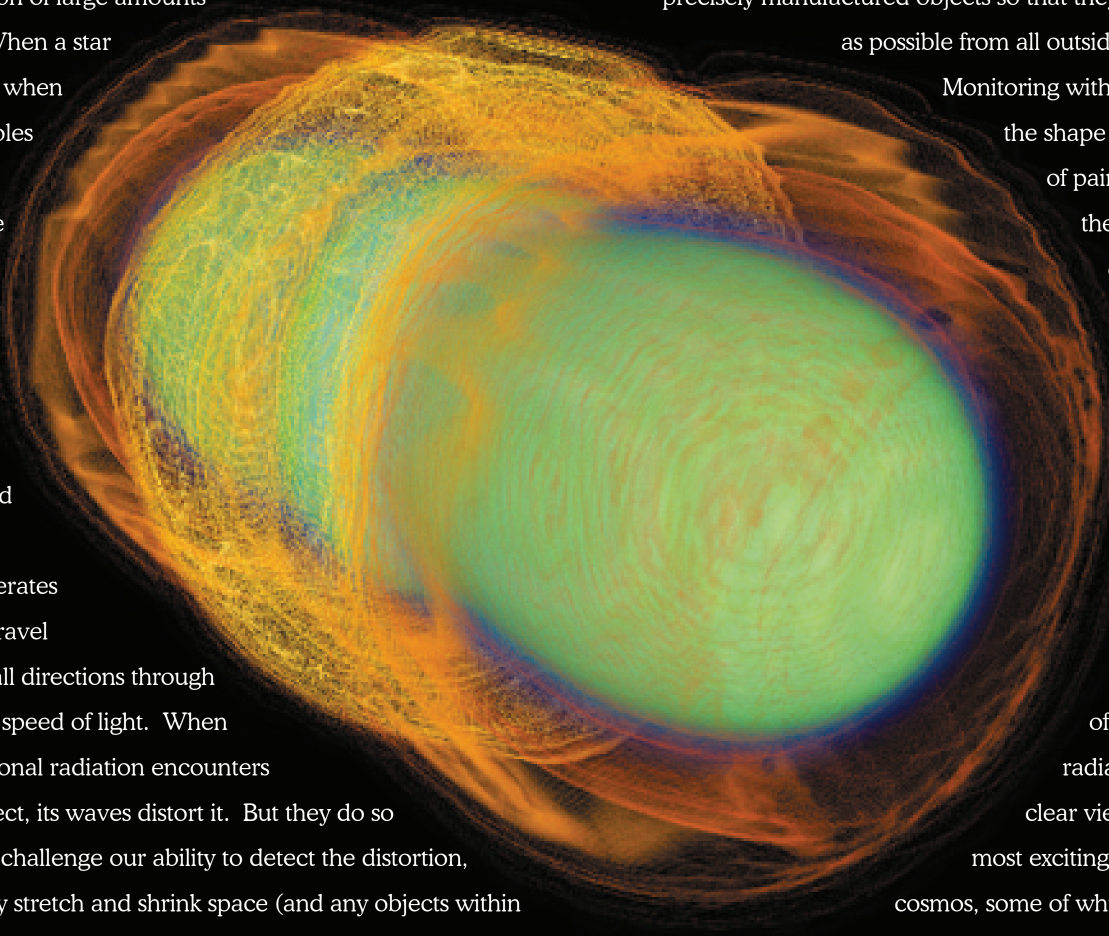
A New Way to See the Cosmos

When Albert Einstein formulated his general theory of relativity in 1916, he noted that the theory predicts the existence of an entirely new form of cosmic radiation. Gravitational radiation, unlike the electromagnetic radiation we know as visible light, radio, and other now-familiar types, consists of ripples in the fabric of space itself, produced by the motion of large amounts of matter. When a star explodes, or when two black holes collide and merge, these episodes of cosmic violence shake the vacuum of space around them. This shaking generates waves that travel outward in all directions through space at the speed of light. When this gravitational radiation encounters another object, its waves distort it. But they do so in ways that challenge our ability to detect the distortion, because they stretch and shrink space (and any objects within it) by amounts that span only a tiny fraction of the size of a single atom!

Astronomers and physicists have long known that the detection of gravitational radiation will allow us to probe deeply into the violent events that produce it. Because this type of radiation interacts only weakly with matter, its waves will emerge relatively unaffected from the heart of catastrophic events in the cosmos. In contrast, light waves and other forms of electromagnetic radiation must slowly leak through masses of material blocking their passage. They inevitably lose much of the information that they originally carried in this passage.

Observation of gravitational radiation requires isolating precisely manufactured objects so that they remain as free as possible from all outside influences. Monitoring with extreme accuracy the shape or the separation of pairs of these objects then allows us to detect the nearly infinitesimal movements that arise from the shaking of space-time by the radiation as it passes by. If we can detect them, the waves of gravitational radiation offer a new, clear view of some of the most exciting events in the cosmos, some of which are otherwise unobservable.

Future generations of detectors may offer the earliest view of the universe from a time just after the Big Bang and well before the first possible moment from which we can see electromagnetic radiation.



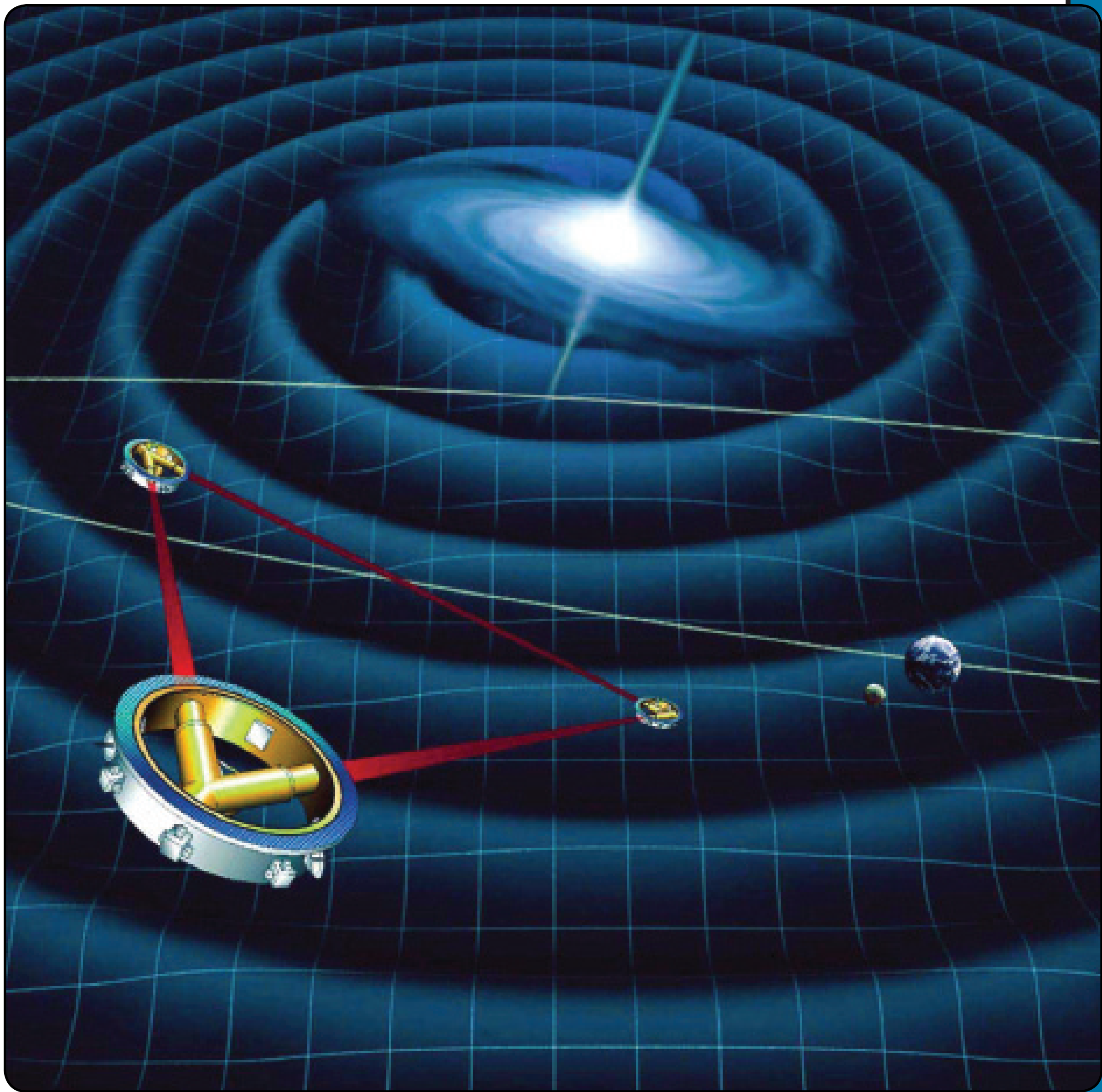
Computer illustration from a simulation of the collision of two neutron stars.

The Laser Interferometer Space Antenna (LISA)

will detect ripples in space produced by colliding supermassive black holes

GRAVITATIONAL radiation consists of ripples in space with long wavelengths, which grow longer roughly in proportion to the amount of mass in violent motion that produces these ripples. Earthbound detectors can find gravitational radiation from individual stars as they collapse or coalesce, but detection of the longest-wavelength gravitational radiation requires a supersensitive detector located in space. The Laser Interferometer Space Antenna (LISA), a joint venture of the United States and the European Space Agency, will deploy a system of reflecting antennas, spaced at distances of millions of kilometers, that reflect laser beams back and forth between them.

These beams will not only measure the distances between the reflectors but also detect any tiny changes in these distances (less than one-hundredth the diameter of a single atom) that arise from the passage of waves of gravitational radiation. This capability will allow LISA to measure gravitational radiation at lower frequencies than an earthbound detector can access. LISA will also be able to detect the gravitational radiation from the coalescence of supermassive black holes.

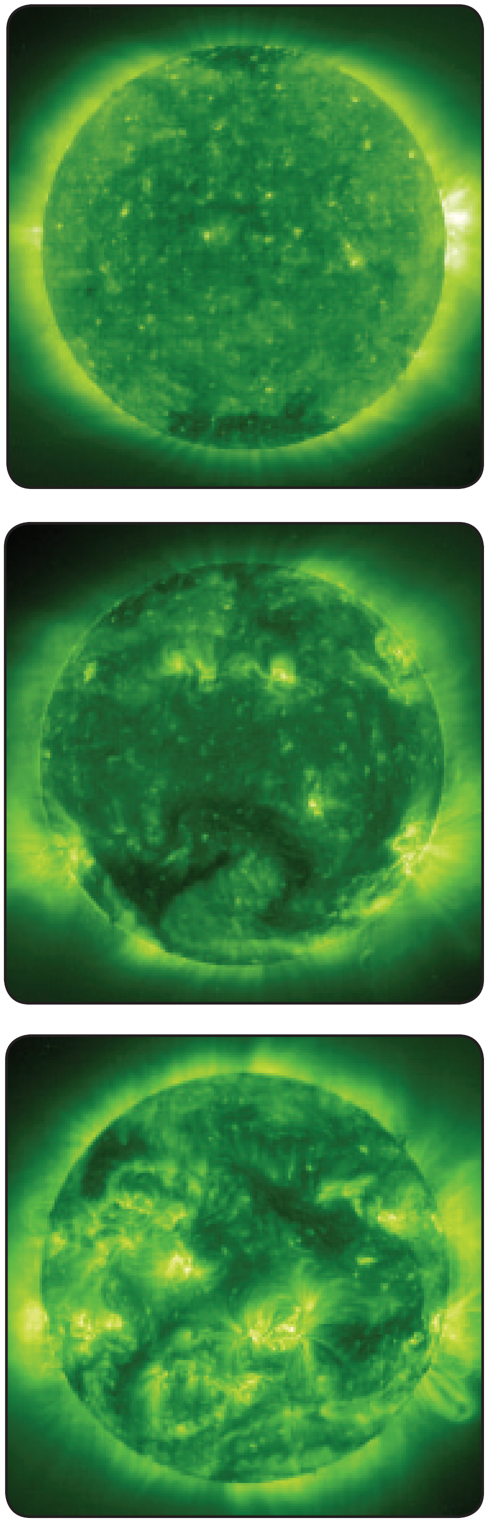


Artist's conception of LISA superimposed on ripples in space-time powered by the collision of supermassive black holes. The individual 3-meter-diameter spacecraft are separated by 5 million kilometers and trail Earth in its orbit.

Solar Astrophysics

OUR Sun, the star closest to Earth, offers us the opportunity to make detailed observations of the exterior and interior of a typical star in its mid-life phase. In addition, the Sun offers us a natural laboratory for the study of plasmas (high-temperature gases in which atoms have been stripped of their electrons) that are influenced by magnetic fields. From the details of the Sun's behavior, we can address questions about key processes within stars. How do they generate energy through nuclear fusion at their centers? How does that energy pass through hundreds of thousands of kilometers of surrounding layers of gas? How does that energy, released in the form of highly energetic particles and ultraviolet and infrared light waves, affect Earth and the Sun's other planets?

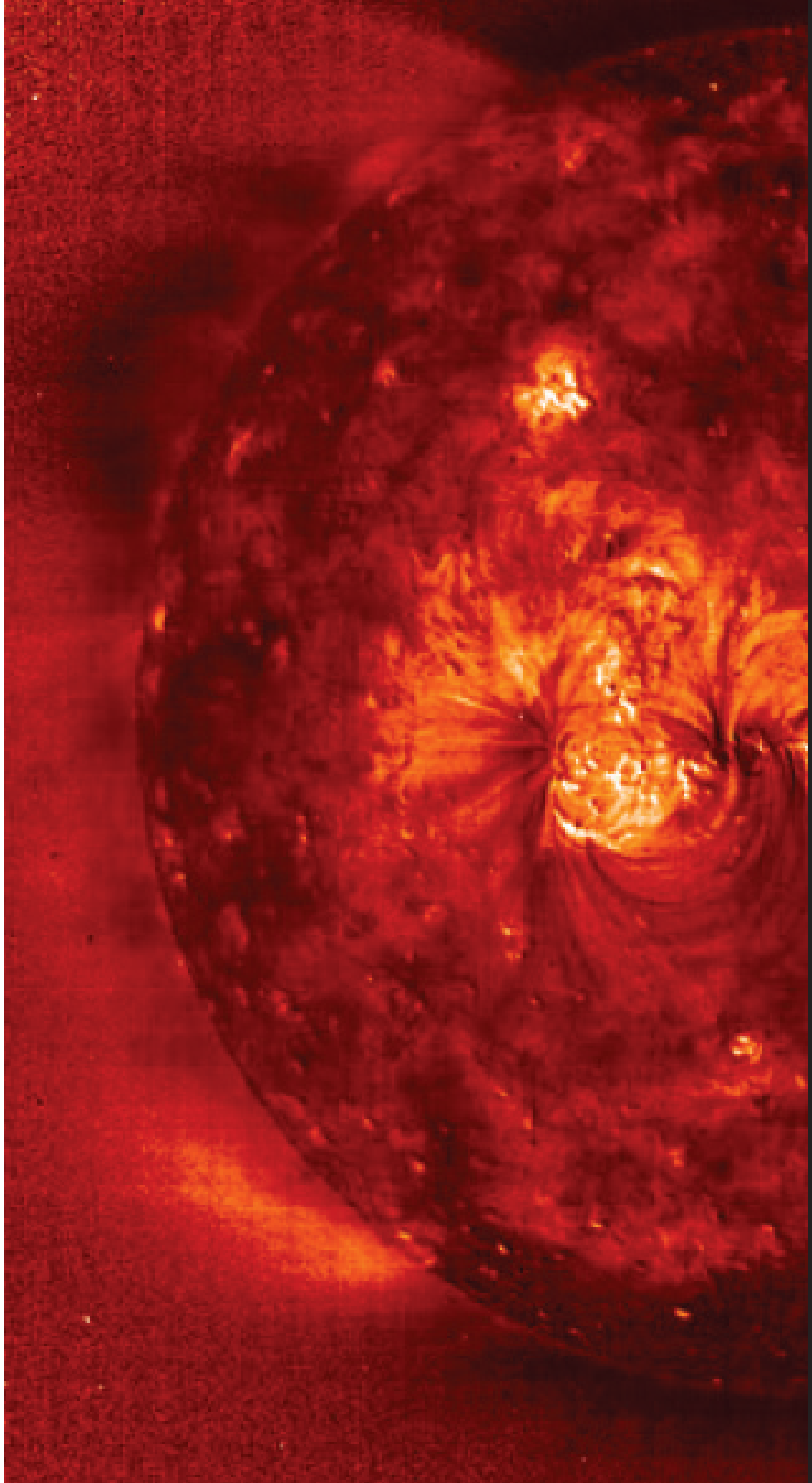
Careful study of the Sun's output of energy as different types of radiation will improve our knowledge of these processes. Better ground-based solar telescopes can reveal conditions on the Sun's surface at scales of distance as small as 70 kilometers—an important scale because the Sun's atmospheric pressure and temperature change noticeably over distances this small. Other solar phenomena, including the temporary cool and dark regions called sunspots, and the violent outbursts visible at and above the Sun's surface, have their origin below the visible layers of the Sun. With specialized instruments, we can deduce the conditions that exist below the surface layers and determine how these transient events arise and develop.



Three x-ray images of the Sun taken almost 3 years apart illustrate how the level of solar activity increases significantly as it approaches solar maximum once every 11 years. The last solar maximum occurred in 2000.

Our Sun continues to pose some difficult questions. How can the solar surface, with temperatures of only about 10,000 degrees Fahrenheit, produce the much hotter chromosphere above it and, above the chromosphere, the still hotter solar corona, where the temperature rises to a million degrees or more? How do the boiling motions in the outer layers of the Sun concentrate magnetic energy? What governs the sudden release of this energy as huge coronal mass ejections and solar flares? These outbursts eject huge numbers of electrons, protons, and other charged atomic nuclei, which disrupt the patterns of Earth's magnetic field when they reach us a few days later. Understanding the details of the Sun's behavior has important applications for both short- and long-term weather forecasting. In addition, solar outbursts disrupt radio, television, radar, and power transmission and create a danger for astronauts; changes in the Sun's energy output, even at a modest level, produce long-term, still poorly understood climate changes on Earth. To the extent that we can better understand how the Sun and its outbursts work, we can take steps to better protect ourselves and our planetary environment.

Observing the Sun with Three New Instruments



X-ray image of million-degree plasma loops and flares from the solar corona.

THE Astronomy and Astrophysics Survey Committee recommends three moderate initiatives, two ground-based and one space-based, to study the Sun's internal structure and dynamics, its changing magnetic fields, and the relationship between these solar aspects and the Sun's effects on Earth.

The Advanced Technology Solar Telescope (ATST) Will Trace the Sun's Dynamic Magnetic Field

First among these recommendations, the ground-based Advanced Technology Solar Telescope (ATST) will have a 4-meter mirror with adaptive optics capable of obtaining far more detailed visible-light solar images than any now available. These images will allow astronomers to test and to refine their theories of how the Sun generates the magnetic fields near its surface and how these fields affect the hot plasma gas above the surface. ATST will have international partners that will join the United States in applying the recent advances in adaptive-optics systems and large-format infrared cameras to solar astrophysics.

The Solar Dynamics Observatory (SDO) Will Peer into the Sun's Pulsating Interior

To study the region below the solar surface, the space-borne Solar Dynamics Observatory (SDO) will improve on the highly successful Solar and Heliospheric Observatory (SOHO), which produced the images on these two pages. SDO will move in a geosynchronous orbit, making continuous solar observations through the entire ultraviolet and visible-light spectral domains, as well as the shortest-wavelength portion of the infrared. With this capability, SDO will help to determine the origin of sunspots, transient regions on the solar surface that have a temperature 1,000 degrees below the average (apparently because of the localized presence of strong magnetic fields). When coronal mass ejections and solar flares appear, SDO and ATST will work in tandem to develop the connections between activity below the solar surface and the eruptions within the solar corona.

The Frequency Agile Solar Radio Telescope (FASR) Will Probe the Mystery of Solar Flares

The Frequency Agile Solar Radio telescope (FASR) will observe radio waves from the Sun, continually probing different heights above the solar surface. This range in altitude takes us from the Sun's corona with its million-degree temperature down through the chromosphere, heated to tens of thousands of degrees. Within the corona and chromosphere, FASR will observe short-lived, explosive phenomena—the flares that eject enormous amounts of hot gas, along with streams of elementary particles.

The Quest to Find Other Earths

OF all the issues that the cosmos poses for humanity, one of the greatest and most resonant focuses on the search for Earth's cousins, planets that offer a world on which life can both originate and flourish. The past half decade has taken us from almost total ignorance of planets orbiting other stars to knowledge of the existence of more than 70 such planets. All of these extrasolar planets have masses comparable to the masses of Jupiter and Saturn, more than 80 times Earth's. Their large masses allow the planets to produce detectable gravitational pulls on their starry masters. Only by observing these tugs have astronomers been able to deduce the planets' existence and their masses. Finding planets with masses comparable to Earth's, either by indirect methods or by direct observation, will require observational systems far superior to those so far devoted to the search for other worlds.

Most of those efforts will require space-borne interferometer systems. Such systems combine the light and infrared waves collected by an array of individual small telescopes to achieve the resolving power of a single giant telescope whose size equals the size of the array. Radio astronomy has long employed interferometer systems to achieve high resolution. Today astronomers are making rapid progress to create optical interferometers for the infrared and visible-light spectral domains. The Space Interferometry Mission (SIM), now under development for launch in the second half of the decade, will demonstrate the feasibility of space-borne interferometer missions to observe visible-light and infrared radiation. But SIM will still enable discovery of planets not by direct observation but indirectly, through highly accurate measurements of the displacement of stars' positions on the sky.

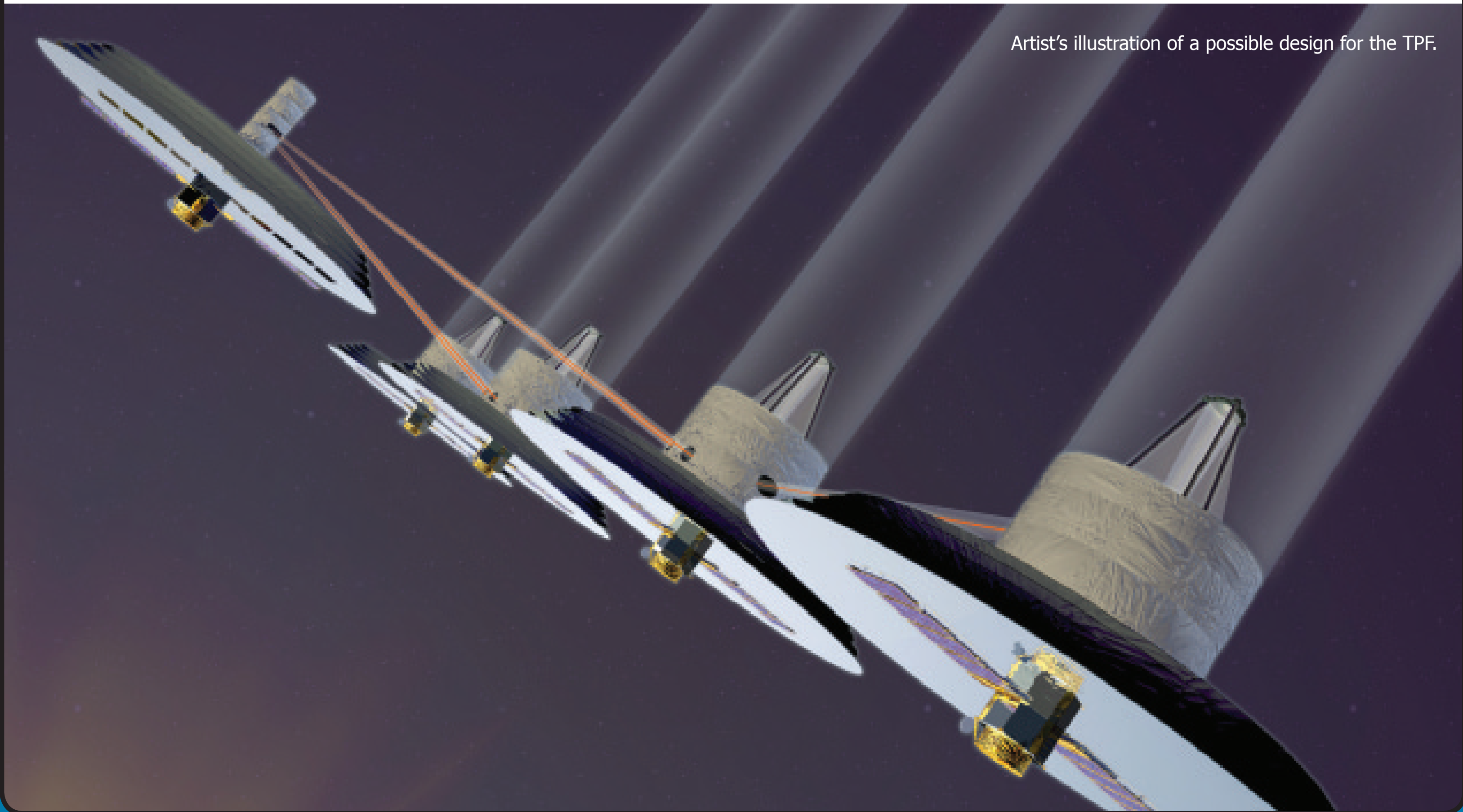
To make direct observations of Earth-sized planets around other stars will require an interferometer system with more powerful telescopes, capable of maintaining their separations at distances sufficiently large to provide much finer angular resolution than SIM's. By the end of this decade scientists should be poised to develop an interferometer array capable of direct detection of Earth-like planets around nearby stars—the Terrestrial Planet Finder (TPF).

Analysis of the infrared radiation and visible light from any such planets can reveal telltale signs of atmospheric gases. Oxygen or ozone would signal the possible existence of conditions favorable to aerobic life forms. Methane in the presence of oxygen would suggest the actual presence of life on these faraway worlds.


Optical image of the Keyhole Nebula (bottom) within the larger Carina Nebula.

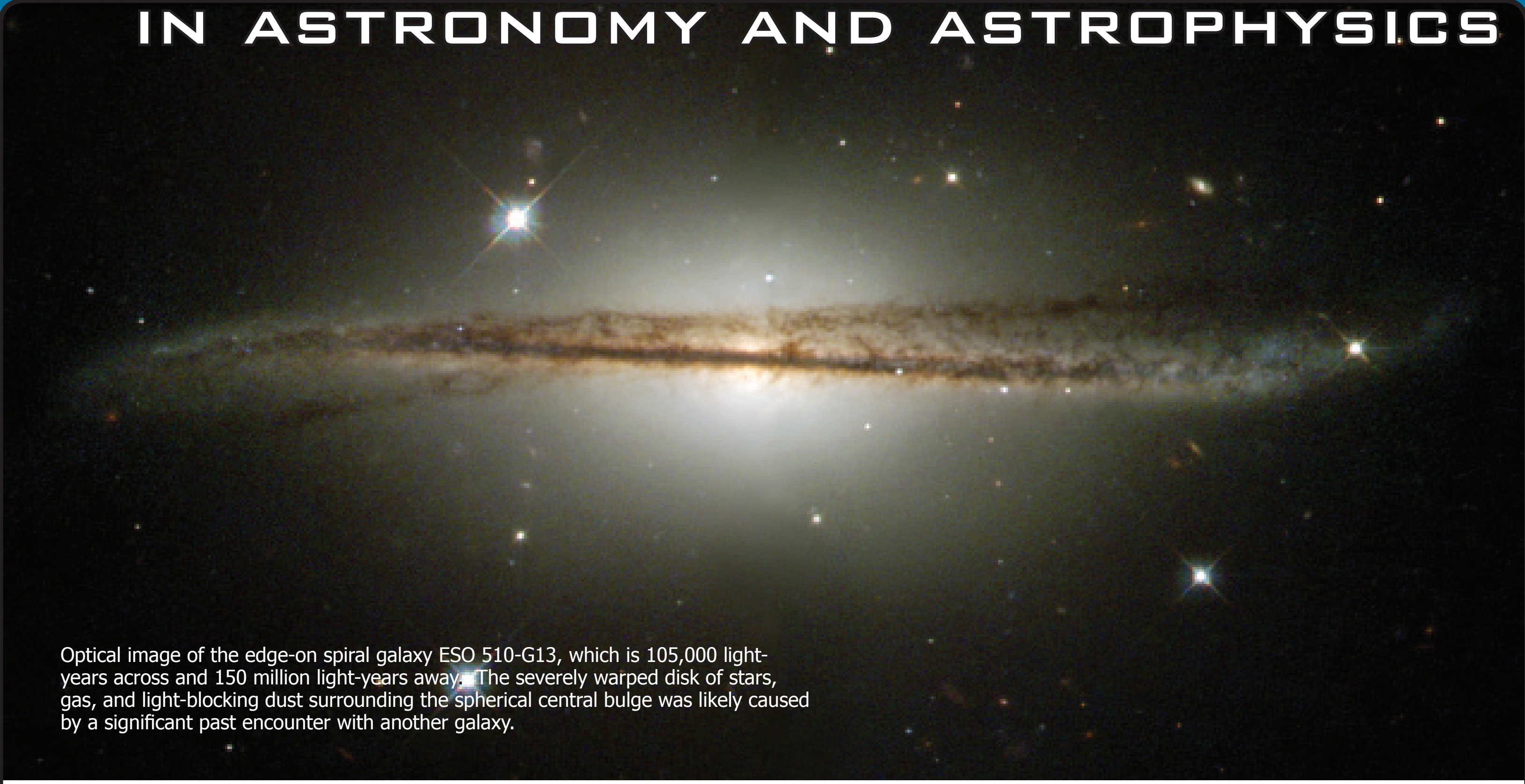
The Terrestrial Planet Finder (TPF) will find Earth's cousins: planets potentially suitable for life

PROBABLY the most ambitious of the projects recommended by the Astronomy and Astrophysics Survey Committee, the Terrestrial Planet Finder (TPF) will offer humanity the means to discover Earth-like planets orbiting other stars. Still in a conceptual stage, one version of the TPF would consist of four infrared-observing telescopes, each with a 3.5-meter mirror and spaced as much as a kilometer apart. So that they will be shielded from radiation that would interfere with their observations, the telescopes will orbit the Sun far from Earth's interfering infrared radiation. The telescopes will deploy panels to keep the Sun's rays from warming them, so that they can maintain temperatures close to 400 degrees below zero Fahrenheit and thus largely avoid emitting their own infrared radiation. The infrared domain offers better prospects than visible light for revealing an Earth-like planet. In this spectral region, a typical star outshines an Earth-like planet by a factor of only one million, rather than by a factor of one billion at visible wavelengths. By using a technique called nulling interferometry, the TPF could overcome this ratio of one million, which threatens to drown a planet's firefly light in the glare of the nearby stellar searchlight. Nulling interferometry effectively darkens the brilliant, pointlike starlight by diverting it along two paths that cancel each other, leaving a nearby planet visible. When not studying nearby stars for signs of extrasolar planets like our own, the TPF will observe other cosmic objects with an angular resolution a hundred times better than that of any previous instrument. This resolution will allow the TPF to study planetary systems in formation and star-forming regions in distant galaxies with a stunning clarity. Among other achievements, the TPF's high-resolution capability could allow it to verify the current hypothesis that the phenomena of quasi-stellar radio sources (quasars) and active galactic nuclei arise from matter swirling into black holes at the centers of galaxies.



Artist's illustration of a possible design for the TPF.

High-Priority Projects in Astronomy and Astrophysics



Optical image of the edge-on spiral galaxy ESO 510-G13, which is 105,000 light-years across and 150 million light-years away. The severely warped disk of stars, gas, and light-blocking dust surrounding the spherical central bulge was likely caused by a significant past encounter with another galaxy.

To address the scientific challenges described in *Astronomy and Astrophysics in the New Millennium*, the Astronomy and Astrophysics Survey Committee recommends undertaking the following projects, arranged in order of priority in three categories: major, moderate, and small. The page in this booklet that describes each project and the science that it addresses is listed in the right column.

MAJOR INITIATIVES

MODERATE INITIATIVES

SMALL INITIATIVE