

THE 1990s: THE DECADE OF DISCOVERY

Astronomers have just prioritized
the ways in which they try to
discover more about the universe.

John N. Bahcall



Astronomers and astrophysicists have learned that the climates and weather patterns of planets in the solar system are driven by many of the same physical processes that create the Earth's environment; that stars form out of clouds of gas and eventually die either in quiet solitude or spectacular explosions; that most of the common chemical elements are created in explosions of stars; that stars group together in isolated galaxies; that galaxies and clusters of galaxies stretch in sheets and filaments as far as the largest telescopes can see; and that the universe itself was born in a violent explosion some 15×10^9 years ago. Most amazingly, we have learned that the laws of nature on Earth apply to the farthest reaches of the observable universe.

Yet each new discovery leads to new puzzles: What kinds of planets form around other stars? What triggers the formation of stars in our Galaxy and in other galaxies? What powers the enormous bursts of energy seen in some galaxies? How did galaxies arise in the primitive universe? Where can black holes be found, and what are their properties? What is the ultimate fate of the universe? These are a few of the questions that capture the imaginations of astronomers and the general public and that stimulate young people to study mathematics, science and engineering.

Observations with underground, ground-based, airborne and orbiting telescopes during the 1980s produced

John Bahcall is chairman of the Astronomy and Astrophysics Survey Committee and professor of natural science at the Institute for Advanced Study, in Princeton.

important discoveries that advanced and consolidated our knowledge in many areas of astronomy. The following is a selection of some of the more important ones:

- ▷ The theory of the origin of the elements in the Big Bang received support from both astronomical observations of stars and sensitive experiments in particle physics.
- ▷ An orbiting satellite launched in 1989 began observing the relic radiation from the earliest years of the universe. Preliminary results indicate the need to revise existing theories of the formation of galaxies and clusters of galaxies.
- ▷ Evidence gathered shows that as much as 90% of the matter of the universe is dark matter with unknown physical characteristics.
- ▷ Quasars have been found at extremely large distances and must have formed when the universe was less than 10% of its present age.
- ▷ Einstein's prediction that gravity can bend rays of light found application in the discovery that galaxies can act as lenses, refracting the light from more distant quasars.
- ▷ Surveys of large numbers of galaxies revealed that the universe is organized on scales of tens of megaparsecs, larger scales than predicted by many cosmological theories.
- ▷ Optical and x-ray images suggest the possibility of giant black holes at the centers of some galaxies and quasars.
- ▷ An orbiting satellite surveying the sky at infrared wavelengths discovered disks of solid material, possibly the remnants of planet formation, orbiting nearby stars. It also found ultraluminous galaxies emitting 100 times as much energy at infrared wavelengths as at visible wavelengths.



A decade of deferred maintenance and refurbishment has led to a variety of problems at the national observatories, including the deterioration of the railroad track used to reconfigure the Very Large Array for operation at different spatial resolutions. (Courtesy of the National Radio Astronomy Observatory—Associated Universities.)

▷ Supernova 1987A burst into prominence in our closest neighbor galaxy, the Large Magellanic Cloud. About 20 antineutrinos from the supernova were detected in underground water Čerenkov detectors, confirming theoretical estimates for the total energy release, average neutrino energy and collapse time.

▷ Neutron stars that spin at the highest stellar rotation rate yet detected, nearly 1000 revolutions per second, were discovered from their regular pulses of radio radiation. Signals from these objects may constitute the most stable clocks in the universe, more accurate than any made by humans, and can be used to search for gravitational waves and probe the dynamics of star clusters.

▷ A deep probe of the interior of a star—our own Sun—was achieved through a technique analogous to terrestrial seismology, measuring pressure waves on the solar surface. These measurements established the extent of the solar convective zone and the effect of depth on rotation speed.

▷ Experiments with solar neutrinos hinted at the first departure from the standard model of electroweak physics, suggesting that neutrinos may have a nonzero mass and that lepton number is not conserved.

▷ The mass and radius of Pluto were determined from observations of its satellite Charon. Other studies of Pluto revealed the surprising fact that this small, cold planet has an atmosphere.

▷ Deuterium was discovered in the Martian atmosphere and was used to measure the past loss of water from Mars.

The decade of discovery

The 1990s promise to be a decade of discovery. The first

10-m telescope, the Keck telescope in Hawaii, will come into operation early in this decade. This telescope will be the first of several very large optical and infrared telescopes constructed in this country since the epoch-making installation of the Hale 5-m telescope on Palomar Mountain more than 40 years ago.

The technological revolution in detectors at infrared wavelengths will increase the sensitivity of telescopes by factors of thousands and is discussed in the article by Frederick Gillett and James Houck (page 32). New radiotelescopes, discussed in the article by Kenneth Kellermann and David Heeschen (page 40), will reveal previously invisible details at millimeter and submillimeter wavelengths, providing resolution that can be as good as 0.07 arcseconds. Interferometry, discussed in the article by Charles Beichman and Stephen Ridgway (page 48), will be used to combine optical or infrared light from different telescopes separated by hundreds of meters to make images hundreds of times sharper than can be achieved with a single telescope. A new branch of astronomy, particle astrophysics, applies techniques of modern physics to answer fundamental questions about astronomical systems and the universe as a whole. The article by James Cronin and Bernard Sadoulet discusses particle astrophysics (page 53). The four Great Observatories of the National Aeronautics and Space Administration will each view the cosmos across different infrared, visible, x-ray, ultraviolet and gamma-ray portions of the electromagnetic spectrum. These instruments, orbiting above the Earth's distorting atmosphere, will answer critical questions and may reveal objects not yet imagined. Space astronomy is discussed in the article by Claude Canizares and Blair Savage (page 60).

Astronomy and Astrophysics Survey Committee

John Bahcall, chair
Institute for Advanced Study
Charles Beichman, executive secretary
Institute for Advanced Study
Claude Canizares
Massachusetts Institute of Technology
James Cronin
University of Chicago
David Heeschen
National Radio Astronomy Observatory
James Houck
Cornell University
Donald Hunten
University of Arizona
Christopher McKee
University of California, Berkeley
Robert Noyes
Harvard-Smithsonian Center for Astrophysics
Jeremiah Ostriker
Princeton University Observatory
William Press
Harvard-Smithsonian Center for Astrophysics
Wallace Sargent
California Institute of Technology
Blair Savage
University of Wisconsin
Robert Wilson
AT&T Bell Laboratories
Sidney Wolff
National Optical Astronomy Observatory

The National Research Council commissioned the Astronomy and Astrophysics Survey Committee, a group of 15 astronomers and astrophysicists, to survey their field and to recommend the most important new ground- and space-based initiatives for the coming decade. The survey committee obtained advisory studies from more than 300 astronomers who participated in one or more of the 15 panels established to represent different wavelength disciplines, as well as solar, planetary, theoretical and laboratory astrophysics. Many other astronomers provided written advice or participated in organized discussions. More than 15% of America's astronomers played an active role in some aspect of this study. The committee also consulted with distinguished foreign scientists on future directions in astronomy. Beginning work in May 1989, the committee submitted its report to the National Academy of Sciences in October 1990. The report was published by the NAS Press in March 1991.

In addition to constructing a prioritized list of new instruments based on its assessment of the opportunities for fundamental scientific advances, the committee evaluated the existing infrastructure; considered the human aspects of the field, including education and international collaborations; explored the consequences of the computer revolution for astronomy; investigated the astronomical opportunities provided by lunar observatories; prepared a popular summary of opportunities for scientific advances in astronomy; and suggested the most promising areas for developing new observational technologies. The committee also examined the ways in which astronomical research contributes to society.

For the decade of the 1990s, the committee places the highest priority for ground-based research on increased support for the infrastructure of astronomy; for space-based research its highest priority is on establishing a program with an appropriate balance between more frequent small and moderate projects and unique large projects. The prioritized list of new-equipment initiatives primarily reflects the committee's assessment of the relative scientific potential of the different projects. The committee also took into account cost-effectiveness, technological readiness, educational impact and the relation of

each project to existing or proposed initiatives in the United States and in other countries.

[In the discussion that follows, italic type is used to set off the committee's recommendations.]

Priorities for ground and space

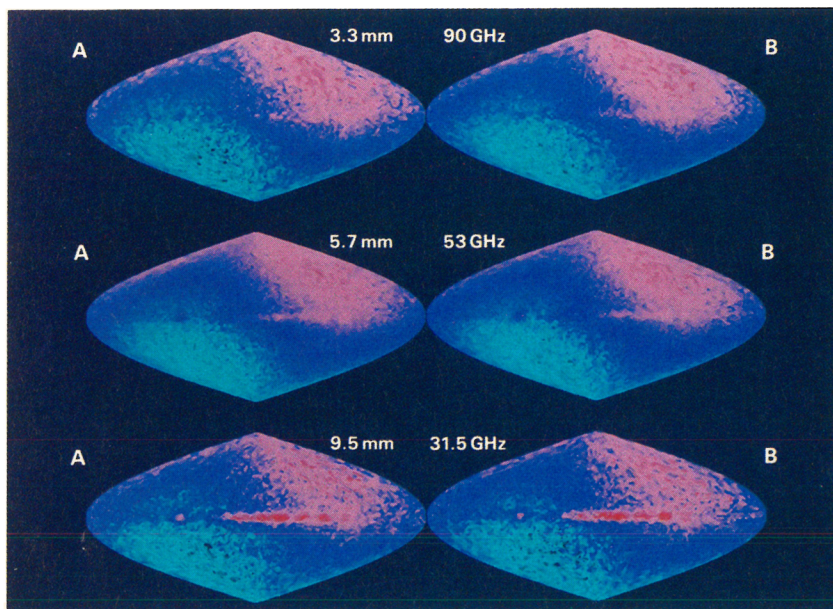
The committee's highest priority for ground-based research is to strengthen the research infrastructure at universities and at the national observatories.

The committee recommends that the NSF:

▷ *Increase the individual grants program in astronomy by \$10 million per year to permit young researchers new opportunities for discovery, to utilize appropriately the large numbers of new data and to enhance support for theoretical astrophysics;*

▷ *Increase the operations and maintenance budgets of the national observatories to an adequate and stable fraction of their capital costs, thereby repairing the damage caused by a decade of deferred maintenance.* The committee estimates that appropriate remedial actions will require increasing the operations, maintenance and refurbishment budgets for the observatories now in existence by a total of \$15 million per year.

For space astronomy, the report highlights the need for a balanced program that includes both the Great Observatories and more frequent, smaller missions. (The Great Observatories are large facilities that make possible "small science" at institutions across the country, since typically only a few researchers work on each observing project.) The committee reexamined the justification for large-scale space-astronomy programs, taking into account failures to meet specifications—as in the case of the



Preliminary COBE full-sky maps from its differential microwave radiometers show results from the two independent channels at three frequencies. The maps are in Galactic coordinates, with the center of the Galaxy centered at the center of each image. The Galactic plane, most apparent at low frequencies, runs horizontally through each map. The only nonlocal anisotropy thus far seen in the maps is the well-understood dipole term, which makes the sky appear hottest in the direction of our motion in the rest frame of the background radiation.

Hubble Space Telescope—and NASA's record of successes in carrying out other complex missions at the frontiers of science and technology.

The committee concluded that large telescopes are required to answer some of the most fundamental questions in astronomy. However, smaller telescopes can be built and launched more quickly to answer specific questions, to respond to technological innovations and to train future generations of scientists.

Instrument initiatives

Progress in astronomy often comes from technological advances that open new windows on the universe or make possible large increases in sensitivity or resolution. During the 1990s, arrays of infrared detectors, the ability to build large optical telescopes, improved angular resolution at a variety of wavelengths, new electronic detectors and the ability of computers to process large amounts of data will make possible an improved view of the universe.

Paralleling these remarkable achievements in observational capability are the advances in astrophysical theory that are being met with new generations of computers. Modern instruments reveal details that often require sophisticated models for their interpretation. Successfully comparing the results of observations with the constructs of theory and predicting new phenomena will require a deeper understanding of astrophysical processes, more clever algorithms, more computational power and improved knowledge of physical constants. Theoretical astrophysics is discussed in the article by Christopher McKee and William Press (page 69).

The survey committee divided its recommendations for instrument initiatives into categories of large, moderate and small programs, depending on the scale of the

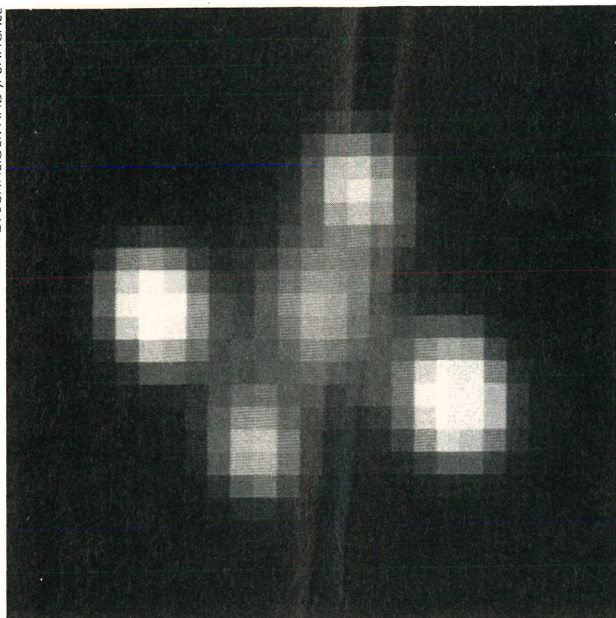
necessary resources. Ground- and space-based facilities were prioritized in a combined list and also separately.

The table on page 29 presents the recommended list of ground- and space-based-equipment initiatives in the large- and moderate-sized categories. The four large programs recommended for construction in the 1990s are described below in order of priority.

Large programs

The Space Infrared Telescope Facility, which would complete NASA's Great Observatory program, would be almost a thousand times more sensitive than Earth-based telescopes operating in the infrared. Advanced arrays of infrared detectors, pioneered in the United States, would give the Space Infrared Telescope Facility the ability to map complex areas and measure spectra a million times faster than any other space-borne infrared telescope. Two successful Explorer missions provide an excellent technical heritage for this facility.

An infrared-optimized 8-m US telescope operating on Mauna Kea, Hawaii, would provide a unique and powerful instrument for studying the origin, structure and evolution of the planets, stars, and galaxies. With diffraction-limited angular resolution better than a tenth of an arcsecond, high sensitivity due to the low telescope background and instruments optimized in the infrared and capable of high spectral resolution, the infrared-optimized 8-m telescope would complement the Space Infrared Telescope Facility across the limited range of wavelengths transmitted by the atmosphere. Plans for this telescope draw on a decade of progress in the technology of building large mirrors (See the article by Buddy Martin, John M. Hill and Roger Angel in *PHYSICS TODAY*, March, page 22.)



An image of the "Einstein Cross" taken from the Canada–France–Hawaii Telescope using simple "tilt correction." The bright point in the center is the core of a galaxy and the other four images are of a distant quasar lensed by the gravitational field of the nearby galaxy. The overall size of the image is about 8 arcseconds. The effective resolution of the image made with a simple adaptive optics system is about 0.4 arcseconds. (Courtesy of Rene Racine.)

Eight other 8-m class telescopes are in various stages of proposal or development throughout the world, including the European 4×8 -m (16-m effective diameter) Very Large Telescope, but none of these other telescopes are infrared optimized. The committee voted unanimously to recommend an infrared-optimized telescope as its highest-priority ground-based major new initiative, both because of the importance of the science that can be done with this instrument and the uniqueness of the facility.

The **Millimeter Array** an array of telescopes operating at millimeter wavelengths, would provide high-spatial- and high-spectral-resolution images of star-forming regions and distant star-burst galaxies. With spatial resolution of a tenth of an arcsecond at a wavelength of 1 mm, the array would bring new classes of objects into clear view for the first time. The Millimeter Array uses the experience and technology developed for the Very Large Array and for two smaller millimeter arrays.

An **8-m optical telescope** operating from the Southern Hemisphere would give US astronomers access to important objects in southern skies. All-sky coverage is essential for pursuing many of the most fundamental astronomical questions.

Small and moderate programs

Small- and moderate-size programs can be carried out relatively fast in response to new scientific or technological developments, focusing research into the currently most rewarding areas and making possible greater participation by young astronomers. Some of the most exciting scientific results of the past decade have come from modest, cost-effective programs.

The committee recommends an increased emphasis in the astronomy research budget for small and moderate programs.

Space-based programs. *Recommendations for moderate-size space programs include a three-phase augmentation of NASA's Explorer program by purchasing a dedicated spacecraft for the Far Ultraviolet Spectroscopy Explorer, by increasing the number of astrophysics missions launched on Delta rockets to six for the decade and by increasing the number of astrophysics Explorers launched on Scout-class rockets to five for the decade.*

The Stratospheric Observatory for Far-Infrared As-

tronomy, a moderate-size telescope in a Boeing 747 aircraft, should open submillimeter and far-infrared wavelengths to routine observation and would help train new generations of experimentalists.

The committee emphasizes that a moderate-class Astrometric Interferometry Mission that is capable of measuring the positions of astronomical objects to a precision of a few millionths of an arcsecond would have a great impact on many branches of astronomy. The committee urges specific funding for flying US instruments on foreign spacecraft.

Ground-based programs. For ground-based astronomy, the committee judged that two innovative techniques, adaptive optics and interferometry, can greatly enhance the spatial resolution of astronomical images. Adaptive optics can ameliorate the distorting effects of atmospheric turbulence and can be applied to existing or planned telescopes at infrared wavelengths and, eventually, at optical wavelengths.

The Large Earth-Based Solar Telescope would permit the investigation in unprecedented detail of magnetic fields and turbulent motions in the solar surface and overlying atmosphere and would at the same time test the application of adaptive-optics techniques. Optical and infrared interferometries promise spatial resolution better than a thousandth of an arcsecond by linking the outputs of widely separated telescopes. New equipment for the Very Large Array of radiotelescopes will make possible observations in a range—0.01 to 0.1 arcseconds—that cannot currently be carried out.

The committee urges the construction of additional 4-m optical telescopes to provide greater access by US scientists to state-of-the-art instrumentation capable of addressing significant astronomical problems. Private and state funds ought to be sufficient to build and operate such instruments, augmented with modest Federal assistance. The committee urges construction of a new Fly's Eye telescope that would increase by a factor of 10 instrument sensitivity to cosmic rays with energies in excess of 10^{19} eV.

The committee emphasizes the importance of continued funding for the development of improved detectors at optical and infrared wavelengths, and of new experiments to detect astronomical neutrinos and dark matter.

Theory, computers and lunar astronomy

The success of modern astrophysics illustrates the close interdependence of theory, observations and experiment. The committee believes that NSF and NASA should increase their support for relatively inexpensive theoretical and laboratory work that is crucial to the interpretation of the results from major observatories.

DOE has traditionally supported theoretical research in areas of importance and immediate applicability to astronomy and astrophysics—including plasma physics, atomic physics, nuclear physics, radiative transfer, properties of matter, cosmology and the physics of the early universe. The opportunity is great for fruitful cross-fertilization between astrophysics and the laboratory-oriented physics that is supported by DOE.

The committee recommends that theoretical astrophysics be funded as a separate program with an approximate budget of \$1 million per year within the grants program of NSF. Within NASA, support for theoretical astrophysics should grow in approximate proportion to its support for the analysis and interpretation of observational data.

Astronomers use computers to collect and study 10^{12} bytes of data every 24 hours and to make theoretical simulations of complex phenomena.

The committee recommends establishment of national electronic archives of ground- and space-based data, the purchase of desktop and departmental computers and the

development of fast networks to link most astronomical computers.

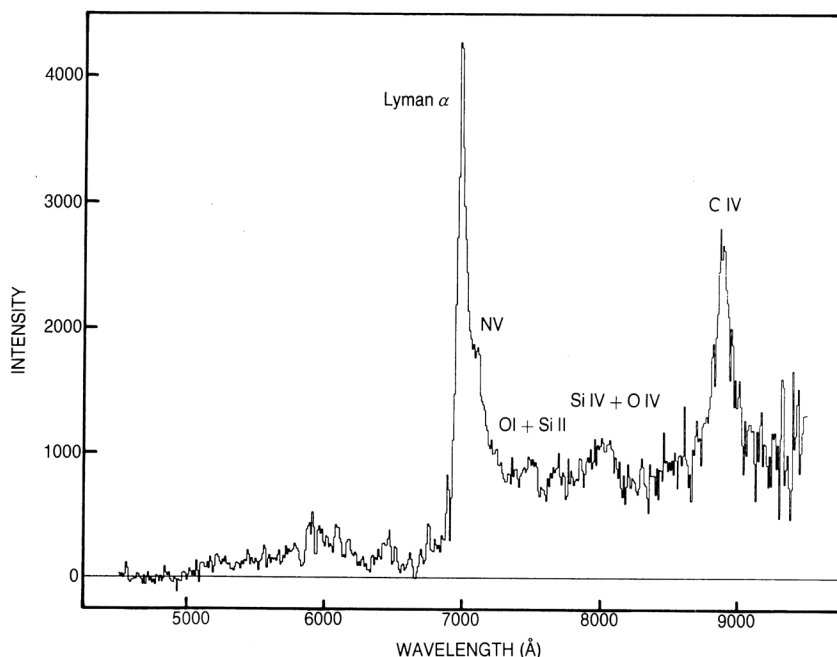
A major space-exploration initiative could return humans to the Moon in the early part of the next century. The committee studied the suitability of the Moon for possible astronomical facilities and concluded that a cost-effective and scientifically productive program would require early technology development, including pilot programs with substantial scientific return.

The committee recommends that an appropriate fraction of the funding for a lunar initiative be devoted to fundamental scientific projects, which can have a wide appeal to the US public; to support of scientific missions as they progress from small ground-based instruments, to modest orbital experiments; and finally, to the placement of facilities on the Moon. The advanced technology should be tested by obtaining scientific results at each development stage.

The committee urges selecting a modest project for the early phase of the lunar program, such as a 1-m-class telescope for survey or pointed observations, that would provide useful scientific data and valuable experience for operating larger facilities in the future. The committee concluded that in the long term the chief advantage of the Moon as a site for space astronomy is that it provides a large, solid foundation on which to build widely separated structures such as interferometers.

Recommended ground- and space-equipment initiatives

Initiative	Cost per decade (millions of dollars)
Large programs	
Space Infrared Telescope Facility (SIRTF)	1300
Infrared-Optimized 8-m Telescope	80
Millimeter Array (MMA)	115
Southern 8-m Telescope	55
Subtotal for large programs	<u>1550</u>
Moderate programs	
Adaptive optics	35
Dedicated spacecraft for FUSE	70
Stratospheric Observatory for Far-Infrared Astronomy (SOFIA)	230
Delta-class Explorer acceleration	400
Optical and infrared interferometers	45
Several shared 4-m telescopes	30
Astrometric Interferometry Mission (AIM)	250
Cosmic-ray telescope (Fly's Eye)	15
Large Earth-based Solar Telescope (LEST)	15
VLA extension	32
International collaborations on space instruments	<u>100</u>
Subtotal for moderate programs	1222
Subtotal for small programs	<u>251</u>
Total	<u>3023</u>



Spectrum of PC 1158 + 4635, a 20th magnitude quasar with the highest known redshift (4.73). The most interesting features of the spectrum, taken with the 200-inch telescope at Palomar Observatory, are the strong emission lines of hydrogen (Lyman α at 7000 Å) and carbon (C IV at 8880 Å) and the absorption due to intergalactic clouds of neutral hydrogen (the depression in the spectrum to the blue of the Lyman α line). (Courtesy of D. Schneider, M. Schmidt and J. Gunn.)

International cooperation

Research in astronomy and astrophysics is an international enterprise. Recent examples of successful international collaborations include the GONG project for studying the motions of the Sun's surface, the IUE and IRAS satellites, and intercontinental radio interferometry, which maps distant quasars and the motions of terrestrial continents. The United States provides access on a competitive basis for scientists of all countries to a number of major national facilities. In turn, the United States should expect that other countries will provide reciprocal access to their major facilities.

International cooperation in building major facilities is most effective when the project draws on the complementary capabilities of different nations or when the projects are too expensive for individual nations to afford. Some projects, such as a permanent observatory on the Moon, are so large and complex that international collaboration may be essential.

Substantial extra costs can be incurred, however, when facilities are built by more than one nation, arising, for example, from the increased complexity of coordinating technical interfaces and the necessity for duplicating some administrative efforts. Sometimes, international collaboration and scientific goals are most effectively advanced when nations build their own unique facilities, providing access to qualified scientists from other nations.

The committee recommends:

- ▷ That international cooperation be considered for the development of a major initiative if such a project draws on the complementary capabilities of different nations or requires resources beyond those that can be provided by the United States alone;
- ▷ Several new projects involving international collaboration as especially deserving of support, including the large

Earth-based solar telescopes (in collaboration with eight other countries), a 300-m radiotelescope in Brazil, the monitoring at multiple locations of neutrino bursts from supernovae, and the very-long-baseline experiments to be conducted in space in collaboration with Japan and the Soviet Union;

▷ A specific budget line for international collaborations that will allow NASA to undertake advantageous joint ventures.

Astronomy and society

Answering questions about the universe challenges astronomers, fascinates a broad national audience and inspires young people to pursue careers in engineering, mathematics and science.

The committee recommends enhancing astronomy's role in precollege science education by increasing the educational role of the national observatories, by expanding summer programs for science teachers and by setting up a national astronomy fellowship program to select promising high-school students for summer internships at major observatories.

Astronomical research assists the nation, directly and indirectly, in achieving societal goals. For example, studies of the Sun, the planets and the stars have led to experimental techniques for investigating the Earth's environment and to a broader perspective from which to consider terrestrial environmental concerns such as ozone depletion and the greenhouse effect.

Research in astronomy derives its support from our curiosity as human beings about the universe in which we live, from the stimulus it provides to young people to study science, from its synergism with other sciences and from the unforeseen practical applications that occasionally ensue. ■